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Original paper

Analyzing and simulating supply chain disruptions to the automobile industry based on experiences of the Great East Japan Earthquake

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Abstract The Great East Japan Earthquake revealed serious weaknesses in the supply chain management (SCM) employed by Japanese industries, and particularly by the automobile industry. Observed supply chain disruptions and production line shutdowns are recognized as symbolic of weaknesses in industrial SCM. The Japanese automobile industry in particular is now keen to improve supply chain resiliency in terms of automobile assembly line continuity. In view of this, we i) review observed negative impacts of the Great East Japan Earthquake on the automobile industry, ii) identify current strategies being evaluated by the automobile industry for improving supply chain resiliency, iii) develop a numerical supply chain model for the automobile industry, and iv) evaluate efforts to improve SCM practice through inclusion of risk mitigation measures. We conclude with recommendations for policy development to further strengthen automobile industry resiliency.

Key words Great East Japan Earthquake; Supply chain management; Numerical modeling; Automobile industry.

1. INTRODUCTION

The Great East Japan Earthquake and the resulting tsunami that occurred on March 11, 2011, highlighted an intrinsic risk of the sophisticated supply chain management (SCM) techniques employed by the Japanese automobile industry (Kanda *et al*. 2012). Fragility of transportation networks prolonged supply and production chain disruption (Ono and Kanda 2012). Among the lessons learned is the high risk of disrupted production lines due to supply chain disconnections in the aftermath of large disasters.

Extensive discussions of the negative impacts of external events on supply chains have been undertaken by many researchers in the last two decades, in particular after the terrorist attack of September 11, 2001, when the Ford Motor Company and Toyota Motor Corporation stopped production

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lines in the United States (US) due to delays in delivering automotive parts from overseas suppliers (Sheffi 2001). Thun and Hoenig (2011) evaluated supply chain risks by applying risk-mapping techniques to survey data from 67 German automobile manufacturing plants. Advantages of supply chain risk management were also tested and verified.

In Japan, a fire at Aisin Seiki's Kariya Plant No. 1 in 1997 demonstrated operational vulnerabilities of SCM based on just-in-time and single-source procurement. Many studies of supply chain vulnerabilities were undertaken in light of past experiences such as the Nihonzaka Tunnel fire accident in 1979, the Kobe Earthquake in 1995, the Chuetsu Offshore Earthquake in 2007, and the Great East Japan Earthquake in 2011 (e.g., Fujimoto 2011). Those studies addressed reduced business continuity capacities in the automotive industry by focusing on supply chain design structures. Among the studies, Matsuo (2015) used detailed case analyses to identify missing mechanisms in supply chain coordination systems and noted the importance of linked supply chain structures and infrastructure.

Based on past experiences, including the Great East Japan Earthquake, Japanese manufacturers have accelerated improvements to risk management practices in SCM with the aim of minimizing financial and market losses due to supply disruptions (Okamura *et al*. 2012; Kanda *et al*. 2013). Options being considered or implemented involve increases in i) parts inventory volume; ii) geographical spread of parts procurement sources, including moving suppliers overseas; and iii) supply chain system visibility. These risk mitigation strategies are, however, considered to involve a possibly deteriorating business environment for automotive parts suppliers, in particular those of local small and medium enterprises, for which these issues need to be properly addressed, and public policy should be established for maintaining the economy and employment at the local and national levels.

In view of this, a numerical model of the automotive supply chain was proposed and discussed as a method for evaluating consequences and implications of recent strategy developments in the automobile industry intended to improve supply chain resiliency (Ono *et al*. 2014). This paper reviews characteristics of the Great East Japan Earthquake in terms of geographical spread and supply and production chains of local manufacturers, mainly in the Tohoku region, where the most severe damage occurred. We focus on the automotive manufacturing system developed in this region, where supply chain fragility was highlighted after the earthquake.

In Chapter 3 we discuss the consequences of supply chain disruptions caused by the Great East Japan Earthquake. Particular attention is paid to the negative impact of the earthquake on motor vehicle production in a global context. We also note that some automotive parts are critical for maintaining assembly line operations because of the very low substitutability of some intermediate goods.

Chapter 4 identifies recent challenges to Japanese manufacturers in terms of supply chain risk management. Issues and possible strategies launched by Japanese manufacturers for improving SCM are discussed with reference to surveys performed in 2011–12 by the Kinki Regional Development Bureau and the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT).

Chapter 5 refers to a numerical model of the automobile industry supply chain in Japan, proposed by Ono *et al*. (2014). Chapter 6 tests reproducibility of the numerical model, and Chapter 7 describes a series of numerical experiments for evaluating the effectiveness and efficiency of SCM improvement strategies. Chapter 8 offers recommendations and a summary of the discussions, findings, lessons learned, and conclusions.

2. CHARACTERISTICS OF HAZARD AND EXPOSURES

2.1. Earthquake and tsunami disaster

The Great East Japan Earthquake comprised five large earthquakes with magnitudes ranging from Mw

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7.2 to 9.0 (Figure 1).

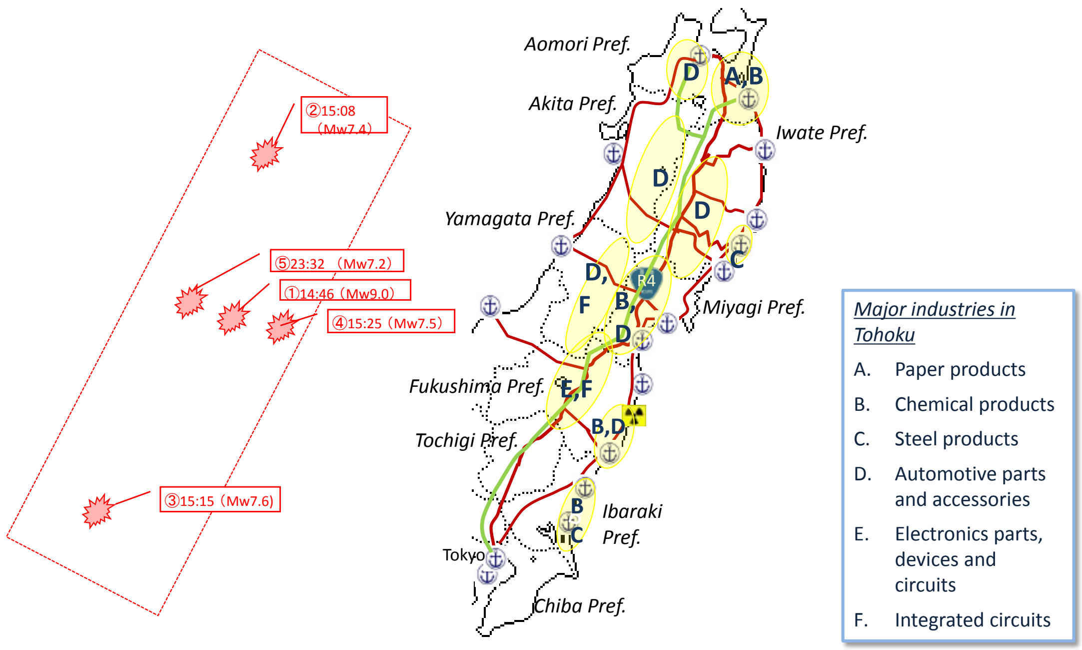

Figure 1. Geography and industries of the disaster area

The disaster was characterized by a huge tsunami with inundation depths exceeding 10 m in populated coastal areas. The tsunami badly damaged urban facilities, transportation networks, local industries, and communities (MLIT 2012).

2.2. Characteristics of the Tohoku region industries

Since the Meiji Era, the government has prioritized the Tohoku region for heavy chemical industry development, so many industrialized areas were created in the Pacific coastal region. These industries have provided automobile and integrated circuit (IC) manufacturers with fine materials and highly purified chemicals by drawing on skills and technologies developed over years.

Table 1 shows the top five products shipped from the disaster area affected by the Great East Japan Earthquake (Japan Small Business Research Institute 2011). Automotive, electronic parts, IC production, and traditional paper goods characterize the industrial structure of the disaster area. Among these, IC manufacturing firms in particular are of great importance to the Japanese economy and trade. A typical example is the Renesas Electronics Corporation, which provides the automobile industry with microprocessors. This company has a 30% global market share (Table 2). In terms of silicon wafers for microprocessor manufacturing, two major suppliers in the global market, Shin-Etsu Chemical Co., Ltd., and SUMCO Corporation, have their main factories in the Tohoku region. The combination of these firms with MEMC in the north Kanto region accounts for 77% of global production capacity (Table 3).

Table 1. Top five shipment categories in the Tohoku region disaster area

Rank	Product category	Value of shipments (\10 bil.)		% to all Japan
		Disaster area	All Japan	
1	Automotive parts and accessories	67	2,654	2.5%
2	Other electronic parts, devices and electronic circuits	33	405	8.1%
3	Integrated circuits	31	431	7.2%
4	Western and machine-made Japanese paper	30	208	14.4%
5	Vehicles (including motorcycles)	27	969	2.8%
All categories		1,165	30,525	3.8%

Source: 2011 White Paper on Small and Medium Enterprises in Japan, Small and Medium Enterprise Agency and Japan Small Business Research Institute

Remarks: Disaster area is defined as those municipalities to which the Disaster Relief Act was applied, as of March 24, 2011.

Table 2 Global microprocessor market share

Manufacturer	Annual output (US$ mil.)	Global share
Renesas Electronics Corporation (Jpn)[1)]	3,240	30%
Freescale Semiconductor Ltd (USA)	1,080	10%
Samsung Electronics Co., Ltd. (ROK)	864	8%
Microchip Technology Inc (USA)	648	6%
Texas Instruments Inc. (USA)	648	6%
Others	4,320	40%
Total	10,800	100%

Note [1)]: 25% of Renesas Electronics's output is manufactured at Naka factory, Ibaraki Pref.

Source: Shukan Economist issued April 26, 2011 (data from Gartner Japan Ltd)

Table 3 Silicon wafer production capacity

Manufacturer	Capacity (Units/month)	Global share
Shin-Etsu Chemical Co., Ltd. (Jpn) [1)]	1,320	33%
SUMCO (Jpn) [2)]	1,280	32%
MEMC (USA) [3)]	480	12%
LG Siltron (ROK)	440	11%
Siltronic (Germany)	400	10%
Covalent Materials Corporation (Jpn)	80	2%
Total	4,000	100%

Note [1), 2)]: 800,000 units are produced at Shirakawa factory, Fukushima Pref., and 300,000 units; at Yonezawa factory, Yamagata Pref..

[3)]: 200,000 units are processed at Utsunomiya factory, Tochigi Pref.

Remarks: As of the end of 2010, crystal wafer basis.

Source: Shukan Economist, issued April 26, 2011 (data from the Semiconductor Industry News)

While the automotive parts and IC industries have mainly developed in the inland foothills along the Trans-Tohoku Expressway, where there is no risk of tsunami damage, these establishments shut down due to supply shortages of fine materials and intermediate chemical products that were mainly provided by coastal industries. Electric power supply failures immediately after the disaster also hindered production, resulting in worldwide concern about supply shortages of microprocessors for automobile manufacturers.

2.3. Automobile industry in the Tohoku region

In the early 1990s, when the Toyota Motor Corporation started creating in the Tohoku region its third domestic automobile manufacturing cluster (following those in central Japan and northern Kyushu), two Toyota subsidiaries, Kanto Auto Works Co. Ltd. and Central Motor Co. Ltd., commenced automobile assembly operations with an annual production capacity of 150,000 cars. From this arose more than 1,000 automotive parts establishments located in the Tohoku region, forming a production complex covering a broad array of operations such as rubber and plastic molding, forging and casting, press-work, machining, welding, plating and polishing, sewing, and on-vehicle electronic component installation as well as molding, tooling, and automatic machine manufacturing (Intelligent Cosmos Research Institute 2012).

