Cost-benefit Analysis of Decentralized Ordering on Multi-tier Supply Chain by Risk Simulator

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Abstract: For the retailer on supply chain, decentralized ordering to multiple suppliers is an effective method to mitigate the risk that the retailer cannot sell the product to customers when the suppliers are down by catastrophic disasters. But decentralized ordering costs the retailer because the retailer procures products from the suppler whose procurement cost is expensive. For the retailers' cost-benefit analysis of the decentralized ordering, we address developing the risk simulator on multi-tier supply chain to evaluate the effect of risk mitigation and the cost by decentralized ordering. In order to develop the risk simulator for the multi-tier supply chain, we combine the risk simulator for the 2-tier supply chain as a building block. In addition, when the 2-tier supply chain is combined, the risk simulator calculates propagation of the risk and the cost from a 2-tier supply chain to the others. Applying the risk simulator to the real supply chain with different parameter values, the authors confirmed that the risk simulator enables to find the relationship between the cost-benefit characteristic and the multi-tier supply chain model.

Keywords: cost-benefit analysis, conditional value at risk, decentralized ordering, multi-tier supply chain, risk simulator

1. Introduction

Supply chain is a sequence of operations such as procurement, production, logistics and sale for supplying products from suppliers to final consumers. Retailers in the supply chain procure products from suppliers and sell products to consumers. In supply chain, there is a problem that catastrophic disasters such as earthquakes may prevent the procurement from suppliers[1][2]. The retailers suffer losses as the procurement risks if they cannot sell the products along with the consumers' demand. So, it is necessary for the retailers to consider not only the procurement cost but also the procurement risk in procurement planning. In this paper, the authors define the risk as the possibility that the retailer cannot sell the products to customers when the catastrophic events happen.

Representative ways to reduce the procurement risk are to increase the urgent stock of the products and decentralize procurement of the product from multiple suppliers [3][4]. The decision-maker of the retailer has to consider how much cost and risk are changed by the urgent stock and decentralizing orders. Conventional researches have addressed evaluating the cost and the risk by simulation on a supply chain model with catastrophic events. The simulation methods to be used are Petri Net [5][6][7] and Monte Carlo method [8][9][10][11].

Most of the conventional researches address evaluating the effect of mitigating risks by the urgent stock [8][9]. The echelon inventory in a multi-tier supply chain can be used to mitigate the risk when the some suppliers are down by catastrophic events. However, it has been pointed out that the large amount of stocks needs much management cost of the stock. And the supplier cannot store the stock for more than several days. Only the urgent stock is not enough as a risk mitigation way.

Because of the problems only in using the urgent stock, some conventional researches address evaluating the effect of mitigating risks by decentralizing orders [10][11][12]. The simulation of the cost and the risk uses Monte Carlo method to decide the amount of the stock stochastically. But these researches are for 2-tier supply chain model, i.e. the supply chain model consists of a retailer and its suppliers. Actually, there are many multi-tier supply chains, which must be addressed as the support of decision-making. In addition, the conventional researches have not considered that the retailer and the suppliers change the procurement plan when the catastrophic disaster happens. For example, when some suppliers are down, the retailer places orders to the surviving suppliers and suppliers sell the products to the retailer for the suppliers' own profit.

The purpose of this research is to support the cost-benefit analysis of decentralized ordering on the multi-tier supply chain with developing the risk simulator based on Monte Carlo method. In order to develop the simulator, the authors utilize the conventional researches on the 2-tier supply chain model, which is described in Chapter 2. The simulation process with propagating the cost and the risk on the multi-tier supply chain model is described in Chapter 3. The authors' discussion on cost-benefit analysis of decentralized ordering on the real supply chain model is described in Chapter 4. Chapter 5 describes the conclusion of this paper.

2. Multi-tier Supply Chain Model by Connecting 2-tier Supply Chain Model

2.1 Multi-tier supply chain model

Supply chain often consists of multi-tier of the suppliers, which means that suppliers of the supplier exist. To identify which tier the supplier is in, we call the supplier that supplies the products to the retailer "1st supplier", a supplier of the supplier "2nd supplier" and so on in the order of the tier from the retailer. Figure 1 shows an outline of the multi-tier supply chain. It is found that the relationship between the z th supplier and the $(z+1)$th supplier in the multi-tier supply chain model is similar to the relationship between the retailer and the supplier in the 2-tier supply chain model.

