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Simulation Modeling of a Conceptual Model for Supply Chain Risks in Japan's Automobile Industry

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Abstract

Japan's automobile industry suffered enormous losses because of the 2011 Tohoku earthquake. Four years earlier, the 2007 Niigata Chuetsu offshore earthquake had damaged Riken's Kashiwazaki plant in Niigata, impeding operations among most Japan's automobile manufacturers. Five years after the 2011 Tohoku earthquake, many plants, including semiconductor manufacturer Renesas and automotive parts supplier Aisin Kyushu in Kumamoto were affected by the 2016 Kumamoto earthquake, the impact affected entire Japan's automobile industry. Thus, production stoppages at lower-tier suppliers have often affected nearly every Japan's automobile manufacturer.

Therefore, the purposes of this study are to describe how disasters affected the supply chain network in Japan's automobile industry, to build a conceptual model that reproduces concentration and consolidation within the supply chain structure, and to compare the propagation of the supply chain disruption using several models.

Keywords: Disruption, Supply Chain, Simulation Model, Automobile Industry

1 Introduction

Riken Corporation which was affected by the 2007 Niigata Chuetsu offshore earthquake is major supplier of piston rings for engines and seal rings for transmissions. At that time, the piston ring market in Japan was an oligopolistic market with only three companies: RIKEN, Teikoku Piston Ring, and Nippon Piston Ring. Riken's Kashiwazaki plant produces approximately half of all piston rings used in Japan's automobile manufactures. The Kashiwazaki plant suffered extensive damage and suspended operations for one week thereafter. Riken's specialized design and production technology prevented Japan other two suppliers from replacing its output, intensifying Japan's automobile manufacturers' dependence. In addition, just-in-time inventory practices had kept component inventories at low levels among automobile manufacturers and upper-tier suppliers. As a result, Japan's automobile production ceased nationwide after the Kashiwazaki plant closed. Toyota, Subaru, Suzuki, and Daihatsu suspended production on July 19th, three days after the earthquake. Nissan suspended production on July 20th, Honda, Mazda, Subaru also ceased on July 21st. Thus, all Japan's automobile manufacturers suspended operations on July 21st, five days after the earthquake.

The 2011 Tohoku earthquake damaged the plant extensively, and Renesas Electronics Corporation (REC)'s Naka plant suspended operations for 82 days. At that time, REC was the world's largest manufacturer of Microcontroller Units (MCUs) by market share and a major

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producer of System LSIs/System on Chip Devices (SoC devices) and Analog & Power Devices. REC's Naka plant produced approximately 20% of the company's MCUs and SoC devices and about 10% of its Analog & Power Devices. In 2010, Japan's automotive sector accounted for $5.358 billion (36.2%) of the $14.8 billion MCUs market, and REC held a 41.5% share of that market, earning $2.221 billion in revenues. REC's Naka plant produced approximately 20% of the company's MCUs and SoC devices and about 10% of its Analog & Power Devices.

Shutdowns at REC and among lower-tier suppliers had enormous effects on automobile manufacturers hard hit by shortages of MCUs and other components. Although most automobile plants suffered little direct damage from the 2011 Tohoku earthquake, Nissan's Iwaki plant suffered from aftershocks throughout the region, and its recovery took longer than elsewhere. Toyota suspended production at all plants from March 14th to March 26th. Its March 2011 domestic production was 129,491 units versus 347,281 for March 2010, a decrease of 217,790 units or 37.3%.

Supply chain risks include not only such disruption risks but also operational risks. Operational risks are referred to the inherent uncertainties such as uncertain customer demand, uncertain supply, and uncertain cost. In most cases, the business impact associated disruption risks is much greater than that of the operational risks [1].

In this paper, by constructing conceptual models: supply variability model for operational risk and supply chain disruption model for disruption risk, it was possible to visualize the effects of two structures: the pyramidal structure and the diamond structure.

2 Prior Research

In the 1980s, before supply chain risks and vulnerability gained attention, Kraljic (1983) expressed supply uncertainty as the term 'supply risks' in his article where he used a matrix based on complexity of supply market and importance of purchasing to classify items into four categories: strategic items, bottleneck items, procurement leverage items, and non-critical items [2].