3. IMPACT OF THE GREAT EAST JAPAN EARTHQUAKE ON INDUSTRY

3.1 Overall view of the negative impact on industry

The Tohoku region contributes to the Japanese economy as a newly emerging industrial cluster that produces fine chemical products and parts and components for manufacturing industries. The Tohoku region ships these intermediate goods to a wide range of global industries, including firms engaged in automobile, electronics, optical, and industrial manufacturing. Among the industrial outputs of Japan, however, the Tohoku region produces a small part; for example, only 13% of electric components and 15% of intelligence and telecommunication devices come from the Tohoku region. Nevertheless, the Great East Japan Earthquake not only affected production in the Tohoku region but also triggered a global chain-reaction shutdown of the manufacturing- and assembly-oriented economy.

The eastern Japan area, comprising the Tohoku region and the northern part of the Kanto region, services about 20% of the Japanese market for ICs, following the 40% of the Kyushu region. There are about 80,000 enterprises in the tsunami-affected area, which produce a combined ¥4.4 trillion output. There are a further 740,000 enterprises in the earthquake-affected area with total output of ¥35.6 trillion (Japan Small Business Research Institute 2011). Figure 2 compares industrial production indices between the disaster area and the rest of Japan based on data provided by the Ministry of Economy, Industry and Trade (METI) (METI 2012a).

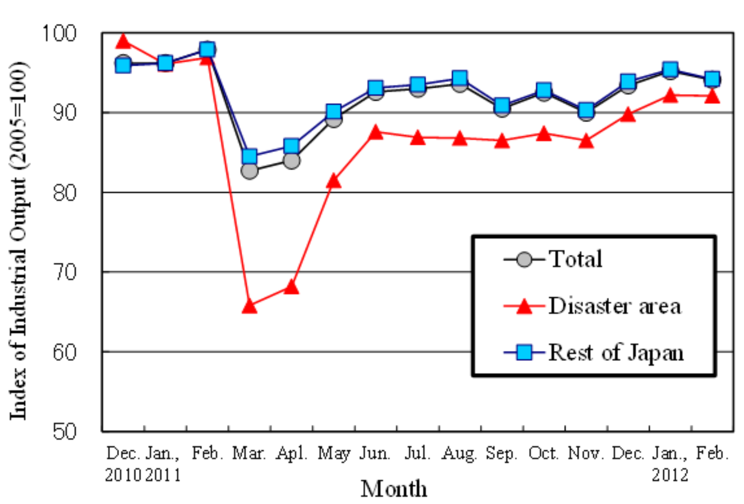

Figure 2. Industrial output indices between the disaster area and the rest of Japan

Output from the disaster area decreased by about one-third in March–April 2011 as compared with the same months in the previous year, while production from the rest of Japan was reduced by 15%. Note that this dramatic slump continued for only two months, while production levels in the disaster area were 5–10% lower until the end of the year.

Among the disaster areas, those directly hit by the tsunami suffered a much harsher impact. Figure 3 illustrates the dramatic decline of industrial output from establishments located in the tsunami-affected area (METI 2012b). Affected industries include chemical products, rubber, ceramics, iron and steel, non-ferrous metals, fabricated metals, electronics, and others. The tsunami seriously damaged facilities in the devastated area, to the extent that over 90% of production capacity was lost until the end of the August.

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Even ten months later, only 40% of capacity had recovered.

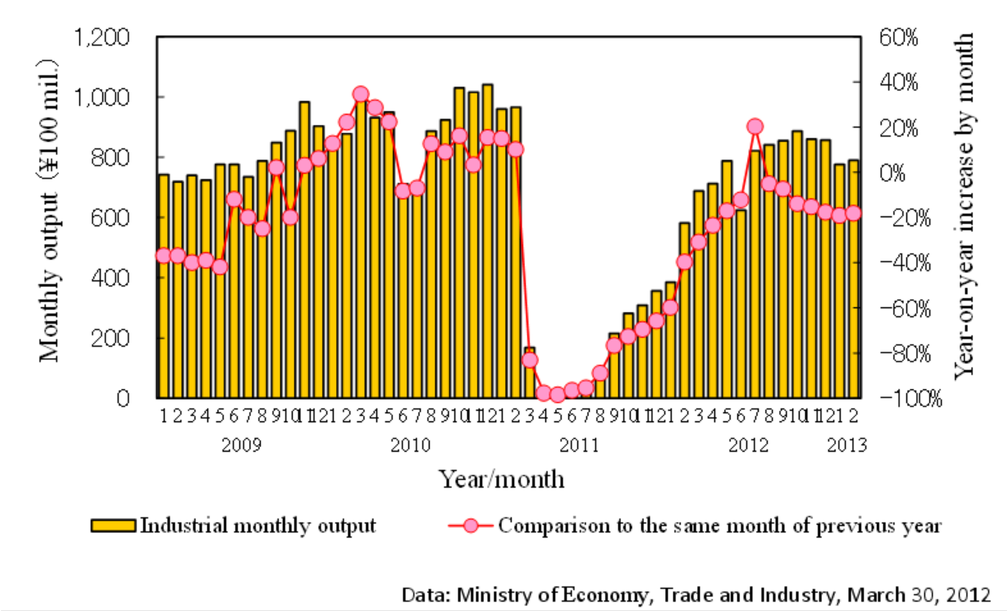

Figure 3. Industrial output in the tsunami-damaged area

According to regional industrial output indices, production of transportation equipment including motor vehicles decreased in March 2011 by more than 40% below previous-month figures in the Kanto, Chubu, and Kyushu regions, 29% in the Hokkaido and Chugoku regions, and 5.7% in the Shikoku region (Table 4). Also observed in the Tohoku area were notable decreases of basic material industries such as petroleum production, iron and steel industry, and the chemical industry. This suggests widespread ripple effects on the production of transportation equipment, likely induced by the shutdown of basic materials production in Tohoku, and particularly of fine chemical and electronic materials.

3.1 Impact of supply chain disruption

The shutdown of establishments in the Tohoku region was caused not only by facility damage but also by disruptions to the supply of intermediate goods needed for operating production lines. Figure 4 shows major bottlenecks for maintaining production lines as experienced by manufacturers across Japan in the aftermath of the Great East Japan Earthquake. Data were obtained from a questionnaire conducted by MLIT. Among respondents, 30.9% of establishments cited upstream supply-chain disruptions as a factor in production shutdown, and 12.1% of establishments attributed problems to business interruptions with clients. A further 16.4% mentioned both reasons, so 60% of companies were affected by the disaster in some way.

Figure 5 contains a schematic view that illustrates some consequences of supply chain disruptions between basic materials industries and the automobile, industrial machinery, and home electronics industries in the Tohoku region.

The fine materials and highly purified chemical products supplied by the basic materials industries in Tohoku are essential for the processing and assembly industries, so the supply shortages of these material caused by the Great East Japan Earthquake set off a chain reaction of production network disruptions. One of the most essential products identified in Figure 5 is micro-processors, for which providing silicon

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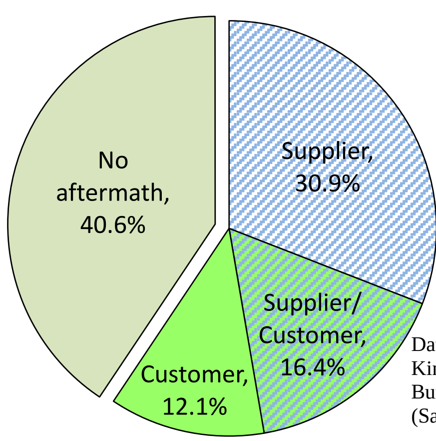
wafers is vital. Ultra-thin copper foil is also a critical basic material because it is needed to produce flexible microprocessor substrates, and Tohoku companies have a 20% global share of these products. The limited operations of these companies due to the Great East Japan Earthquake adversely affected microprocessor production in Tohoku, which consequently affected operation of automobile, industrial machinery, and home electronics assembly lines.

Table 4. Industrial output indices by region for Feb–Mar 2011

	Hokkaido				Tohoku				Kanto				Chubu			
	Industry	Feb.	Mar.	Mar/Feb	Industry	Feb.	Mar.	Mar/Feb	Industry	Feb.	Mar.	Mar/Feb	Industry	Feb.	Mar.	Mar/Feb
1st	Transportation equipment	142.4	100.8	▲29.2	Petroleum products	99.6	5.9	▲94.1	Transportation equipment	80.9	40.3	▲50.2	Transportation equipment	101.5	56.6	▲44.2
2nd	Furniture	84.6	61.9	▲26.8	Furniture	73.2	24.1	▲67.1	Rubber products	79.9	58.1	▲27.3	Non-ferrous metals	97.8	77.9	▲20.3
3rd	Non-ferrous metals	429.7	316.9	▲26.3	Iron and steel	102.6	35.3	▲65.6	Petroleum/coal products	91.3	67	▲26.6	Furniture	73.5	64.5	▲12.2
4th	Wood/Wood products	100	86	▲14.0	Pulp/paper/paper products	99.1	40.3	▲59.3	Iron and steel	103.1	76.9	▲25.4	Electrical machinery	104.6	93.1	▲11.0
5th	Textiles	74.2	66.1	▲10.9	Chemicals	123.4	65.3	▲47.1	General equipment	93	71.5	▲23.1	Plastic products	92.4	82.4	▲10.8
Over all		97.4	91.9	▲ 5.6	Over all	99.5	64.7	▲35.0	Over all	91.1	74.2	▲18.6	Over all	100.2	82.1	▲18.1

	Chugoku				Shikoku				Kyushu				Japan overall			
	Industry	Feb.	Mar.	Mar/Feb	Industry	Feb.	Mar.	Mar/Feb	Industry	Feb.	Mar.	Mar/Feb	Industry	Feb.	Mar.	Mar/Feb
1st	Transportation equipment	111.9	79.5	▲29.0	Fabricated metals	70.6	61	▲13.6	Transportation equipment	127.4	72.4	▲43.2	Transportation equipment	99.3	52.9	▲46.7
2nd	Food and tobacco	123.9	95.8	▲22.7	Transportation equipment	105.4	99.4	▲ 5.7	iInformation communication equipment	76.4	45.7	▲40.2	Non-ferrous metals	93.8	78.3	▲16.5
3rd	Fabricated metals	82.6	66.3	▲19.7	Mining	93.6	88.4	▲ 5.6	Plastic products	113	104	▲ 8.0	Rubber products	96	81.1	▲15.5
4th	General equipment	80.9	65.8	▲18.7	Petroleum/coal products	119.8	113.3	▲ 5.4	General equipment	116.5	109.5	▲ 6.0	Furniture	74.9	64	▲14.6
5th	Pulp/paper/paper products	93.4	84.4	▲ 9.6	Non-ferrous metals	107.9	104.8	▲ 2.9	Ceramics, stone and clay products	100.3	95.5	▲ 4.8	General equipment	93.9	80.3	▲14.5
Over all		97.4	91	▲ 6.6	Over all	97.5	98.4	0.9	Over all	105.6	97.1	▲ 8.0	Over all	97.9	82.7	▲15.5

Note: Indices of industrial products were estimated and published by the respective Regional Bureaus of Economy Trade and Industry.
Source: Indices of industrial products. Ministry of Economy, Trade and Industry



Data: Questionnaire survey, Kinki District Construction Bureau, 2011
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Figure 4. Major production shutdown causes