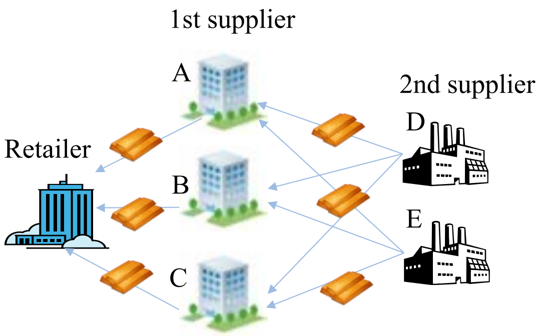

Figure 1. Outline of multi-tier supply chain

Because we have already developed the 2-tier supply chain model, we develop the multi-tier supply chain model with connecting the 2-tier supply chain model as a building block. Figure 2 shows the 2-tier supply chain model that we have developed. The following information is given on the retailer and the suppliers, respectively:

- **Retailer:** The purpose of the retailer is to ship the product to the customers with avoiding stockout for the customers' demand. Assuming that the demand D follows the Gaussian distribution $N(\mu_D, \sigma_D^2)$ where μ_D is the average of the demand and σ_D^2 is the variance of the demand, the retailer has the safety stock SS with the safety sock coefficient k for the variance of the demand. And, in order to avoid stockout caused in the catastrophic events, the retailer can have the urgent stock as an additional stock below the upper limit Cap. Furthermore, even if some of the suppliers are down due to the catastrophic events, decentralizing orders to multiple suppliers allows the retailer to procure additional products from surviving suppliers. For decentralizing orders, the retailer decides an order rate o_s to a supplier s.
- **Supplier:** A supplier s ships the amount of products that the retailer requests with the order rate o_s. The shipment takes l_s[days] as lead time. The prices c_s of the product differ from one supplier to another. In order to express the event that a supplier is down by the catastrophic events, we set the probability of the breakdown p_s and downtime d_s. While the supplier is down, the supplier can not supply the products. If some suppliers are down, the authors consider the situation where the retailer can place an additional order to the surviving suppliers. The amount of the additional order is a certain rate f_s of the order rate o_s. We call f_s additional procurement rate.

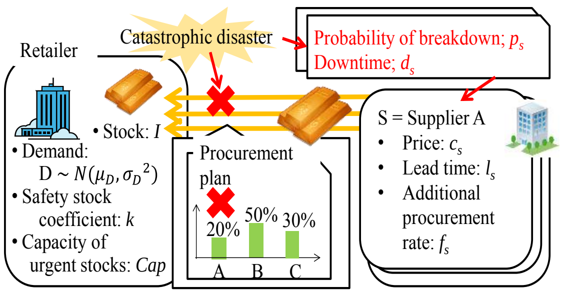

Figure 2. 2-tier supply chain model

2.2 Evaluation criteria

One of the most serious risks for the retailer is the risk that the retailer goes bankrupt because the retailer cannot sell the products to the customers for a certain period without procurement from the suppliers. A guideline [13] of the business continuity management for such a risk indicates that it is important for the retailer to shorten the recovery time that means the period until the retailer can sell the products after the retailer cannot. Following the guideline, the authors regards the recovery time as the procurement risk. On the other hand, decentralizing orders and urgent stocks cost the retailer. So, it is also necessary to calculate the cost of the retailer's plan. The definitions of the recovery time, the decentralized ordering cost, and the urgent stock cost are shown in the followings:

- **Recovery time:** Let I_t and U_t denote thestock and the urgent stock at tth day, respectively. The recovery time is defined as the period when the total stock $(I_t + U_t)$ is below the demand D after the supplier stops at Tth day ($t \geq T$).
- **Decentralized ordering cost:** In order to decentralize orders to the suppliers, the retailer has to place orders to more expensive suppliers than the cheapest one. So, the retailer pays higher expenses compared to the situation where the retailer procures from only the cheapest supplier. Therefore, the decentralized ordering cost $E_D(O)$ for the orders $O = \{o_1, o_2, \ldots\}$ is defined as follows:

$$E_D(O) = D\left(\sum_{s=1}^{n} c_s o_s - \min_s c_s\right) \quad (1)$$

- **Urgent stock cost:** If the retailer has the urgent stock, the retailer has to pay the expenses for managing the urgent stock. Based on the general calculation method of the cost of the capital in accounting [14], the urgent stock cost $E_I(U_t)$ for the urgent stock U_t is defined as follows:

$$E_I(U_t) = kBU_t \quad (2)$$

where k is the cost of the capital and B is the selling price to the customers from the retailer.