Subsequently, natural disasters such as earthquakes, floods, economic crisis, and pandemics have disrupted supply chain, it has become more important building supply chain risk management and creating resilient supply chain. For instance, Christopher and Peck (2004) suggested three categories (internal to the firm, external to the firm but internal to the supply chain network, and external to the network) of risk which can be further sub-divided to produce a total of five categories (process risk, control risk, demand risk, supply risk, and environmental risk) [3]. Yossi and Rice described how resilient companies build flexibility into each of five essential supply chain elements: the supplier, conversion process, distribution channels, control systems, and underlying corporate culture. And they illustrated how building flexibility in these supply chain elements not only bolsters the resilience of an organization but also creates a competitive advantage in the marketplace [4]. Tang (2006) reviewed various quantitative models for managing supply chain risks, and related various supply chain risk management strategies examined in the research literature with actual practices [1]. Moreover, Wagner and Bode (2006) investigated the relationship between supply chain vulnerability and supply chain risk, supply chain characteristics such as a firm's dependence on certain customers and suppliers, the degree of single sourcing, or reliance on global supply sources are relevant for a firm's exposure to supply chain risk [5]. In terms of more empirical research using models, Klibi and Martel (2012) proposed a supply chain risk modeling approach to support the generation of plausible future scenarios including extreme events [6]. In addition to the above study, there are existing research studies on supply chain risk management, such as Jüttner (2005), Ghadge et al. (2013), Kumar and Bhat (2014), Shenoi et al. (2018) and Gani et al. (2022). However, there are few studies that address the theme envisaged by this research [7][8][9][10][11].

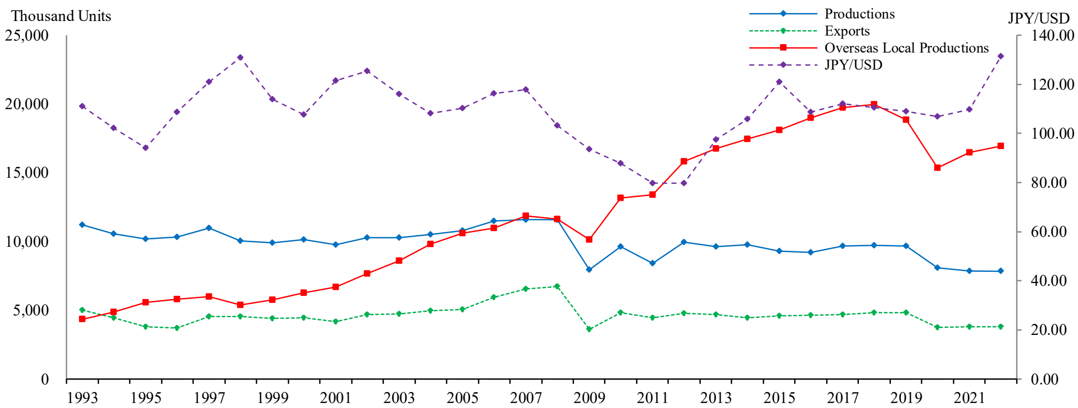
These previous studies on supply chain disruption or supply chain risk can be broadly divided into two approaches: one that interpret phenomena theoretically and qualitatively and the other that evaluate phenomena analytically and quantitatively. This study falls somewhere in between and aims to bridge these two approaches.

3 Supply Chain Risks of Japan's Automobile Industry

3.1 Structural Configuration and Vulnerability of Japan's Automobile Industry

The supply chain serving Japan's automobile industry is a complex network of interlocking assembler–supplier relationships. This keiretsu structure historically has enabled Japan's automobile manufacturers to remain lean and flexible while exercising a degree of control over supply akin to vertical integration [12]. Japan's automobile industry resembles a pyramid composed of several tiers of suppliers beneath seven main assembly groups or single assemblers: Toyota-Daihatsu-Hino, Nissan-Subaru-Nissan Diesel, Honda, Mazda, Mitsubishi, Isuzu, and Suzuki [13].

However, during the 1990s, Japan's automobile industry faced serial crises, including the collapse of Japan's "bubble" economy, the Yen's appreciation against the US dollar, the 1995 Kobe earthquake, and an increase in Japan's consumption tax from 3% to 5% in 1997. In response to these events, Japan's automobile industry accelerated its shift to overseas production, and promoted establishment of a global supply network. Figure 1 shows the changes of productions, exports, and overseas local productions of Japan's automobile industry, and the yen exchange rate from 1993 to 2022.