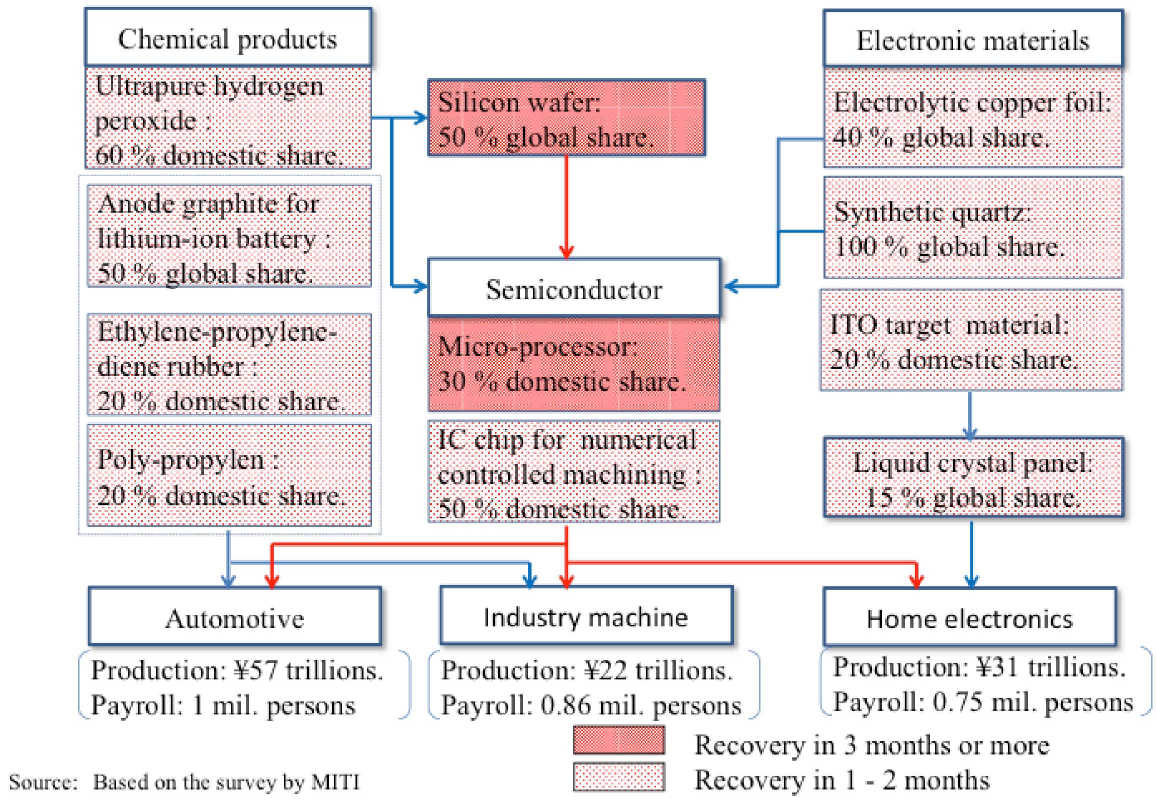


Figure 5. Schematic view of supply chain disruption in Tohoku

3.2 Consequences for national and global production

As stated in the previous section, one of the most important manufacturing clusters in Japan was developed in the Tohoku region to produce parts, components, and ICs for the automobile, electronics, and optical industries. However, the supply chain was partially disrupted by the Great East Japan Earthquake, resulting in paralyzing the entire manufacturing cluster. This production shutdown was not limited to the Tohoku region, but extended throughout the country and even to overseas manufacturers throughout the global supply chain network.

Figure 6 compares indices of industrial production (IIP) for transportation equipment in the disaster area and the rest of Japan in 2011 with those for the same month in 2010. The IIP estimation was performed by Teikoku Databank Ltd. under commission by METI (Teikoku Databank, Ltd. 2012).

Transportation equipment production in the disaster area decreased to a relative level of 0.76 in March and 0.71 in April 2011. Note, however, that the IIP in the rest of Japan decreased even more, to 0.55 in March and 0.51 in April 2011. As Table 4 shows, automotive parts supply shortages in the Tohoku region triggered by the Great East Japan Earthquake had a much bigger impact on automobile production across the nation than in Tohoku.

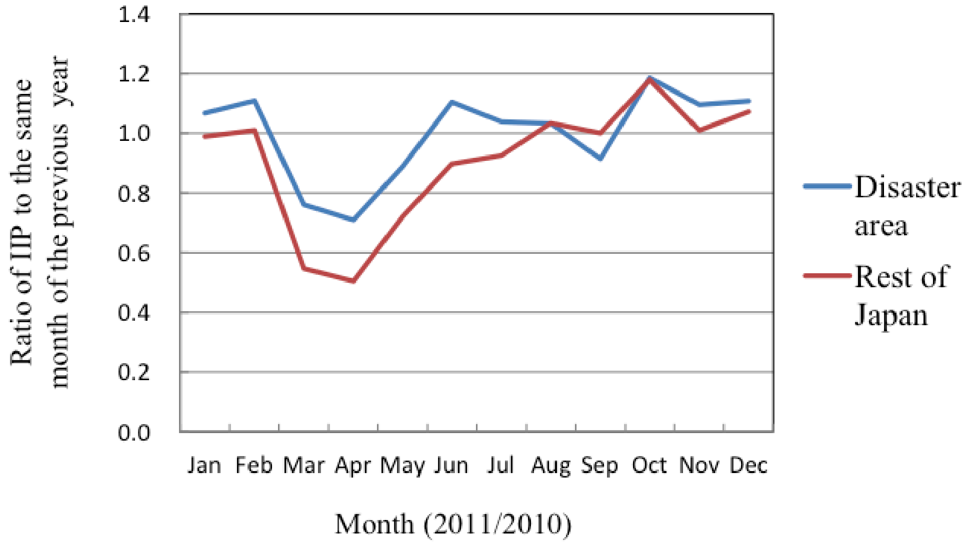


Figure 6. IIP of transportation equipment in 2011 versus the same month of 2010

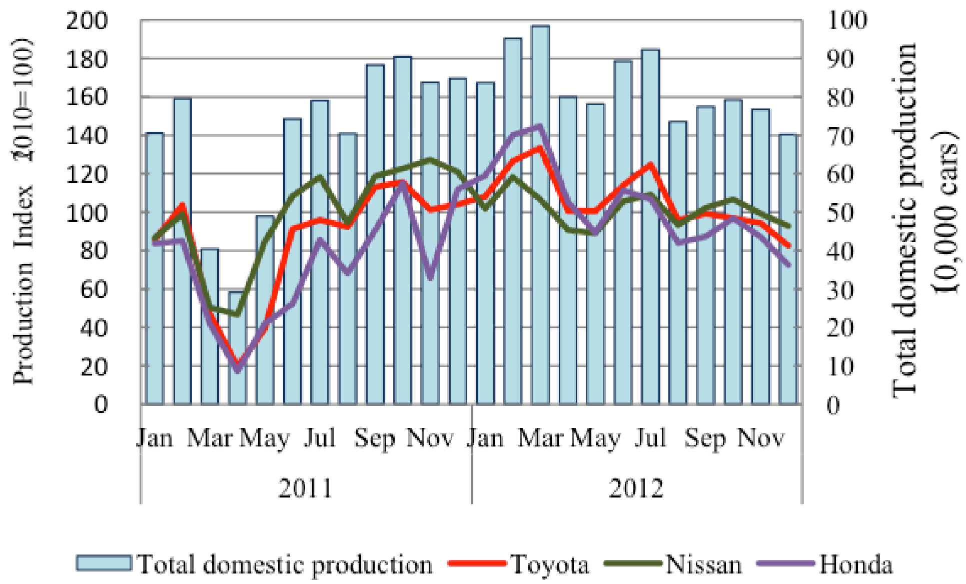


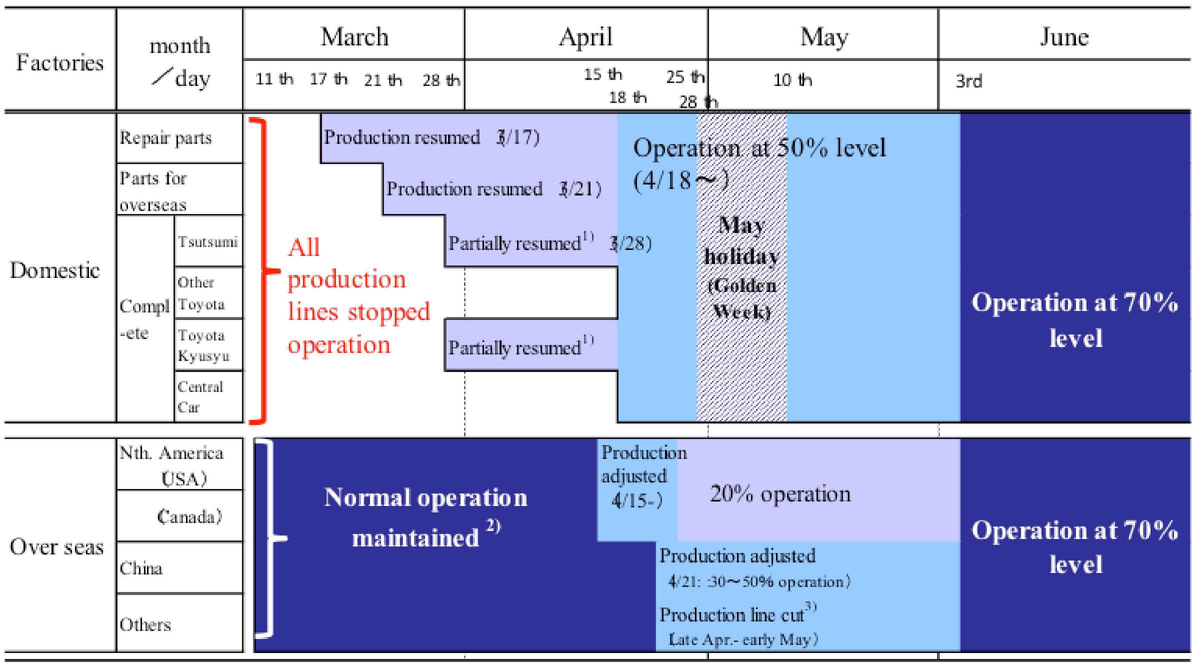
Figure 7. Automobile production in Japan

Figure 7 shows automobile production in Japan for 2011–12. Data were provided by the Japan Automobile Manufacturers Association. In that figure, monthly production as indices (average production in 2010 = 100) for Toyota, Nissan, and Honda are shown by lines, and the total amount of domestic production is shown as bars.

The Great East Japan Earthquake directly damaged automobile production lines in the Tohoku and Kanto regions, but also indirectly interrupted assembly line operations in many other areas of Japan due to supply chain disruptions. As Figure 7 shows, production levels of Japanese automobile manufacturers were significantly reduced from March to May 2011. Honda Motor Co., Ltd. maintained only 17% of monthly production in April as compared with the previous year, and Toyota Motor Corporation only

20%. In April 2011 Japanese manufacturers produced 290,000 cars domestically, only 36% of April 2010 production (800,000 cars). Comparing this with the IIP for transportation equipment nationwide (Figure 6) suggests that supply chain disruption caused by the Great East Japan Earthquake affected nationwide automobile production in Japan with a much bigger negative impact than that of other transportation equipment production.

Figure 8 illustrates Toyota's operations across the world in the three months following the Great East Japan Earthquake.



Note 1) Production limited to Prius and Lexus. Source :Estimation by authors based upon information disclosed by Toyota.
2) No overtime, no holiday work basis
3) Limitted assembly line operations in UK, France and Turky; engine factories in UK and Poland closed. No detail are announced.