3. Risk Simulator on Multi-tier Supply Chain

3.1 Outline of the risk simulator

Figure 3 shows the outline of the simulator for the multi-tier supply chain model. As described in Section 2.1, the multi-tier supply chain model consists of the 2-tier supply chain model. So, the risk simulator on the multi-tier supply chain also apply the 2-tier supply chain simulator to every pairs of 2-tier between the zth supplier and the $(\mathrm{Z}-1)$th supplier.

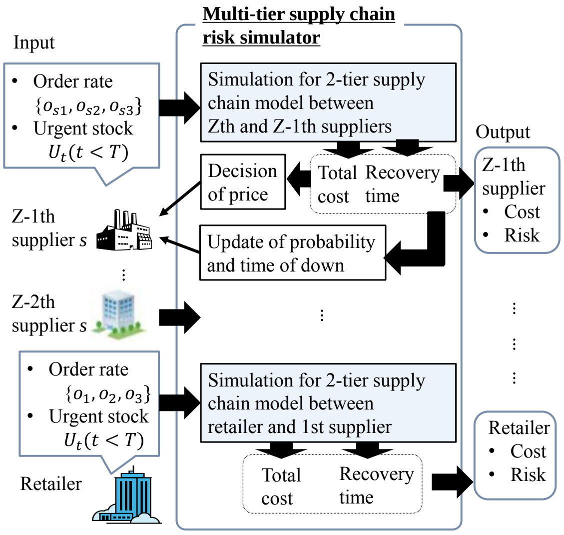

Figure 3. Outline of the risk simulator on the multi-tier supply chain model

The z th supplier s places orders $O_s = \{o_{s1}, o_{s2}, \ldots\}$ and has the urgent stock U_{st}, which are decided as inputs to the simulator. In evaluating the risk on Z-tier supply chain model, firstly the simulator evaluates the orders from the $(\mathrm{Z}-1)$th supplier to the Zth supplier. The simulation on the 2-tier supply chain model outputs the cost and the recovery time on the $(\mathrm{Z}-1)$th supplier. How to simulate the cost and the recovery time on the 2-tier supply chain model that we have developed is described in Section 3.2.

As a difference from the 2-tier supply chain model, the $(\mathrm{Z}-1)$ th supplier's price, probability of breakdown, downtime change by the $(\mathrm{Z}-1)$th supplier's order; if the $(\mathrm{Z}-1)$th supplier places orders to the cheapest but frequently down supplier, the $(\mathrm{Z}-1)$ th supplier's price is cheap but probability of breakdown and downtime is large. So, the risk simulator on the multi-tier supply chain needs the function to propagate the cost and the risk from the zth supplier to the $(\mathrm{Z}-1)$th supplier as shown at "Decision of price" and "Update of probability and time of being down" in Figure 3. The propagation of the cost and the risk is described in the section 3.3.

Finally, the risk simulator outputs the cost and the risk that are based on the recovery time, decentralized ordering cost and the urgent stock cost that are described in Section 2.2. The relationship between the cost and the risk is trade-off. So, it is necessary to show how much risk is mitigated or has to be accepted when the retailor saves or pays more cost. The simulation output for cost-benefit analysis is described in Section 3.4.

3.2 Simulation for 2-tier supply chain model

According to the definition of the recovery time in Section 2.2, the recovery time is the duration in lacking stocks for the demand to the retailer. Because the stock changes day by day, the proposed method simulates the stocks in decentralizing orders and the urgent stock after the catastrophic disaster.

Figure 4 shows the outline of the simulator that estimates the recovery time, the decentralized ordering cost, and the urgent stock cost. First, the decision-maker on the retailer inputs the orders O and the urgent stock $U_t(t < T)$ to the simulator. Based on the formulas (1) (2) with these inputs, the simulator estimates sum of the decentralized ordering cost and the urgent stock cost as the total cost.