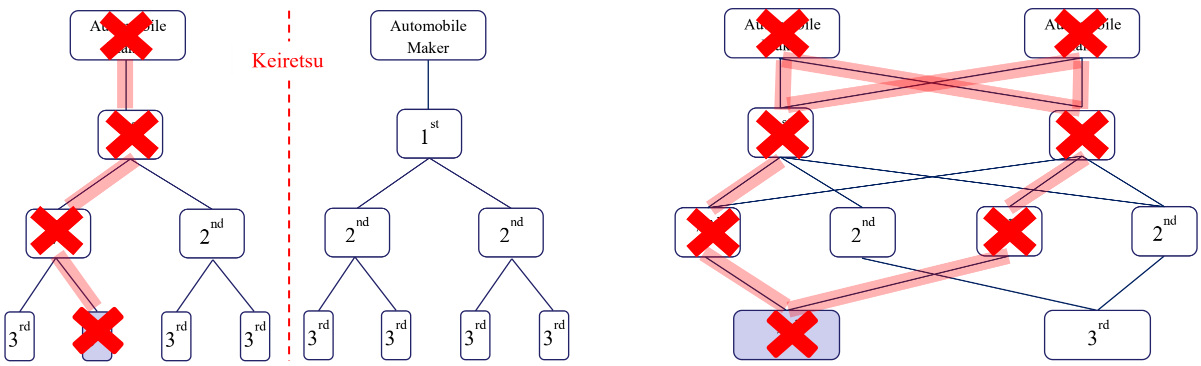


Source: Active Matrix Database System of JAMA, Bank of Japan Time-Series Data Search.

Figure 1: The Changes of Productions, Exports, Overseas Local Productions, and JPY/USD

Some Japanese companies supply parts to assemblers outside their keiretsu, numerous lower-tier suppliers provide their products across their keiretsu, and some major parts manufacturers supply the entire Japan's automobile industry. The supply of first-tier and second-tier parts (functional components) is decentralized among several suppliers, whereas the supply of lower-tier parts (simple components) is centralized in one company that uses specialized process technology [14]. In other words, while the lower-tiers have become more concentrated in specific suppliers which have a competitive advantage in quality and price, the suppliers in first- or second-tier become more dispersed. Thus, Japan's automobile industry became a diamond-like structure.

In the pyramidal structure in Figure 2a, when a disaster occurs and a supplier in the lower tier are affected, the damage was limited within the keiretsu group of automobile manufactures. However, in the diamond structure in Figure 2b, the damage will spread throughout the automobile industry. The supply of components from lower-tier suppliers was interrupted during the earthquakes of 2007 and 2011, and the impact affected entire Japan's automobile industry. Thus, in the diamond structure of centralized lower-tier suppliers production stoppages at suppliers' plants affect nearly every Japan's automobile manufacturer.



(a) Pyramidal Structure (b) Diamond Structure

Figure 2: The Difference of the Damages between two Structures

3.2 The Effects of Earthquakes

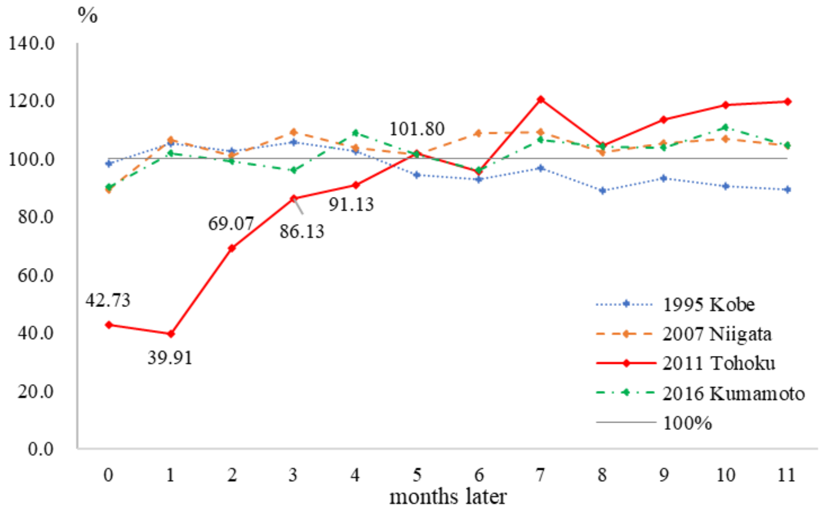
Table 1 shows the human and household damage, and the production decline of Japan's automobile manufactures for the four earthquakes: the 1995 Kobe earthquake, the 2007 Niigata Chuetsu earthquake, the 2011 Tohoku earthquake, and the 2016 Kumamoto earthquake. Japan's domestic automobile production in January 1995, the year of the 1995 Kobe earthquake, was 758,837 units, a decrease of 14,021 units, or 98.2% from 772,858 units in January 1994. Furthermore, when comparing the production decline in the 1995 Kobe earthquake and other earthquake disasters, production was reduced by 7.2 times in the 2007 Niigata earthquake, 38.6 times in the 2011 Tohoku earthquake, 4.9 times in the 2016 Kumamoto earthquake.