Figure 8. Post-disaster operations at Toyota Factories

Domestic assembly lines of Toyota factories were shut down immediately after the disaster to confirm the safety of employees and their families and to allow investigation of damage to production lines and supply chains. By 38 days after the disaster domestic assembly lines had recovered to about 50% of normal operation capacity, increasing to 70% levels in June.

Overseas factories not directly affected by the disaster suffered from poor supply of parts and components from Japan, dramatically reducing production to around 40% of previous levels at 40–45 days after disaster. Negative impacts on the order of 20% operation levels in North America and 30–50% in China were seen. These overseas production disruptions suggest that delivered parts in transit may serve as a substantial warehouse stockpile for about 40 days, retarding negative influences of supply shortages on overseas automobile production.

Figure 9 displays time-series productions for complete passenger cars, microprocessors, and automotive parts such as engine parts, drivetrains, transmissions, control parts, suspension and brake parts, car audio equipment, car navigation systems, and cooling devices for car air conditioners. These data are shown as indices taking production values of October 2010 as 100. Microprocessor sales records are also

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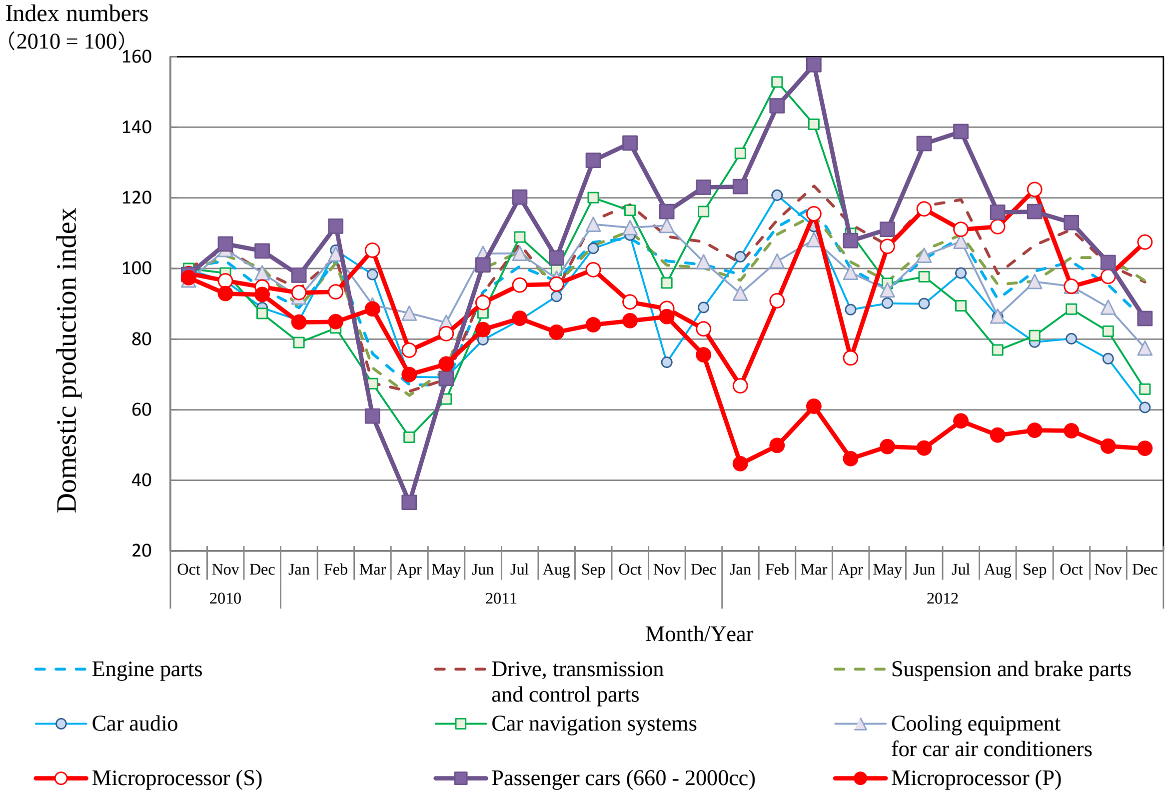
indicated in the figure. Note that the microprocessor supply decreased by only 20–30% in April 2011, while automobile production dropped by about 80% in the same month. Reduced automotive parts values are between these, except for car air conditioner parts.



Note: Engine parts, drive, transmission, and control parts, and suspension and brake parts: Japanese yen basis. Others are quantity basis.

Data: Machinery statistics, Ministry of Economy, Trade and Industry

Figure 9. Production of microprocessors, automotive parts, and passenger cars

The above observations lead to a hypothesis that an absence of only a few parts can shut down whole automobile assembly lines. This is likely because of the low substitutability of parts supplied to automobile assembly lines, which generally require 20,000–30,000 parts to produce one car. The experience of the Great East Japan Earthquake clearly indicates supply chain vulnerabilities due to the involvement of critical elements in automobile assembly lines. As such one must consider the substitutability of critical automotive parts to analyze supply chain structures and characteristics for further improving SCM.

4. RECENT RISK MANAGEMENT CONSIDERATION BY MANUFACTURERS

The Kinki Regional Development Bureau, MLIT conducted a series of surveys in 2011–12 to investigate manufacturer SCM improvement strategies following the Great East Japan Earthquake. The surveys included questionnaires and interviews, and targeted Japanese manufacturers capitalized at more than ¥1 billion. This chapter identifies changes in the supply chains of Japanese manufacturers after the disaster, and discusses issues and possible strategies for improving SCM.

3.3 Risk awareness and strategies of Japanese manufacturers

Figure 10 shows negative impacts on production caused by the Great East Japan Earthquake. The data was obtained from 636 manufacturers through a questionnaire survey. Among the direct impacts (items i–iv), damage due to ground motion was by far the most common response given in 15.5% of answers. The most common indirect impact (items iv–xiii) was shutdown of supply sources (15.3%), followed by disruption of transportation, power supply shortages, and planned blackouts conducted to compensate for power grid functionality loss. Items v–xiii are indirect impacts, with the first six of those classified as supply chain disruptions.

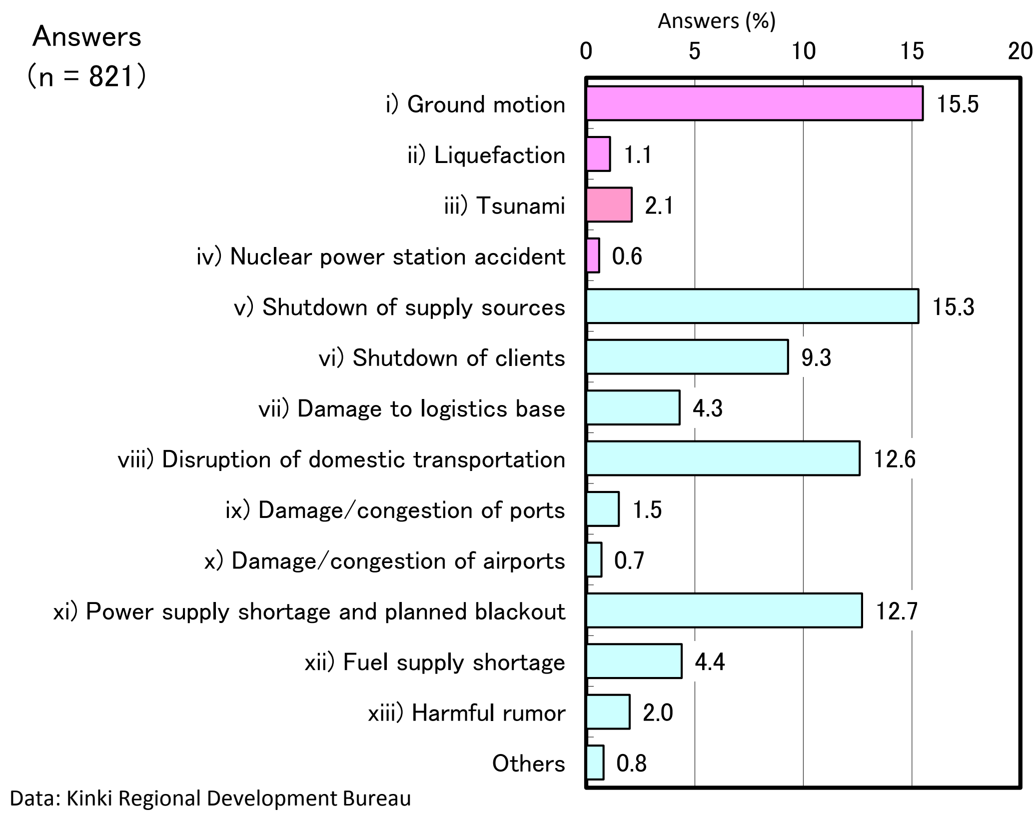


Figure 10. Causes of production shutdown due to the Great East Japan Earthquake

Japanese manufacturers considered and announced their strategies to strengthen supply chains to cope with the supply chain disruptions listed in Figure 10. The survey highlighted recent near-term strategies of the manufacturers as listed in Figure 11. In general, the most common countermeasure against supply chain disruption is likely geographically spreading out domestic supply sources, followed by expanding overseas procurement networks and employing new suppliers. Note that manufacturers focused on risk diversification considerations in preference to other options.

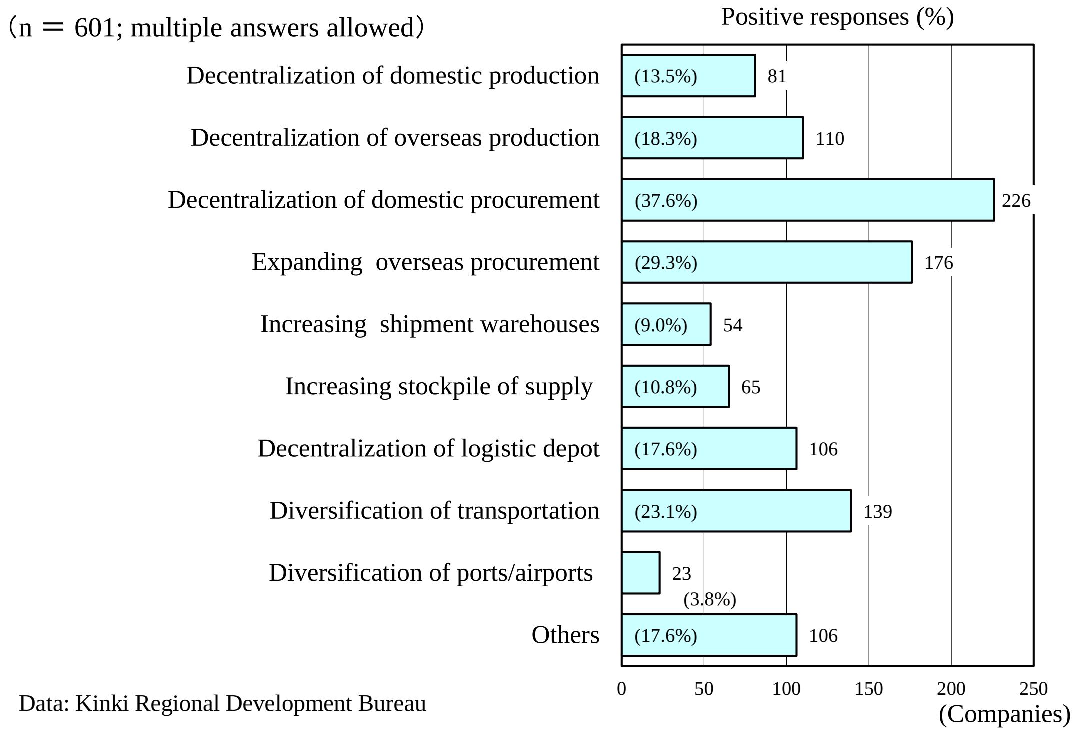


Figure 11. Strategies for strengthening SCM considered by Japanese manufacturers

Figure 12 indicates changes, as of 2012, in the number of supply chain nodes within Japan. Data was obtained from 165 manufacturers, of which about 60% declared no change in the number of nodes. However, the numbers of suppliers and logistics depots upstream of the supply chain were slightly decreased, while those of distribution centers and sales offices showed no clear change. The number of production sites decreased. Manufacturers likely have not yet decentralized supply chain nodes and production sites within Japan, despite many manufacturers planning to do so immediately after the Great East Japan Earthquake.