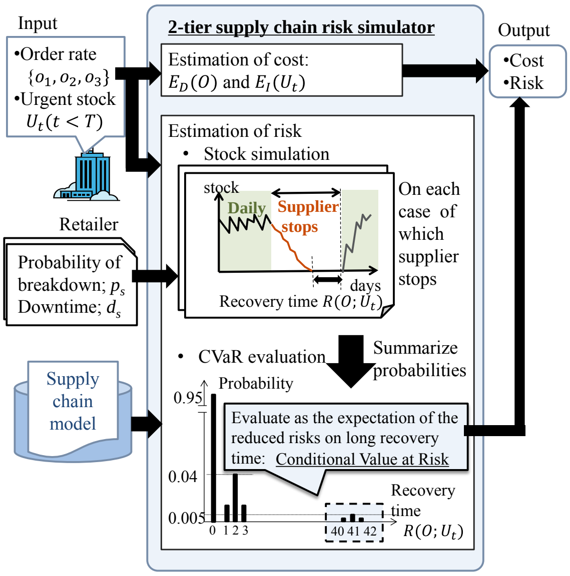

Figure 4. Simulation process on the 2-tier supply chain model

Besides, in order to estimate the recovery time, the simulator estimates the fluctuation of the stock with stopping the supplier based on the probability of the breakdown p_s. Concretely, the simulator uses the Monte Carlo method; a certain number of trials run for simulating the fluctuation of the stock but the supplier stops in $p_s$times of the trials. As a result of simulating the recovery time with stochastically stopping the suppliers, the simulator decides the probability distribution of the recovery time. For evaluating only the long recovery time that makes the retailer go bankrupt, we introduced the Conditional Value at Risk (CVaR) [15]. The detail of the estimation of the recovery time and the evaluation with CVaR is as follows:

- **Estimation of the recovery time:** According to the definition of the recovery time in Section 2.2, the recovery time is the duration in lacking stocks for the demand to the retailer. Because the stock changes day by day, the proposed method simulates the stocks in decentralizing orders and the urgent stock after the catastrophic disaster. Figure 5 shows the simulation model of the changes in stocks to estimate the recovery time. The process of estimating the recovery time is described in the following:

1) The demand of the customer is decided by the Gaussian distribution $N(\mu_D, \sigma_D^2)$.
2) Based on the demand D and the retailer's plan, the retailer places orders to the suppliers.
3) The cost of the retailer's plan is calculated.
4) Although the supplier receives the orders from the retailer, some suppliers become down at probability of breakdown. If the supplier is down, the supplier cannot supply.

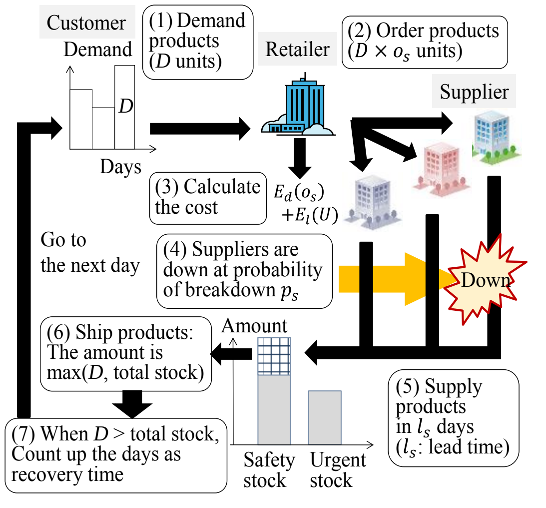

Figure 5. Simulation model to estimate recovery time

5) Only surviving suppliers can supply the products in l_s days and the retailer replenishes the stock with the products to be supplied.

6) The retailer ships the products from the stock that has been replenished in the step (5).
7) When the total stock of the safety stock and the urgent stock is not sufficient for the demand, the simulation counts up the day as recovery time.

The recovery time is derived from the simulation result shown in Figure 6. Until the catastrophic disaster happens, the stock is replenished from the suppliers and follows the normal distribution. When the catastrophic disaster hits some suppliers, the stock is deceased by shipping for the customers' demand due to the stop of the procurement from the supplier. The demand that is over the remained stock is regarded as the loss for $R(o_s;U)$ days. By decentralizing orders, the retailer can procure from surviving suppliers. So, the gradient of the decrease in the stock by decentralizing orders is smaller than one by ordering to one supplier. This indicates that decentralizing orders can decrease the recovery time. Additionally, the urgent stocks also can decrease the recovery time.

- **Risk evaluation with *CVaR:*** Because which suppliers stop depends on the probability of the breakdown, the recovery time $R(o_s;U)$ is expressed as a probability distribution by applying Monte Carlo method. Figure 7 shows the probability distribution of the recovery time.