Figure 3 shows the year-on-year change in domestic production for all Japan's automobile manufacturers up to one year after earthquakes. The 2011 Tohoku earthquake took five months to return to normal production, but the other three earthquakes all returned to production one month after the earthquake occurred.

Table 1: The Earthquake Damages

Earthquake	Magnitude	Seismic Intensity	Casualty	Fatality	Missing	Household Damage	Production Decline	Year-on-Year
1995 Kobe	M7.3	7	43,792	6,434	3	639,686	14,021	0.98
2007 Niigata	M6.8	6+	2,345	15	0	42,010	101,636	0.90
2011 Tohoku	M9	7	26,992	15,854	3,155	1,269,223	541,285	0.43
2016 Kumamoto	M7.3	7	2,739	55	0	198,649	69,238	0.90

Source: Active Matrix Database System of Japan Automobile Manufacturers Association (JAMA).



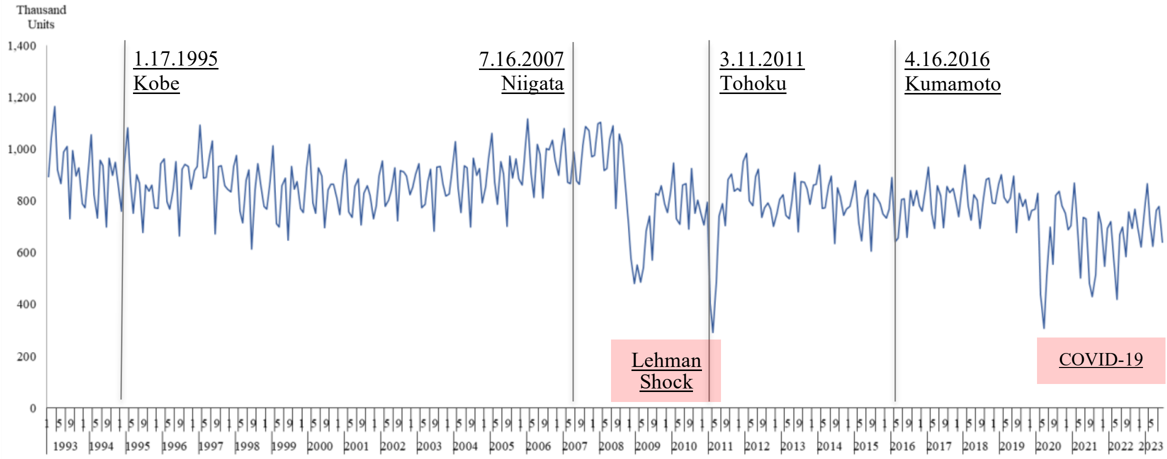
Source: Active Matrix Database System of JAMA.
Note: The previous year's result indexed at 100.

Figure 3: The Changes in Japan's Domestic Automobile Production (%)

3.3 The Effects of Economic Crises

Figure 4 shows the changes in Japan's domestic automobile production from January 1993 to August 2023. Certainly, the impacts of reduced production during economic crises such as the Lehman shock and the Corona shock are very clear. However, except for the 2011 Tohoku earthquake, the impacts of reduced production caused by earthquakes are not clear as they are hidden within the production fluctuations.

Furthermore, while economic disruptions such as the Lehman shock and the Corona shock resulted in a long-term slump in demand, supply chain disruptions such as natural disasters resulted in temporary interruption of supply.



Source: Active Matrix Database System of JAMA.

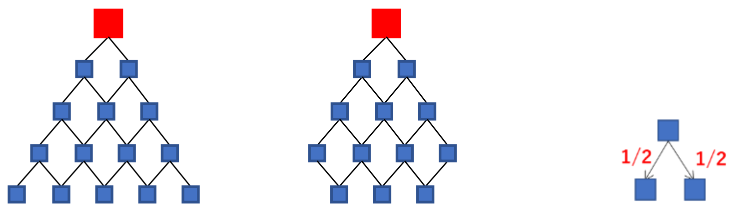
Figure 4: The Changes in Japan's Domestic Automobile Production (Jun.1993 - Aug. 2023)