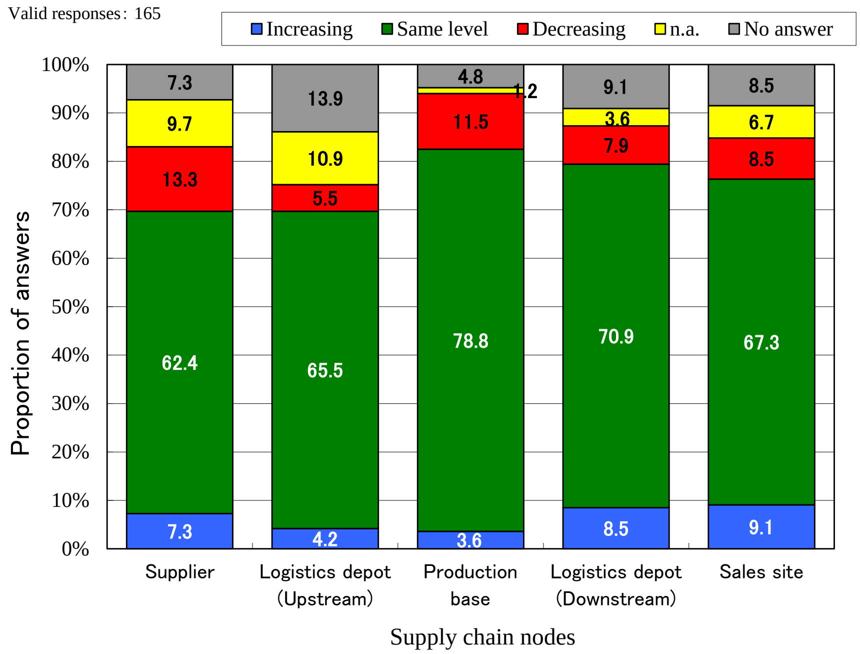


Figure 12. Changes in the domestic supply chain of Japanese manufacturers

Note that manufacturers emphasized logistics cost-cutting over risk mitigation measures.

Figure 13 shows changes in overseas supply chains. At that time, 25.5% of manufacturers responded that they would increase the number of supply sources. Because of the appreciated Japanese yen until 2013, manufacturers were keen on increasing overseas production sites and supply sources, and were reluctant to expand domestic supply chains. This is considered to be clearly reflected in the survey results.

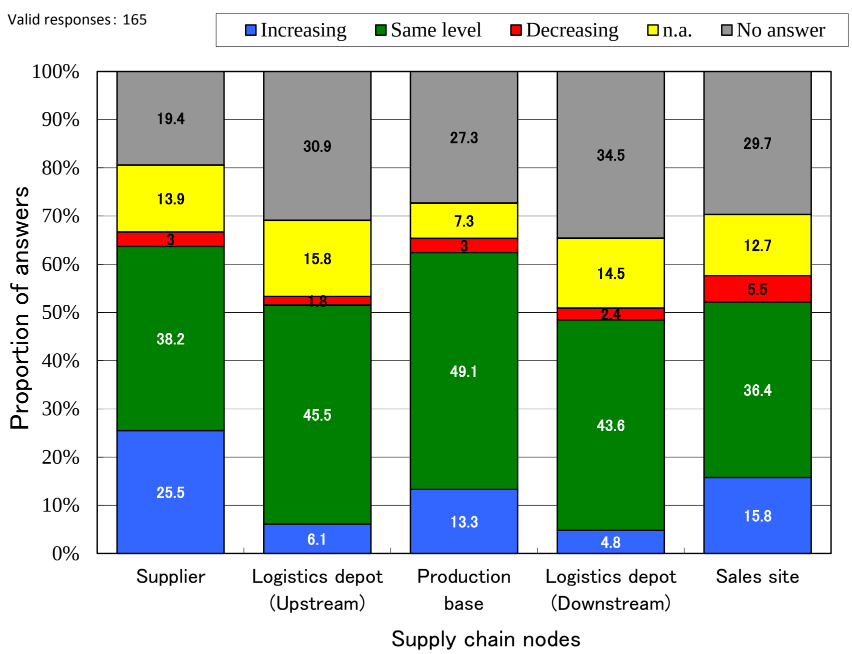


Figure 13. Changes in the overseas supply chains of Japanese manufacturers

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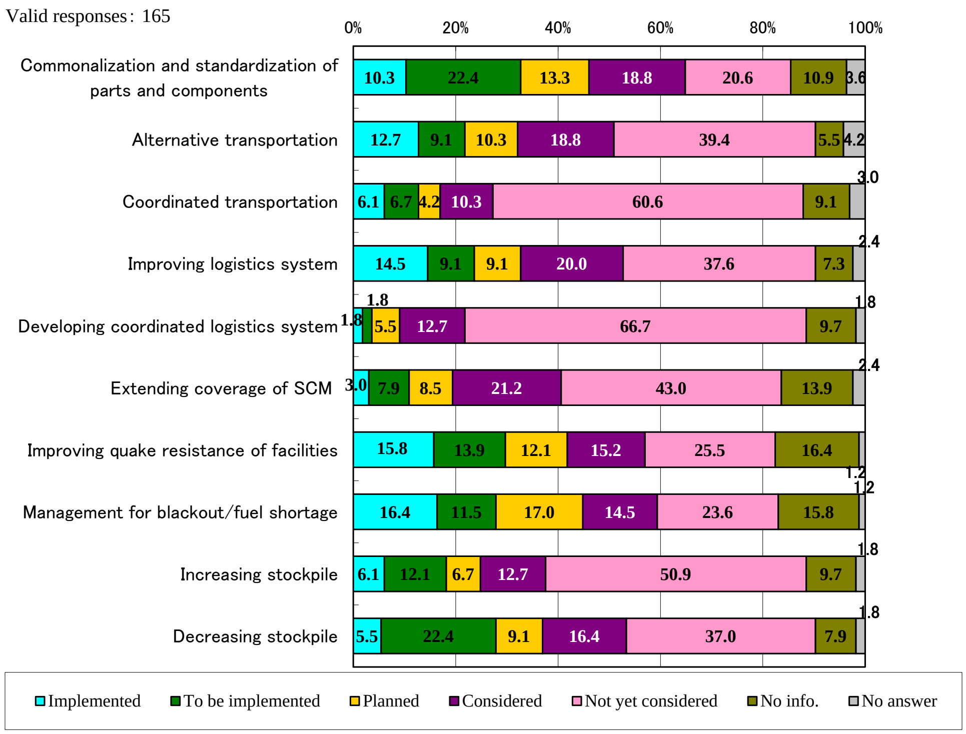

Figure 14. Current measures undertaken for improving risk management in SCM

Figure 14 identifies efforts made by manufacturers for improving supply chain risk management. About 40% of manufacturers reported a current commitment to developing a common architecture for parts and components, reinforcing facilities against earthquakes, and facilitating preparedness for blackouts and fuel shortages.

However, among options such as mutual cooperation in securing means of transportation, developing common logistics systems, and visualizing supply chains, only 10% were implemented or being implemented by manufacturers. Stockpile levels of materials, parts, and components were rather decreasing. We thus consider that manufacturers in Japan are taking only limited steps for inclusion of risk management into SCM, and they are mainly focusing on in-house answers.

3.4 Strategies for improving SCM

Chapter 3 analyzed and discussed the unprecedented impact of the Great East Japan Earthquake on local industry based on data released by the government and local authorities. Section 4.1 identified recent considerations and implementations of SCM improvement strategies through a questionnaire survey conducted by MLIT.

Since the 1995 Great Hanshin–Awaji Earthquake, major manufacturers have recognized the significance of risk management regarding supply chain disruptions. Many manufacturers have thus initiated emergency response plans, which were however created by corporate planning, administration, personnel, and financial divisions, and mainly focus on confirming employee safety, damage assessment, and operational cash flow management after a disaster. Only logistics personnel seriously considered the risks of supply chain disruptions and its consequences before the Great East Japan Earthquake, which motivated manufacturers to start considering logistics aspects of risk management. Challenges undertaken by logistics section personnel include the following:

A) assessing natural disaster risks to supply chains;
B) appraising acceptable business risk as a constraint of business operations;
C) preparation of a business continuity plan (BCP) for improving supply chain resiliency; and
D) strengthening parts procurement and logistics controls, and risk mitigation by means such as increased inventory levels, geographically diffuse procurement sources, assistance in early production restoration, and visualization of supply chain systems.

As Section 4.1 highlighted, however, initially considered options to mitigate natural risks on the supply chain such as geographically diffusing domestic procurement sources and expanding overseas supply chain networks have not progressed in the past year. Due to chronically decreased competitiveness and poor business performance, Japanese manufacturers are financially discouraged to invest in supply chain reconstruction. Manufacturers are instead inclined to tackle production system improvements such as communalizing and standardizing parts and components, shifting procurement overseas, securing alternative means of transportation, and system development for visualizing supply chains. These do not necessarily require large financial investments or sweeping policy reform. Increasing stockpiles would seem to be attractive, but the survey indicated that parts inventories are instead being trimmed. The situation is thus one of increased fragility of SCM methodologies focusing on curtailing transportation, inventory and distribution costs.

It is widely recognized among manufacturers that supply shortages of parts and components easily halt production line operations. Japanese manufacturers are thus in urgent need of strengthening SCM for securing parts and components. In view of this, options being tackled by manufacturers include further visualizing the status of lower-tier suppliers in order to quickly remove possible supply chain bottlenecks. It is reported that over 2,000 support personnel from the Renesas group and outside groups were dispatched to recover the company's Naka Plant when it suffered serious damage in the Great East Japan Earthquake (Maruya 2012). Also ongoing is shifting procurement sources overseas to create more stable and lower-risk supply chains. Parts inventory increases are continuously being considered, while long-term struggles in the global market have discouraged Japanese manufacturers from taking further steps toward introducing inclusive risk reduction and mitigation mechanisms into SCM.

5. NUMERICAL MODELING OF AUTOMOBILE INDUSTRY SUPPLY CHAIN

This chapter discusses the development of an algorithm for numerically modeling automobile industry supply chains. Our goal in modeling is to evaluate the resiliency of automotive supply chains in the aftermath of large disasters, so we set monthly production of motor vehicles and automotive parts as major output variables by considering currently available statistics of the Japanese automotive industry. As input variables reflecting the shock of the disaster in production, we consider the shutdown period of complete automobile assembly lines and supply disruptions of automotive parts from the disaster area. The model parameters are expected to be determined by past production records and production disruptions observed in the aftermath of the Great East Japan Earthquake.

Ono *et al*. (2014) proposed a numerical model to describe a simple two-tier supply chain system for the automobile industry. The model includes an automobile assembly line and parts suppliers in six categories: engine parts, electric equipment for internal combustion engines, chassis and body parts, suspension and brake parts, drivetrains, transmission and control parts, and miscellaneous parts. Motor vehicle production levels are constrained by the automotive parts supply, and thus determined by the parts supply with the lowest stocks. The automobile assembly line and the majority of parts suppliers are located outside of the disaster area, but some portion of the parts is assumed to be produced within the disaster area. As such the proposed numerical model comprises one automobile assembly line and twelve automotive parts suppliers. Alternative parts suppliers within Japan and overseas are also included in the numerical model, which is illustrated in Figure 15.