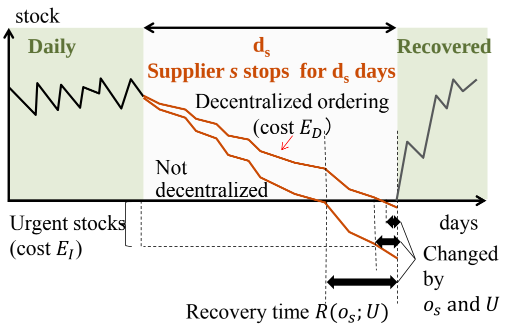

Figure 6. Estimation of the recovery time based on simulation of the stock

The upper part of Figure 7 shows the distribution of $R(o_s;U)$ in the centralized plan without the urgent stocks. And, the lower part of Figure 7 shows the distribution of $R(o_s;U)$ in the decentralized plan with the urgent stocks. Comparing both of the distributions, we can find that $R(o_s;U)$ is reduced in the decentralized plan with the urgent stocks. A typical method evaluates the probability distribution as an average of the distribution. But, the average values tend to underestimate the long recovery time; the reduction of 2 days at a rate of 0.04 (average=0.08) seems better than the reduction of 10 days at a rate of 0.005 (average =0.05) in the example of Figure 6. For the decision-maker, it is important to evaluate the long recovery time.

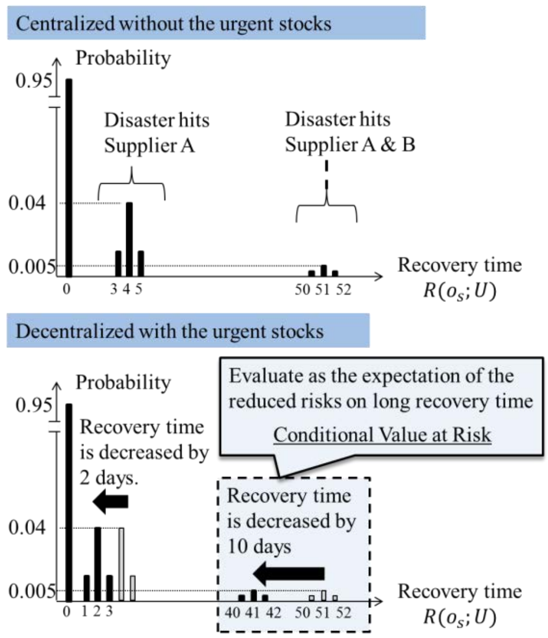

Figure 7. Probability distribution of the recovery time and CVaR evaluation

In order to estimate the recovery time, we introduce Conditional Value at Risk (CVaR) that is often applied for a rare event causing a heavy loss. CVaR is the average of values over a certain threshold. In applying CVaR to the evaluation of the procurement risk, CVaR is decided by the following:

$$\mathrm{CVaR} = \mathrm{E}(R(o_s;U)|R(o_s;U) > \mathrm{VaR}_\alpha)$$

where $\mathrm{E}(\cdot)$ is expectation and VaR_α is the threshold that is decided as Value at Risk(VaR). VaR indicates the maximum loss within $(1-\alpha)\%$ confidence interval. In the example of Figure 5, $R(o_s;U) = 40$ is the maximum loss within $(1-\alpha)\%$ confidence interval. By using CVaR for the risk evaluation, it is possible to consider only the long recovery time, $R(o_s;U)$ is within the range of $40 \leq R(o_s;U) \leq 52$ in the example of Figure 6.

3.3 Propagation of the *Cost* and *Risk*

The cost and the risk are propagated to the suppliers and reflected to the suppliers' price and the probability of downtime. The price and the probability of downtime (the probability of breakdown and downtime) are decided by the following formula:

- **Selling price:** We assume that the selling price c_{sr} of the supplier $s$to the supplier r depends on the total procurement cost of the supplier s. The total procurement cost from the suppliers $u(\in U)$ is sum of $c_{us}o_{su}$. And the simulator decides the price as the weighted procurement cost with a certain weight w.

$$c_{sr} = w\sum_{u\in U} c_{us}o_{su} \quad (3)$$

- **Probability of downtime:** The $(Z-1)$th supplier cannot supply the products when the procurement from the Z th supplier stops. So, the simulator decides the probability of downtime $P^{Z}_{s,Z-1}$ of the supplier s in $(Z-1)$th tier when the Zth supplier stops. In addition, independently from the Zth supplier stopping, the supplier s in $(Z-1)$th tier stops during d_s[days] at a rate of the probability of breakdown p_s, which can be shown as the probability of downtime $P_{s,Z-1}$. So, the total probability distribution of the downtime of the supplier s is $(P^{Z}_{s,Z-1}+P_{s,Z-1})$.