4 A Conceptual Model the Supply Chain Disruption

4.1 The Basic Model

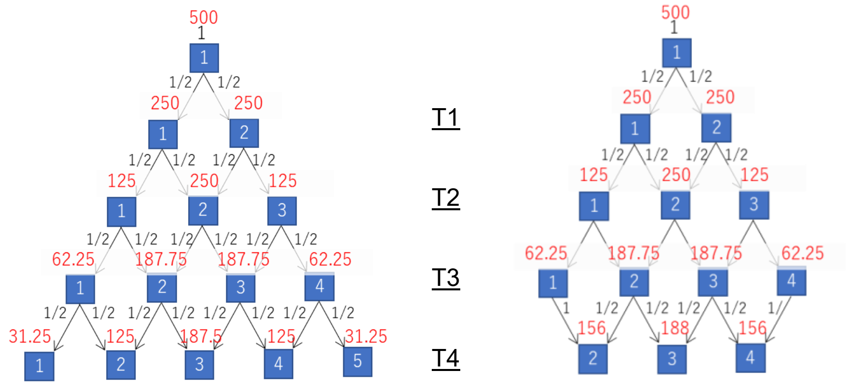
There are two types of structures: the pyramidal structure and the diamond structure. The pyramidal structure has one manufacture and fourteen suppliers in four tiers, and demand are more concentrated in the center of each tier (Figure 5a). The diamond structure has one manufacture and twelve suppliers in four tiers, and demand are more concentrated in the center of each tier and there is a consolidation in the fourth-tier (Figure 5b). These models consist of some simple demand units (Figure 5c). Assume that the top of manufacturer orders the same quantity of the same item to two suppliers in the first-tier, and that each supplier orders the same quantity of the same item to two lower-tier suppliers. Each supplier supplies the order quantity to higher-tier suppliers.

This is taking a cue from the Galton Board, which is often used when explaining the normal distribution. In this board, beads pass through the inside closer to the center more frequently. Similarly, there are setting suppliers like the pins on the Galton Board and ordering like flowing the beads on a board. Components in the required quantities are sequentially supplied from suppliers of the lower-tiers based on demand (Figures 6 and 7). Even if the number of suppliers within the fourth-tier changes, the quantity of demand and supply in the higher-tiers does not change. This means that it is difficult for the upper-tiers and manufactures to see the state of consolidation in the lower-tier.



(a) Pyramidal Structure (b) Diamond Structure (c) Demand Unit

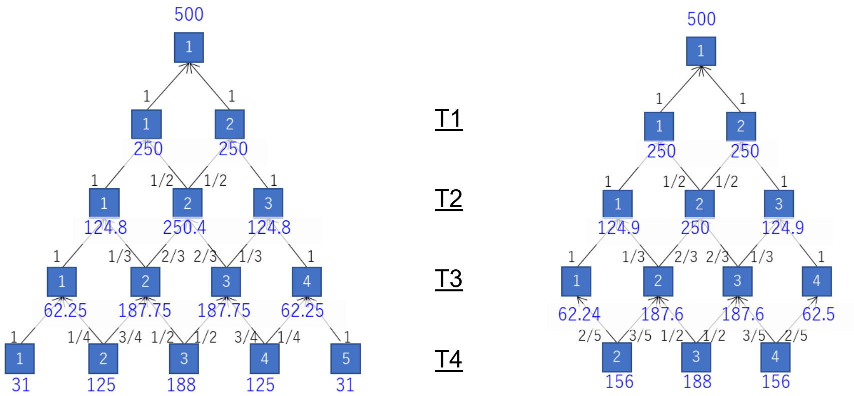
Figure 5: Two types of Structures and the Demand Unit



(a) Pyramidal Structure (b) Diamond Structure

Note: Red Figures : Order Quantities per Day, Black Figures : Order Ratio

Figure 6: Quantity and Ratio (Demand)



(a) Pyramidal Structure (b) Diamond Structure

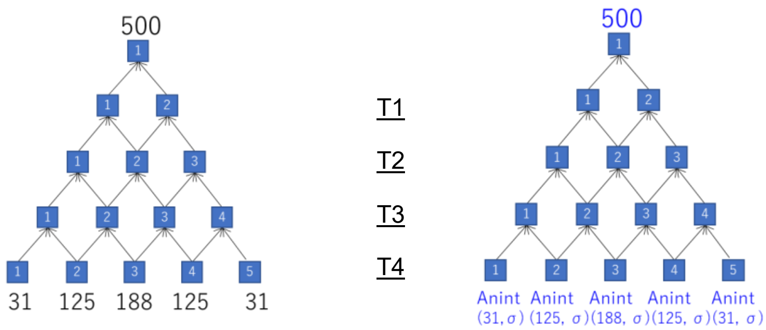
Note: Blue Figures : Supply Quantities per Day, Black Figures : Supply Ratio