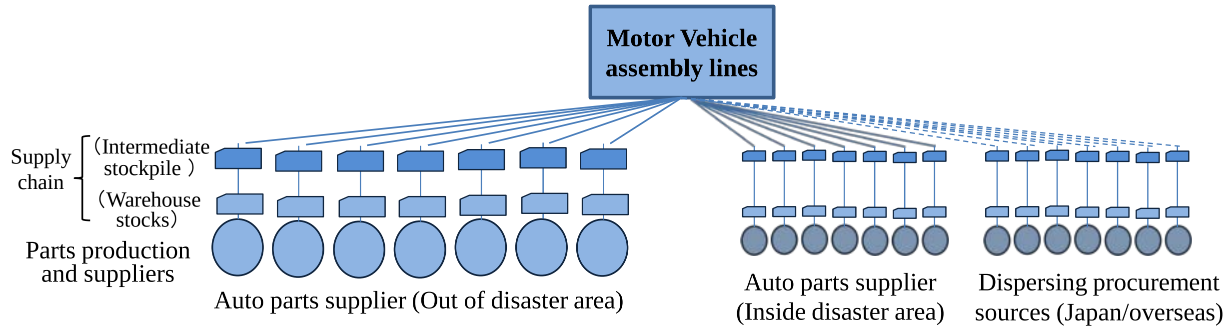

Figure 15. Schematic view of the supply chain model

Suppliers produce automotive parts in accordance with production plans prepared in advance by considering production records from the previous year. Daily production amounts are controlled so as to avoid stock shortages or dead stock at warehouses. The parts are shipped to intermediate stockpiles, where they await delivery orders from assembly lines. Intermediate stockpiles are under inventory control of the automotive parts supplier. Parts in the intermediate stockpiles are delivered to the assembly line to maintain production, but this is possible only when the intermediate stockpile has enough volume. In the proposed supply chain model, these productions, shipments and deliveries are numerically repeated on a daily basis.

Since no substitutability between the parts productions within and outside of the disaster area is assumed, supply disruption from the disaster area can cause assembly line shutdowns. The assumption is based on the experience of automobile production disruption due to parts supply shortages in the aftermath of Great East Japan Earthquake.

The following expressions describe the supply chain model. The relationship between motor vehicle production and parts supply is formulated by Eqs. (1) and (2), where t is the number of days after a disaster, i is a suffix expressing areas (1 for the areas not experiencing the disaster and 2 for the disaster-affected area), and j is a parts category suffix.

$$P^t = Min\left(P_0^t,\ \alpha_{ij} \times S_{ij}^t\right) \text{ -------------------------- (1)}$$

$$S_{ij}^t = H_{ij}^{t-1} \text{ -- (2)}$$

Here,

P_0^t : Planned motor vehicle production for day t (cars/day).

P^t : Actual motor vehicle production on day t (cars/day).

S_{ij}^t : Possible input of parts with category j produced at area i (hereinafter described as “parts ij”) into motor vehicle assembly lines on day t (million yen/day).

H_{ij}^t: Intermediate stockpile volume of parts ij on day t (million yen).

α_{ij} : Motor vehicle production per unit of parts ij (thousand cars/hundred million yen).

Balances of parts at intermediate stockpiles and supplier warehouses are as follows:

$H_{ij}^{t} = H_{ij}^{t-1} - S_{ij}^{t} \quad + s_{ij}^{t} \ + s_{oj}^{t}$ -------------------- (3)

$W_{ij}^{t} = W_{ij}^{t-1} - d_{ij}^{t} \quad + p_{ij}^{t}$ -------------------------- (4)

Here,

W_{ij}^{t}: Volume of parts *ij* stocked in supplier warehouses on day *t* (million yen).

s_{ij}^{t} : Volume of parts *ij* delivered to an intermediate stockpile on day *t* (million yen/day).

s_{oj}^{t}: Volume of parts *i* procured from alternative suppliers within Japan or overseas on day *t* (million yen/day).

d_{ij}^{t}: Volume of parts *ij* shipped from supplier warehouses to intermediate stockpiles on day *t* (million yen/day).

p_{ij}^{t} : Volume of parts *ij* produced by supplier factories on day *t* (million yen).

Because of transportation times, there exist the following relationships among the volumes of parts *ij* shipped from warehouses and delivered to intermediate stockpiles:

$s_{ij}^{t} = d_{ij}^{t-\tau ij}$ --- (5)

$s_{oj}^{t} = d_{0j}^{t-\tau oj}$ --- (6)

Here,

τij : Lead time between shipment from a warehouse and delivery to an intermediate stockpile for parts *ij* (days).

τoj : Lead time from ordering to delivery to an intermediate stockpile of parts *i* (days).

Warehouse shipment volumes are determined by comparing production plans and current production, taking transportation lead times into account.

$d_{ij}^{t} = \mathrm{Max}\,(P_0^{t+\tau ij}/\alpha_{ij},\ P^{t-1}/\alpha_{ij}\ ) \times \beta h$ --------- (7)

Here, βh is a parameter for adjusting stockpile volume. *βh* equals 1 when the stockpile volume is less than a controlling value, and *βh* equals 0 when the volume exceeds the controlling value.

The available volume for parts shipments is less than the warehouse stock.

$d_{ij}^{t} \le W_{ij}^{t}$ --- (8)

Parts are produced to meet motor vehicle production plans.

$p_{ij}^{t} = (P_0^{t+\tau ij}/\alpha_{ij} \quad) \quad \times \beta w$ ---------------------- (9)

Here, βw is a parameter for adjusting warehouse stocks. βw equals 1 when the stockpile volume is less than a controlling value, and *βw* equals 0 when the stockpile volume exceeds the value. α_{ij} is a parameter showing the input–output relationship between motor vehicle production and parts supply, as estimated from monthly statistics provided by the Ministry of Economy, Industry and Trade (METI). Seventy-two weeks of data from 2007–12 were used for correlation analysis. Examples are shown in Figure 16.

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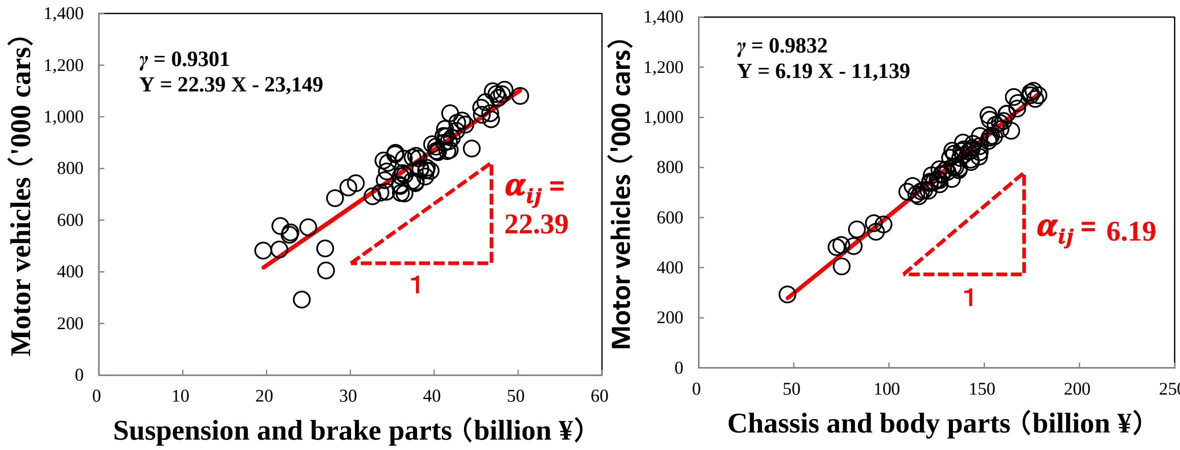

Figure 16. Examples of α_{ij} based on motor vehicle production and parts supply

6. REPRODUCTION OF THE IMPACT OF GREAT EAST JAPAN EARTHQUAKE

In this chapter we demonstrate reproducibility of the model in terms of negative impact of the Great East Japan Earthquake on the Japanese automobile production in 2011.

As stated in Section 3.3, motor vehicle assembly lines in Japan shut down immediately after the Great East Japan Earthquake. Automotive parts production in the disaster area also stopped due to the damage. As a consequence, parts suppliers located out of the disaster area suspended operations. Utilizing a back-analysis technique, the period of the immediate shutdown of assembly lines and stoppage of six category parts factories were determined to minimize deviations between model estimates and actual production of motor vehicles in 2011. Controlling values of the intermediate and warehouse stocks of parts suppliers were also estimated accordingly (Table 5).

Table 5. Estimated exogenous variables

Motor car production	Automotive parts (i = 1 ~ 6)	α (cars/mil.J¥)	Production shutdown (days)	Targeted inventory level
Estimated shutdown period of assembly lines. ↓ **18.8 days**	Chassis and body	6.2	51.5	Ranges from 244% to 700%
	Engine	10.6	44.6	
	Drive, transmission and control	3.7	48.0	
	Suspension and brake	20.4	23.6	
	Electric equipment for internal combustion engines	25.0	17.8	
	Miscellaneous parts	20.1	51.7	

Figure 17 demonstrates goodness of fit of the model by comparing model reproductions and actual production records for 2011. Coefficients of determination are 0.9861 for motor vehicle production and 0.9910 for automotive parts production, which likely indicate high reproducibility of the model.

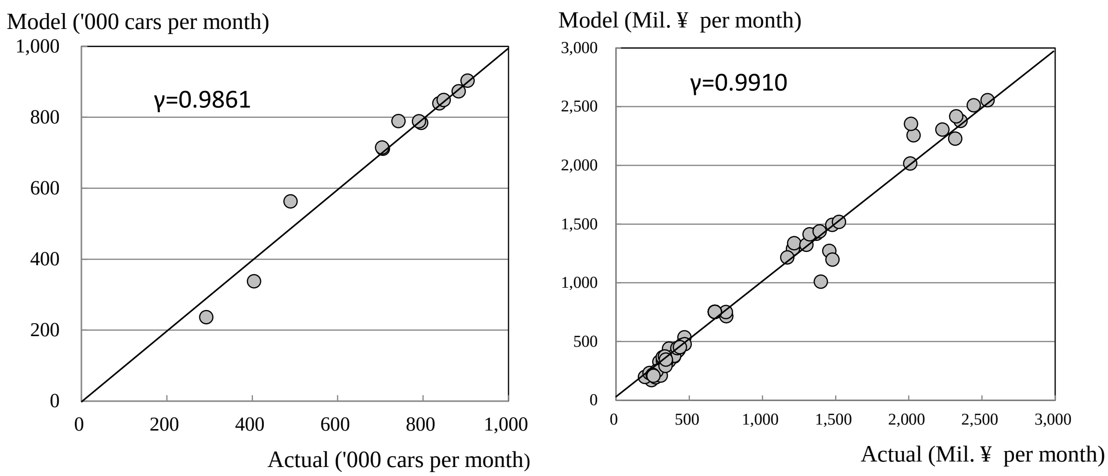

Figure 17. Reproducibility of the model

Figure 18 compares motor vehicle production in terms of actual and model-estimated amounts. The model mostly reproduces the negative impact of the Great East Japan Earthquake on production in 2011.