Repeating the above simulation between both tiers in the supply chain model, the simulator outputs the recovery time and the cost on the retailer and the suppliers.

3.4 Simulation output for *cost-benefit analysis*

Finally, the simulator outputs the total cost and the CVaR of the recovery time. If the several plans of orders are inputted to the simulator, the simulator outputs the scatter plot of the total cost and the CVaR of the recovery time as shown in Figure 8. In Figure 8, light-colored circle indicates the evaluation of plans when the retailer can change the suppliers' plans; the plans are derived from several kinds of parameter values on the suppliers. And the dark-colored circles indicate the evaluation of plans when the suppliers' plans are fixed; the plans are derived from a certain parameter values on the suppliers. As the example scatter plot in Figure 8 shows, the relationship between the CVaR of the recovery time and the total cost is trade-off; when the recovery time is decreased, the total cost is increased. And, it is possible to find the Pareto optimal plans whose total cost or CVaR of the recovery time is smaller than the other plans. In case of the graph in Figure 8, if the suppliers' plans are fixed, the retailer cannot obtain the Pareto optimal plans. So, the retailer can negotiate with the suppliers to change the suppliers' plans by using the graph.

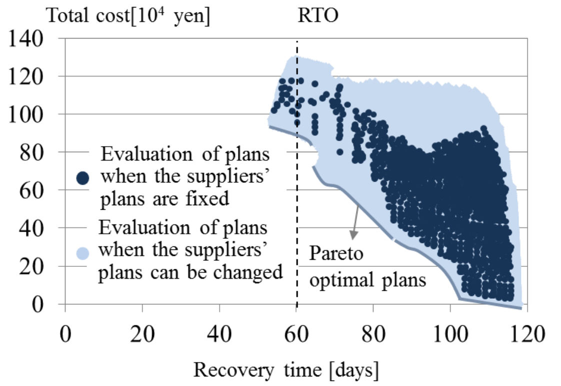

Figure 8. Scatter plot of recovery time and cost

In decision-making, when the decision-maker sets the recovery time objective (RTO) that is generally introduced in the business continuity management [13], the decision-maker can know the plan to minimize the total cost with keeping the recovery time below RTO as shown in Figure 8. And if the decision-maker accepts longer RTO, the decision-maker can know cheaper plans from the Pareto optimal plans with changing RTO.

4. Numerical Experiment

4.1 Target of experiment

The target supply chain model is the same as the 3-tier supply chain model shown in Figure1. The information of the supply chain model is from the literature[16].The retailer that deals with aluminum sash as a product procures from the 1st 3 suppliers (A, B and C) that procure from the 2nd 2 suppliers (D and E). Table 1 shows the retailer's parameter values and Table 2 shows the suppliers' parameters. The probability of the breakdown is based on the occurrence probability of the great earthquake in Japan [17].

Table 1. Parameter values of the retailer

Parameter	Value
Average demand [unit]	1600
Variance of Demand [unit]	50
Selling price [yen]	1.5× Buying price (w = 1.5)
Safety stock coefficient	1.65

Table 2. Parameter values of the retailer

Name of supplier	A	B	C	D	E
Price [yen]	2.0× Buying price ($w = 2.0$)	2.04× Buying price ($w = 2.04$)	2.08× Buying price ($w = 2.08$)	500	508
Probability of breakdown[%]					
Case 1	0.83	0.126	0.06	0.75	0.24
Case2	0.83	0.126	0.06	5.75	0.24
Case 3	2.4	1.2	1.0	0.75	0.24
Lead Time [day]	5	5	5	3	3
Time for recovery [days]	96	96	96	60	60
Rate of flexible procurement [%]	20	20	20	20	20

In this experiment, we assume that the user of the simulator is a decision-maker in the retailer. The user inputs the candidate plans of the order rates to the supplier A, B, C and the amount of the urgent stock. The simulator outputs the scatter plot of the CVaR of the recovery time and the total cost. In the candidate plans, the order rates are decided by changing the rate by 5% and the amount of the urgent stock is decided by changing the amount by an amount of the average demand in Table 1. This simulation aims at the decision support of the retailer's plan by showing the scatter plot.

In order to execute the simulator, it is necessary to input not only the retailer's plan of the orders but also the suppliers' plans of orders. To analyse the effect of decentralizing ordering clearly, we assume that the suppliers have no urgent stocks. As shown in Table 2, there are 3 kinds of the probabilities of breakdown, large probability and small probability, to find the relationship between the effect of decentralized ordering and the probability of breakdown.