Figure 7: Quantity and Ratio (Supply)

4.2 The Supply Variability Model

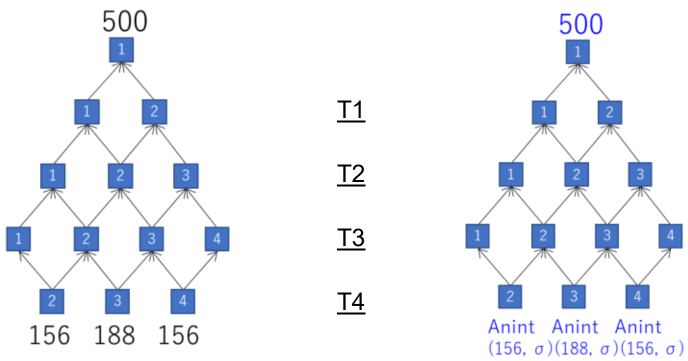
4.2.1 The Outline of the Supply Variability Model

The supply variability model simulated daily supply fluctuations during normal situations. Daily supply fluctuations used the standard deviation of a normal distribution. The larger the value of the standard deviation, the more the market is significantly influenced by the unstable supply from suppliers and creating a supplier-oriented situation. Simulation experiments were conducted with some scenarios in each structure for the standard deviation of supply: 0, 5, and 10 (Figures 8 and 9). In this model, the replication length was set to one hundred days.



Model	P_Basic	P_σ5	P_σ10
Demand	500	500	500
Supply(T4)	31,125,188,125,31	σ= 5	σ=10

Figure 8: Supply Variability Models (Pyramidal Structures)

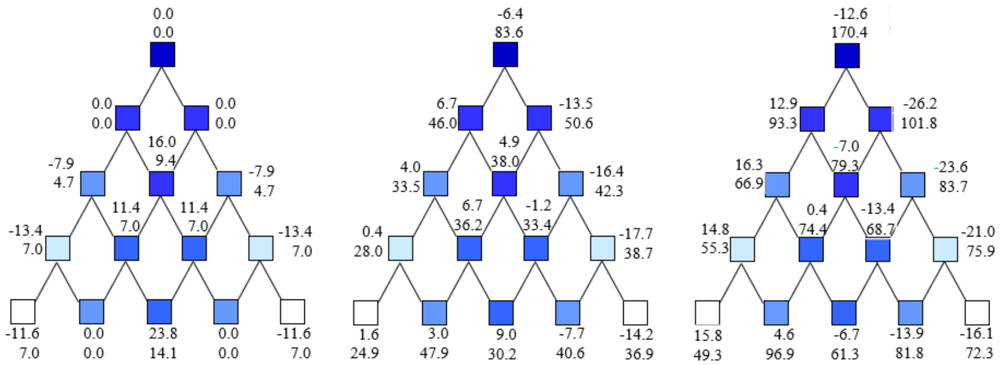


Model	D_Basic	D_σ5	D_σ10
Demand	500	500	500
Supply(T4)	156,188,156	σ= 5	σ=10

Figure 9: Supply Variability Models (Diamond Structures)

4.2.2 The Simulation Results of the Supply Variability Model

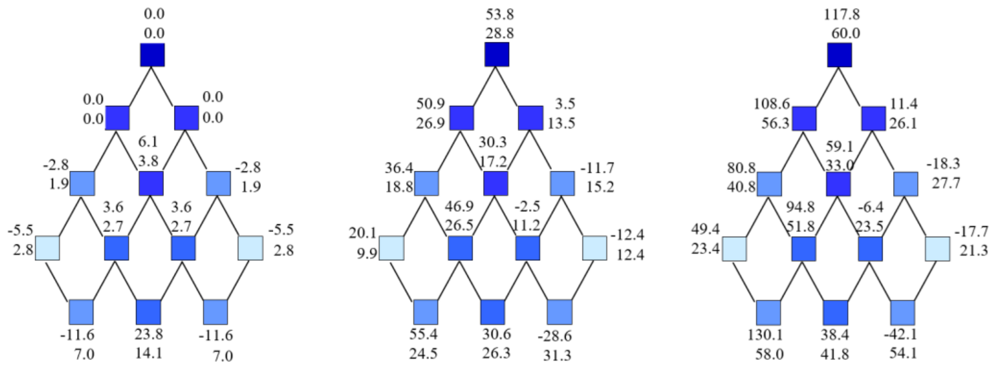
Figures 10 and 11 show the results of the simulation of the supply variability model. The upper figures on each supplier show average inventory levels, and the lower figures show inventory variability. The average inventory level, the more it becomes negative, indicates a higher risk of stockouts, while the more it becomes positive, signifies a higher risk of overstock. When the standard deviation of supply variability was small, the risk of stockouts was higher on the outside of structures, and the risk of overstock was higher on the inside. In contrast, both risks became higher at the upper-tier suppliers as the standard deviation increases in both structures.