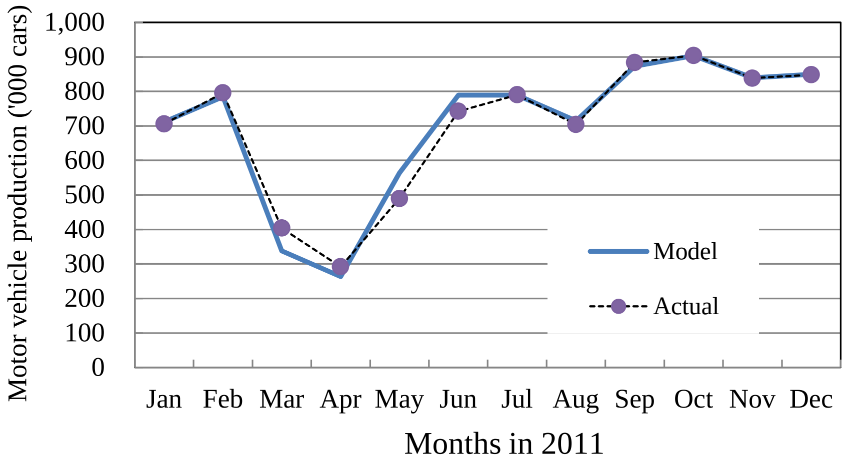

Figure 18. Motor vehicle production in 2011

Figure 19 compares production of chassis and body parts and of engine parts in terms of actual and model-estimated amounts.

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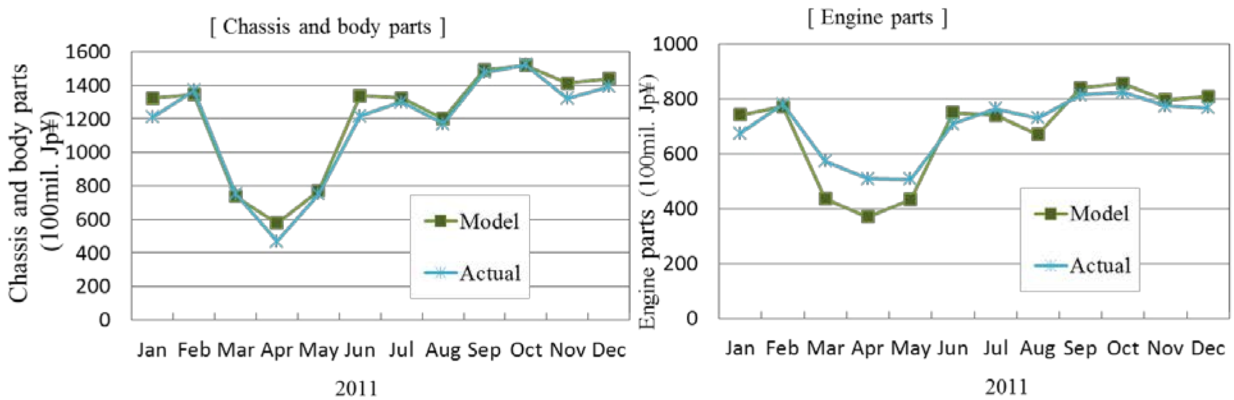

Figure 19. Production amounts of automotive parts in 2011

Model values for chassis and body parts demonstrate quite good performance in reproducing the negative impact, while model values for engine parts are a bit below actual production. The deviations between model values and actual productions are 26.9% for engine parts, 23.4% for suspension and brake parts, and 22.9% for drive, transmission and control parts. These deviations are likely due to the single inventory control parameter used in the model and to the model's simple design and structure.

7. REVIEW AND EVALUATION OF SCM IMPROVEMENT STRATEGIES

7.1 Strategies and resiliency metrics

As discussed in Section 4.2, among the strategies recently being considered by Japanese automobile manufacturers, three may require review and evaluation for effectiveness and efficiency toward securing the automotive parts industry in Japan.

Among those strategies undertaken since the Great East Japan Earthquake to improve SCM, of particular importance from the viewpoint of public policy development are increasing inventory volumes at intermediate stockpiles and parts factory warehouses and geographical diffusion of parts procurement sources, including shifting procurement abroad. From past natural disasters, automobile manufacturers also learned about the effectiveness and efficiency of mutual assistance (for example, providing emergency rehabilitation material, equipment, and personnel) among supply-chain participants in recovering production facilities, especially those of bottleneck parts suppliers. These lessons were first learned from the fire accident at Aisin Seiki, a Japanese automotive parts manufacturer, which resulted in supply disruptions for proportioning valves mainly supplied to Toyota assembly lines. These lessons were reaffirmed during the aftermath of the Great East Japan Earthquake.

This chapter discusses the effectiveness and efficiency of the above-described risk mitigation measures based on the supply chain model. The decrease in motor vehicle production seen in 2011 is considered as an evaluation benchmark.

As a resilience metric for automobile supply chains, we introduce a production recovery ratio Γ, defined as the ratio of the recovered motor vehicle production to the total decline of production due to the disaster.

$$\Gamma = \left\{1 - \frac{\sum_1^{365}(P_0^t - P_r^t)}{\sum_1^{365}(P_0^t - P_a^t)}\right\} \times 100 \quad (\%),\ p_0^t,\ p_a^t,\ p_r^t \in M_{2011} \text{ ------ (10)}$$

Here, the following variables are used:

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P_0^t : Planned motor vehicle production on day t.

P_a^t : Actual motor vehicle production on day t.

P_r^t : Motor vehicle production on day t recovered through proactive measures undertaken by automobile manufacturers.

M_{2011} : Planned, actual, and simulated motor vehicle production in 2011.

7.2 Procurement diversification strategy

We tested the effects of procurement diversification by mainly focusing on geographically diffusing suppliers and shifting procurement overseas. Figure 20 (left) shows the effect of diffusing parts suppliers both inside Japan and overseas.

The production recovery ratio increases in proportion with the diversification ratio δ shown on the horizontal axis, and reaches levels of about 50–60% when α equals 70%. Here, the diversification ratio is defined as the ratio of the procurement amount from spreading suppliers to the total parts procurement amount illustrated in Figure 20 (right). Geographically diverse suppliers have no risk of experiencing the same hazard as those in the disaster area.

The diversification ratio is 33% when half of automotive parts procurement is shifted to other areas, 50% when parts production is equally shared by two suppliers from different areas, and 67% when three suppliers are involved.

In the figure, the lead time for procuring automobile parts is also considered. This lead time is attributed to the time needed for transportation of the parts and represents moving parts suppliers from Japan to Southeast Asia, for example (Table 6).

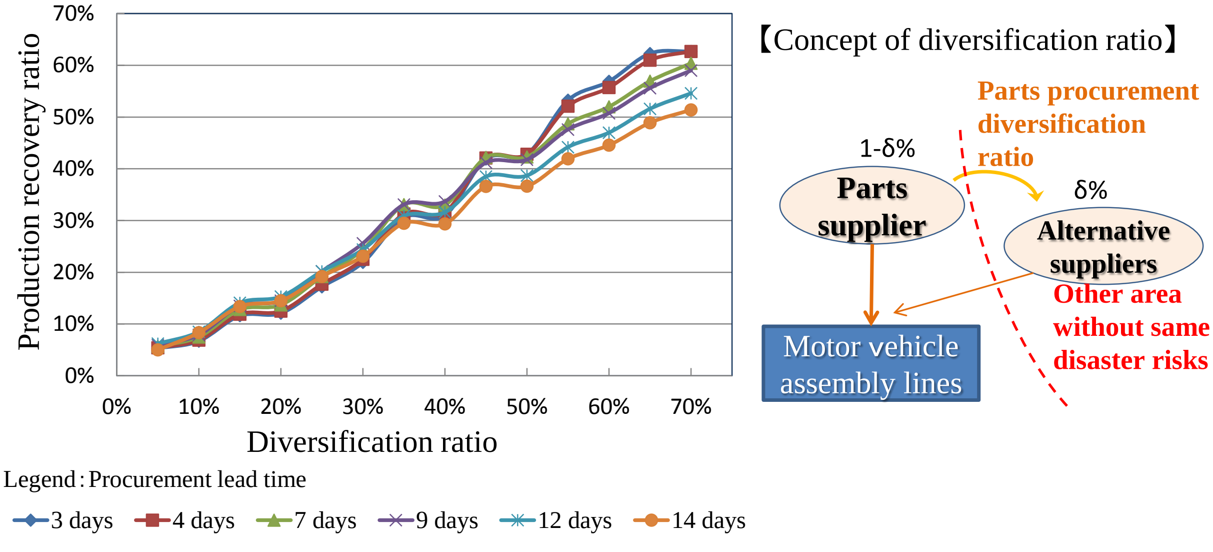

Figure 20. Effect of spreading procurement sources

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Table 6. Transportation lead times for automotive parts procurement

Dispersed area	Lead time
Inside Japan	3 - 4 days
China (Central)	7 days
China (South)	9 days
Southeast Asia	12 - 14 days

Figure 21 compares daily motor vehicle production for diversification ratios of 33% and 67%. Assembly line operations are estimated to be suspended for 18.8 days on average to secure worker safety and supply chain connections and to investigate facility damage and market situations. Supply chain disruptions during the aftermath of the Great East Japan Earthquake caused another assembly line shutdown from April 18 to May 9, 2011, shown in the daily motor vehicle production chart with diversification ratio of 33% (Figure 21, left).

In comparison, a diversification strategy with an α value of 67% completely gets rid of the assembly shutdown, where the production recovery ratio is measured as 62.7% (Figure 21, right). This indicates that the maximum possible improvement of the production recovery ratio through removing supply chain disconnections is 62.7%.

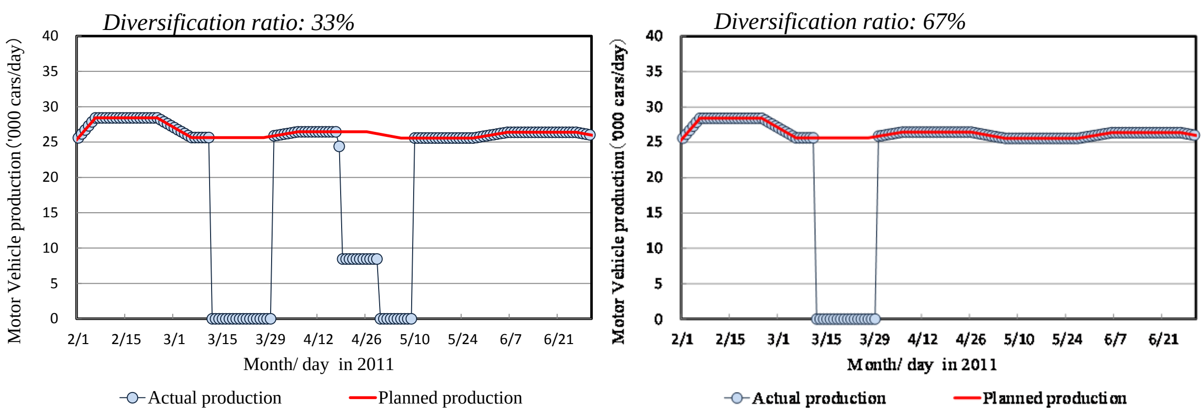

Figure 21. Effects of diversification ratios on motor vehicle production

It would also be possible to improve production recovery ratios if the geographically diverse suppliers could play a supporting role in coping with parts supply shortages. Based on numerical experiments employing the supply chain model, we identified an additional increase in production recovery ratios obtained by such backup production arrangements (Figure 22).

Figure 22 shows that the production recovery ratio increases by 9% for each 100% backup production arrangement with domestic parts suppliers. The "backup ratio" in that figure is defined as the proportion of additional production capacity to the original geographically diverse supply amount. For overseas suppliers with longer procurement lead times, however, the efficiency of such backup production arrangements likely decreases dramatically. For example, the improvement effect of backup suppliers in Southeast Asia is only 27% that of domestic suppliers.