4.2 Experimental result

Figure 9, Figure 10 and Figure 11 show scatter plots of evaluation results of the retailer's plans of the case 1, the case 2, and the case 3 respectively. Because the probability of breakdown is increased in order of case 1, 2 and 3, CVaR of recovery time are also increased in the order. The authors focus on the Pareto optimal plans that the decision-makers take into account for procurement planning. In order to clarify how well decentralizing orders contributes to generating the Pareto optimal plans, the authors classify ordering patterns on the Pareto optimal plans. Pareto optimal plans are shown by dark solid lines in Figure 9, Figure 10 and Figure 11 with classification patterns.

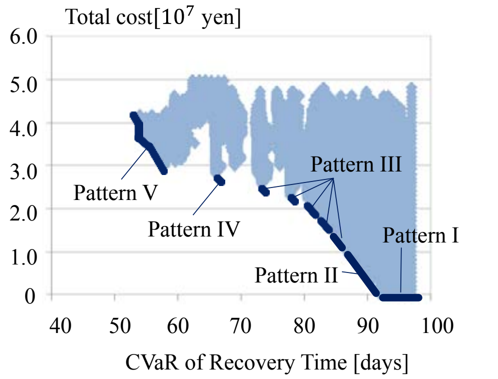

Figure 9. Evaluation results of the retailer's plan (case 1)

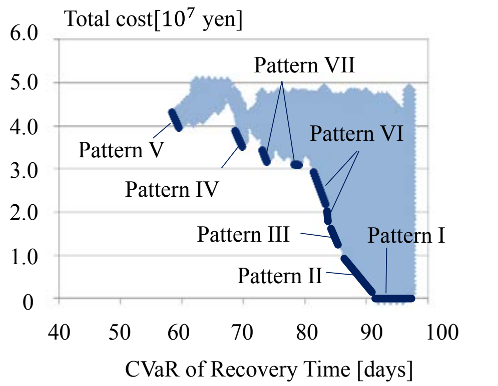

Figure 10. Evaluation results of the retailer's plan (case 2)

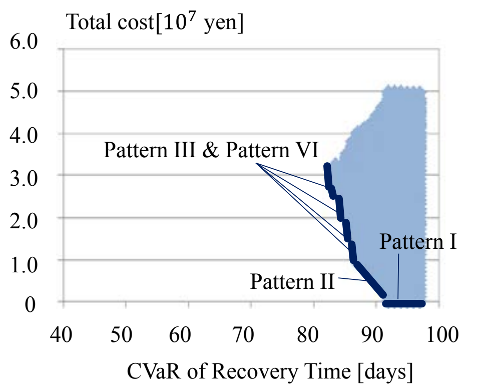

Figure 11. Evaluation results of the retailer's plan (case 3)