(a) P_ Basic (b) P_σ5 (c) P_σ10

Note: Upper Figures : Average Inventory Levels, Lower Figures : Inventory Variability

Figure 10: The Results of the Simulation of Supply Variability Model (Pyramidal Structure)



(a) D_ Basic (b) D_σ5 (c) D_σ10

Note: Upper Figures : Average Inventory Levels, Lower Figures : Inventory Variability

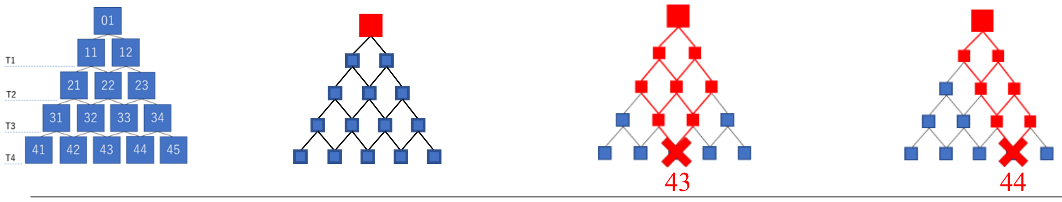
Figure 11: The Results of the Supply Variability Model (Diamond Structure)

4.3 The Supply Chain Disruption Model

4.3.1 The Outline of the Supply Chain Disruption Model

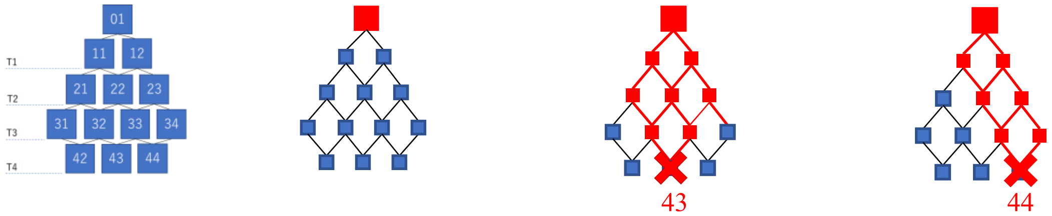
The supply chain disruption model is a simulation model that reproduces in which fourth-tier supplier stop production during emergencies, such as natural disasters, economic crises, and pandemic. This model is used the supplier number. The tens digit in the number is the tier number, and the ones digit is the serial number. For example, "No. 43" is the third supplier from the left in the fourth-tier, and "No. 44" is the supplier next to it.

Two experiments were conducted in each structure: one in which the central supplier (No.43) in fourth tier was affected, and another where the outer supplier (No.44) in the fourth-tier was affected (Figure 12 and 13). In this paper, each model is referred to as the No.43 disruption model and the No. 44 disruption model.



Model	P_Basic	P _No.43_Disruption	P_No.44_Disruption
Demand	500	500	500
Supply(T4)	31, 125, 188, 125, 31	31, 125, 0, 125, 31	31, 125, 188, 0, 31

Figure 12: Supply Cain Disruption Models (Pyramidal Structures)

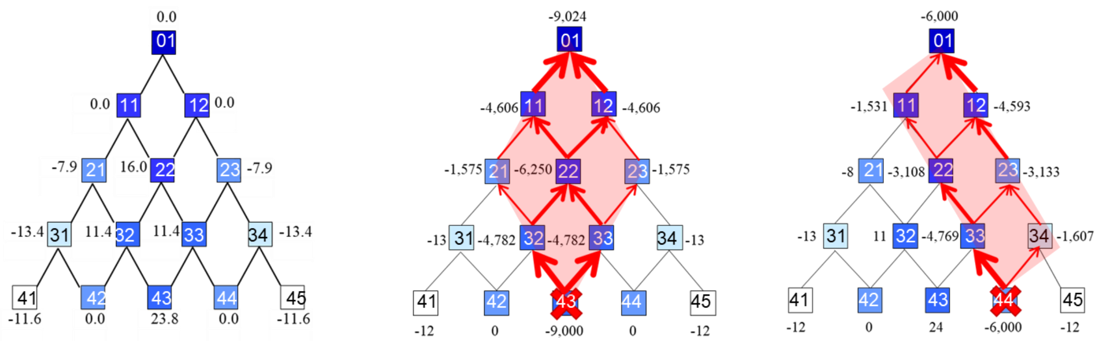


Model	D_Basic	D _No.43_Disruption	D _No.44_Disruption
Demand	500	500	500
Supply(T4)	156, 188, 156	156, 0, 156	156, 188, 0