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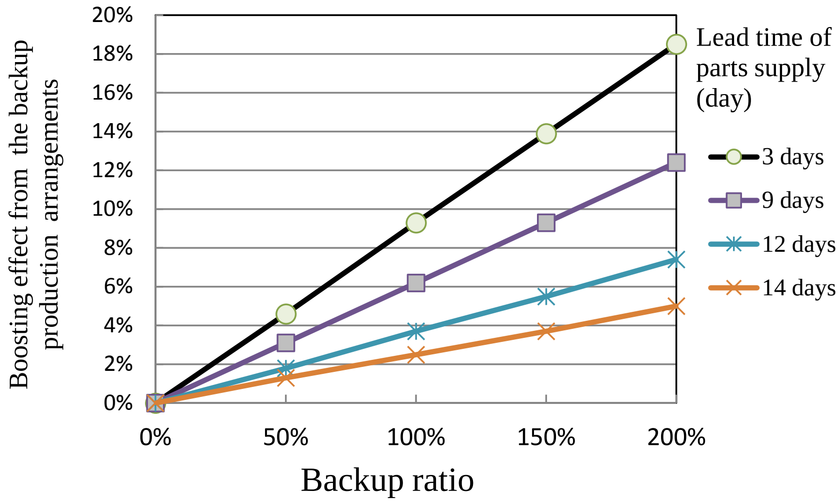

Figure 22. Effect of backup production arrangements

7.3 Inventory reinforcement strategy

We simulate motor vehicle production in 2011 assuming that parts suppliers have backup parts inventories ranging from two to four times normal stock amounts.

When parts suppliers double inventories at intermediate stockpiles and factory warehouses, from 2.5 days' to 5 days' supply, there is an estimated 12.3% increase in the production recovery ratio. When inventories are tripled the increase is 29.3%, and when they are quadrupled the increase is 39.9% (Figure 23, left). Inventory reinforcement strategies are thus evaluated to be less efficient countermeasures, considering the burden imposed on suppliers.

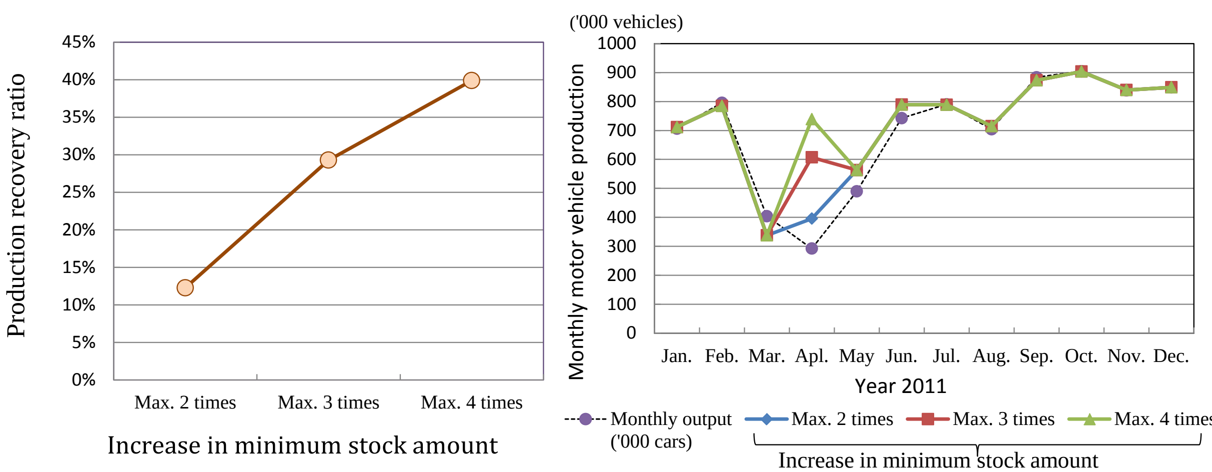

Figure 23. Effects of increased minimum stock amounts

The effect of inventory reinforcement appeared to affect motor vehicle production in only April 2011 and did not extend to May. We also note that the production turndown in March was caused by the immediate assembly line shutdown, and so is not directly benefitted by the inventory reinforcement

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strategy (Figure 20, right).

7.4 Bottleneck supplier rescue strategy

We reviewed efficiency and effectiveness of assistance in recovering the production facilities of bottleneck parts suppliers by providing them with material, equipment and personnel. Such efforts were actually undertaken by the automobile industry during aftermath of the Great East Japan Earthquake.

As shown in Figure 24 (left), the production recovery ratio was calculated by assuming a “recovery period reduction ratio” between 10% and 50%. This ratio is defined as the proportion of the reduced period to the whole period required to recover facilities without assistance.

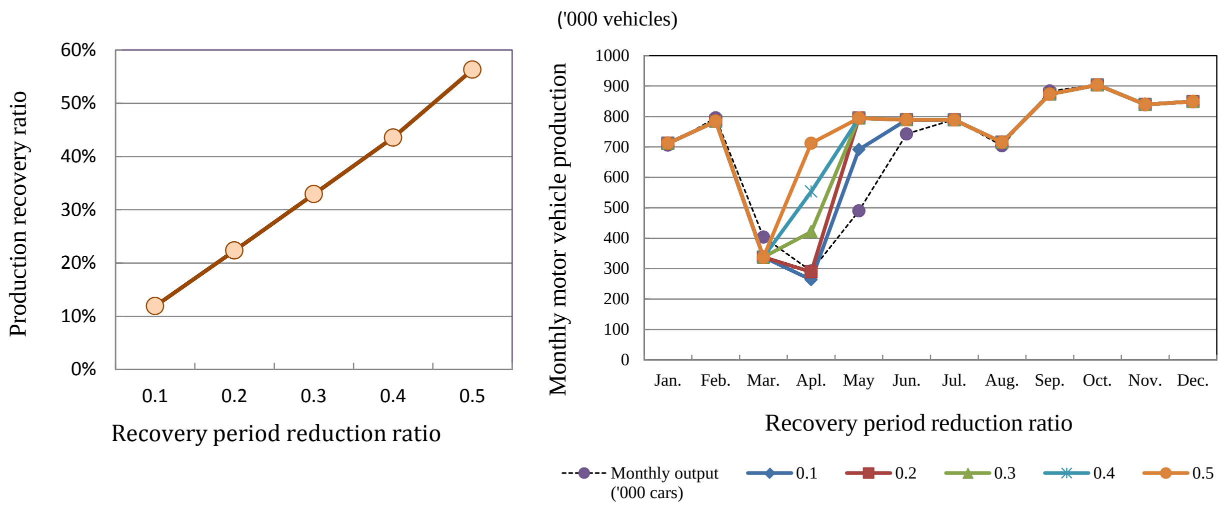

Figure 24. Effect of assisting bottleneck suppliers

The production recovery ratio increases in proportion with the recovery period reduction ratio. Elasticity of the motor vehicle production recovery ratio to the recovery period reduction ratio is measured at 1.1. Such rescue strategies aided assembly line operations in April and May, but there is no improvement in March. This is likely due to the same reasons as with the inventory reinforcement strategy described in Section 7.3.

We consider identifying bottleneck suppliers in the supply chain as essential for mobilizing a rescue strategy. First- or second-tier suppliers such as Aisin Seiki can be easily recognized as bottleneck suppliers, but information about lower-tier suppliers is always limited at best. Visualizing the entire up-stream supply chain is thus needed.

7.5 Summary and further discussion

The above evaluations provide the following implications and suggestions.

i. Diffusing parts procurement sources within Japan in combination with backup production arrangements is an effective proactive measure for reducing negative impacts on the motor vehicle production. Overseas suppliers make only limited contributions to production improvements in terms of mitigating supply disruption risks and providing backup production. This is mainly due to longer delivery lead times.

ii. Increasing inventories at intermediate stockpiles and factory warehouses may not be sufficiently efficient and effective, considering the financial burden on parts suppliers.

iii. Mutual assistance among automobile supply chain participants to facilitate restoration of production facilities looks like one of the best practices for directly resolving the bottleneck problem. Meanwhile, improving visibility of the supply chain system is also an essential requirement.

Modern manufacturing activities deeply depend on supply chain systems comprising a wide range of business entities, so manufacturers are always at risk of disruption due to uncontrollable natural and human-made hazards. Supply chain disruption risks must thus be addressed with the participation of local, national, and global societies. Among the notable challenges from this viewpoint is the concept of developing area BCPs under which manufacturers and service providers are requested to take concerted actions for securing common business infrastructure functions such as transportation, communications, and utilities supplies (Baba *et al*. 2013).

We also learned that the disaster resulted in large production and employment losses not only by manufacturers but also parts suppliers, logistics companies, and other business entities comprising the supply and production chain. Some strategies for improving SCM may involve self-serving views that impose a burden on parts and component suppliers, such as further increased inventories. These issues must be addressed in the context of regional and national industrial policy development.

In view of the above, authorities are required to undertake policy development for i) further inclusion of effective and efficient risk reduction and mitigation mechanisms into SCM, ii) communalization and standardization of parts and components to improve the compatibility of intermediate goods among a wide range of manufacturers, and iii) facilitating preparation of effective and efficient business continuity management systems (BCMS). These policies are also expected to encourage parts suppliers to actively participate in efforts for further stabilizing and improving supply chains based on their own inventive approaches.

8. CONCLUSIONS

We first examined geographical features and local industries in the Tohoku region that were adversely affected by the Great East Japan Earthquake. We also reviewed the impact of the earthquake on production and supply chains in the Tohoku region. Production disruptions in the IC and automobile parts industries were highlighted in the context of impacts on global supply and production chains. Section 4 discussed recent changes in the supply chains of Japanese manufacturers and consequences for future SCM improvement.

In view of the review and discussions, we introduced a numerical supply chain model and verified its reproducibility. The model was used to evaluate the efficiency and effectiveness of SCM improvement strategies in the automobile industry. Mutual assistance arrangements to recover disaster-damaged facilities and diffusion of parts procurement within Japan were both assessed in terms of efficiency and effectiveness of early recovery of supply chain disruption. Reinforcing parts inventory was found to be less efficient when considering supplier burdens. From these observations, we consider that manufacturers should pursue strategies through public policy development.

Securing stable basic industry operations such as automobile manufacturing in Japan is vital for the local, national and global economy. Once the operations of such industries are disrupted, the economy will suffer serious negative impacts such as lowered GDP, reduced labor share, and decreased intermediate input. Failure to maintain supply and production chains not only harms economic vitality at local, national, and global levels, but also discourages operation and investment in the private sectors.

In this context, we recommend that local, national, and global communities increase policy considerations for i) securing geographic diffusion of parts procurement sources to minimize supply chain fragility, facilitate standardization, and develop authentication systems for parts and components; ii) encouraging the automobile industry to further strengthen mutual assistance arrangements to accelerate supply chain damage recovery and to promote procurement diffusion domestically; and iii) preparing a common information platform to assist companies in visualizing supply chains. These measures are expected to encourage not only final product manufacturers, but also parts, component, and material suppliers to actively participate and invest in establishing robust and resilient supply and production chains, thus contributing to the creation of more stable and sustainable economies at local, national, and global levels.

We also recommend encouraging industrial and logistics communities to prepare BCMS to minimize disruption risks of supply and production chains. Community-based BCP like that mentioned in Section 7.5 may provide a common platform and overarching protocol.

We close by pointing out the necessity of further studies in collaboration between academia and business that fully employ data and lessons learned from the Great East Japan Earthquake to better identify and understand the structure and mechanism of multiple effects on supply chain disruption in local, national, and global contexts. Developing risk management methodologies applicable to industry SCM is urgent to avoid a repeat of the economic losses and threat to human lives that Japan experienced. To that end we sincerely hope that data and lessons learned will be secured, shared, and utilized while remembering the vast human and economic losses suffered on March 11, 2011.

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