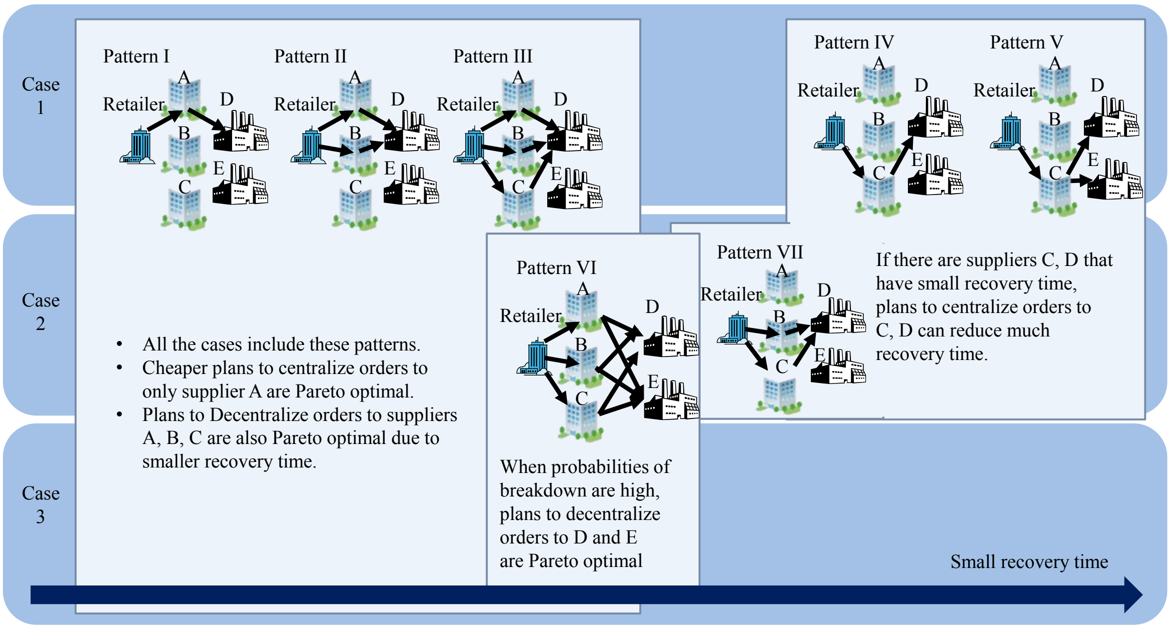

Figure 12. Ordering patterns in Pareto optimal plans

Figure 12 shows the patterns of the Pareto optimal plans that we find in Figure 9, Figure 10 and Figure 11. And Table 3 shows the breakdown of Pareto optimal plans in each pattern. The details of the patterns are described as follows:

- **Pattern I** indicates the plans that lead to the lowest cost without reducing the recovery time. Not only the retailer but also the suppler procure products from only the supplier that provides the cheapest products.
- **Pattern II:** The retailer decentralizes orders to the suppliers A and B in order to reduce the recovery time.
- **Pattern III:** The retailer decentralizes orders to the suppliers A, B and C.
- **Pattern IV:** The retailer procures from only the supplier C. The supplier C procures from the supplier D.
- **Pattern V:** The retailer procures from only the supplier C. The supplier C procures from the supplier D and E.
- **Pattern VI:** The retailer procures from A, B and C that procures from C and D. The retailer and all the suppliers decentralize ordering to reduce the recovery time.
- **Pattern VII:** The retailer procures from B and C that procure from D and E. The retailer and all the suppliers decentralize ordering to reduce the recovery time.

First, we compare the results of case 1 and case 2. The probability of the breakdown on D is high in case 2, which makes patterns VI and VII compared to case 1. Because the supplier D has high probability of breakdown, the retailer can make derived plans from Pattern III. As Pattern VI indicates, decentralizing orders to D and E are effective. On the other hand, due to low probability of breakdown on B and C in case 2, placing more orders to B and C is also effective.

Next we compare the results of case 2 and case 3. The probabilities of breakdown on A, B and C are high. So centralizing orders to D or E, indicated as Pattern IV, V VII, cannot reduce the recovery time any more compared to Pattern VI.

Table 3. The number of Pareto optimal plans in each pattern

	Pattern							Total
	I	II	III	IV	V	VI	VII	
Case 1	6	8	32	20	34	0	0	100
Case 2	6	9	27	4	4	25	3	78
Case 3	6	21	13	0	0	36	0	76

According to Figure 12 and Table 3, the authors analyze the effectiveness of decentralized ordering as follows:

- In case 3 where the probabilities of breakdown on A, B, C are high, decentralizing orders can reduce recovery time as Pattern III and VI indicate. This means that decentralizing orders are effective if the suppliers are often down.

- In comparing Patten III to VI and Pattern IV to V, decentralizing orders to D and E also contributes to reducing recovery time. For the retailer, not only decentralized ordering to A, B, C but also decentralized ordering to D, E are important.

Through the above discussion, it is confirmed that the proposed risk simulator can show the effectiveness of decentralizing orders on the case where the supplier has high possibility of breakdown. And the scatter plot of the evaluation values by the simulator supports the cost-benefit analysis by the decision-maker. By using the simulator for the retailer's and the suppliers' discussion, they can find appropriate plans to reduce the cost and the recovery time.

5. Conclusion

In this paper, we proposed the risk evaluation simulator on the multi-tier supply chain model to support the cost-benefit analysis of decentralizing ordering. By combining the risk evaluation simulator on the 2-tier supply chain model that we have already developed, the simulator on the multi-tier supply chain model was developed. To propagate the recovery time and the total cost to the retailer, we introduced the functions to decide the selling price and the probability of downtime based on the recovery time and the total cost.

Applying the developed simulator to 3-tier supply chain model, the recovery time and the total cost are evaluated on each retailer and supplier. As a result of the simulation, the authors found several patterns of the Pareto optimal solutions for the retailor. By comparing the patterns of both cases, decentralizing orders are necessary to obtain the Pareto optimal solutions on the case where the supplier has high possibility of breakdown.

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