Figure 13: Supply Cain Disruption Models (Diamond Structures)

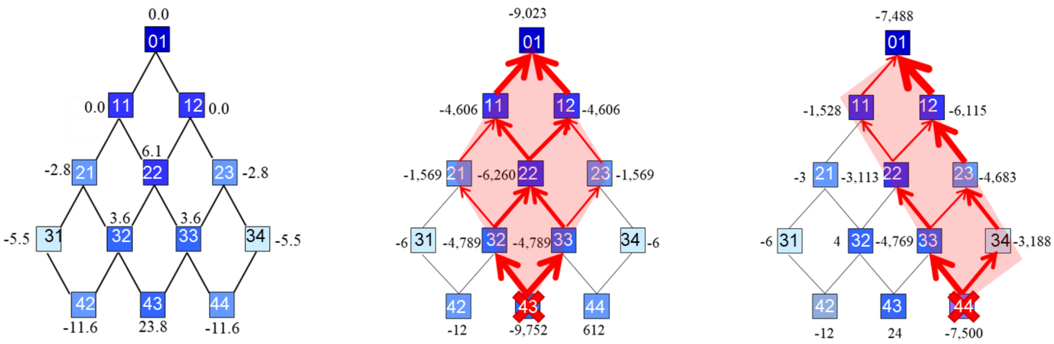
4.3.2 The Simulation Results of the Supply Chain Disruption Model

Figures 14 shows the results of the simulation of the supply chain disruption model of the pyramidal structure. The numbers are the average of the inventory (+) or the lack of inventory (-). The thickness of the red arrow line indicates the extent of the quantity that cannot be supplied due to production stop. In the basic models, the inventory (+) and the lack of inventory (-) ware not large value, but when production stopped at No.43 or No.44, the impact soon spread to the upper tiers. When the supplier in the lower tier stopped production, the impact was greater in the No.43 disruption model than in the No.44 disruption model. The No.43 disruption model is that disruption occurs in the center of the fourth-tier, and the No.44 disruption model is that disruption occurs in the outside of the fourth-tier.



(a) P_ Basic (b) P_Disruption_No.43 (c) P_Disruption_No.44

Figure 14: The Results of the Supply Chain Disruption Model of the Pyramidal Structure



(a) D_ Basic (b) D_Disruption_No.43 (c) D_Disruption_No.44

Figure 15: The Results of the Supply Chain Disruption Model of the Diamond Structure

Figures 15 shows the results of the simulation of the supply chain disruption model of the diamond structure. The results of the basic model and the No.43 disruption model are almost the same as the pyramidal structure, but the result of the No.44 disruption model have changed from the pyramidal structure. When No.44 stopped production, the impact was greater in the diamond structure than in the pyramid structure. This is because in the diamond structure, concentration and consolidation occur in the lower-tier, while in the pyramid structure, only concentration occurs.

5 Conclusion

In this study, by building the two types of conceptual models: the supply variability model and the supply chain disruption model, it was possible to visualize how disasters affected the supply chain network and production systems. In the experiment of the supply variability model, when the standard deviation of supply variability was small, the risk of stockouts was higher on the outside of structures, and the risk of overstock was higher on the inside. In contrast, both risks became higher at the upper-tier suppliers as the standard deviation increases in both structures: the pyramidal structure and the diamond structure. In the experiment of the supply chain disruption model, when the supplier in the lower tier stopped production, the impact soon spread to the upper tiers, and the impact was greater in the No.43 disruption model where disruption occurs in the center of the fourth-tier, than in the No.44 disruption model where disruption occurs in the outside of the fourth-tier. When No.44 stopped production, the impact was greater in the diamond structure where concentration and consolidation occurs in the lower tier, than in the pyramid structure where only concentration occurs.

These conceptual models are very simple and easy to understand the propagation of the supply chain disruptions. While these models are consistent with previous theories, in the future, it needs to consider for the validation and the verification them when building models of real-world supply chains that are very large, complex, and constantly changing.

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