The Effect of Redundant Capacity Strategy on Supply Chain Resilience Using Simulation

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***Abstract*— Supply chain resilience is an important adaptive capability and must exist in every supply chain network. Disruptions that occur in the supply chain will have a major impact on customer satisfaction. When customers are not satisfied, a company may start dealing with the effects of disruptions to its supply chain over time. Dissatisfied customers will issue fines or switch suppliers to meet their needs. Several strategies need to be implemented to minimize the impact that occurs due to disruption, especially the impact on customers. The total cost and total recovery time will be affected by customer behavior when there is a disruption to the supply chain network. Structural simulation will use agent-based modeling by implementing a redundant capacity strategy at each production plant. The percentage of redundant capacity will vary with several different conditions. Recovery time and total cost from the disruption that occurs will be influenced by customer behavior. Customer behavior is divided into two categories: critical customers and cumulative customers. The two customer behaviors will have a different impact on the strategy chosen. A supply chain resilience assessment index will be obtained for time to recover, and the total cost caused by disruption. The selection of the best strategy must be known before the strategy helps the company analyze recovery times in a disruptive situation using a redundant capacity strategy.**

Keywords—Supply Chain, resilience, disruption, simulation, agent-based modeling.

I. INTRODUCTION

Indonesia is an archipelagic country located in the Ring of Fire. This geographical condition will make Indonesia vulnerable to natural disasters (floods, earthquakes and volcanoes). 2021, the number of natural disaster events in Indonesia has reached 3058 events. The supply chain system that exists in the company must be able to handle disruptions that may occur. Companies and their supply chain networks must develop supply chain resilience (SCRES) in order to overcome existing disruption [1, 2].

SCRES is defined as the adaptive capability of the supply chain system to reduce the possibility of sudden disruption, prevent the spread of disruption by maintaining every existing structure and function, and immediately return to the initial performance of the supply chain system by implementing plans that are effective [3]. There are several strategies to increase supply chain resilience, including mitigation and reactive strategies [4]. There are several disruptions that can be prevented from occurring, but there are also disruptions that cannot be prevented by the company, so anticipation can reduce the impacts that arise. Companies need tools to determine how big the consequences of disruptions are and how effectively the strategy will be implemented [5]. When a company is able to determine a good strategy, supply chain performance can be optimized with the most effective time and cost.

The supply chain network is a large structure with several different companies (upstream companies to downstream companies) producing a finished product [6]. The existing structure of the supply chain network can be observed more closely in the relationships between its components. Analysis of the structure of the supply chain network can assist in making decisions to find out which components are most vulnerable and at risk [7]. If we only do an analysis of the structure of the supply chain network, dynamic post-disruption recovery will not be visible [8]. Simulation has a better ability to deal with more complex and continuously changing problems over a certain period [9].

Simulation can be carried out using a supply chain network with several stages. Once the simulation has been run and the results obtained, a comparison between the different SCRES strategies can be made. In practice, a cost analysis of the simulated strategy will assist in making the decision to choose the most cost-effective strategy. The total time for a supply chain network to return to its initial performance after a disruption can be used to determine long-term plans for a company to fulfil backorders.

In earlier research, mitigation tactics and backup plans put in place by businesses had an impact on the economic effects of catastrophes [7]. In fact, the economic consequences are not only influenced by the decisions taken by the company, and customers can greatly determine the economic condition of a company. Customer behaviour can be different when their demands cannot be met. Unfulfilled requests will have an impact on the company with several kinds of penalties, such as lost orders, lost customers, fines for not being able to fulfill contractual agreements, and a bad company image [10].

Only a few studies have been conducted to examine the consequences of consumer behavior on the company. As a result, using simulation, this research examines redundant capacity to demonstrate the influence of the strategy on supply chain resilience for two different categories of consumers. The findings may provide firms with insights into how to lessen the impact of interruptions in their supply chain resilience performance.

II. METHODS

2.1. Supply Chain Resilience Strategy

In the first step, we identify some supply chain resilience strategies. In most cases, mitigation strategies that exist in supply chain networks are to provide redundant or repetitive structures, by having several plants to produce products [7]. Redundant supply chain networks allow companies to continue to serve customers while continuing to recover after disruptions occur [12]. Customer behavior can change when customer satisfaction is not achieved. In addition, companies can also avoid losing time, costs, and effort when they are able to respond to sudden changes due to existing disruption [13]. Having several plants will divide the risk so that the worst possibility when the supply chain does not work becomes smaller. This step will greatly affect the level of resilience of the existing supply chain structure.

Redundant capacity is also widely implemented by companies to anticipate the effects of existing disruptions. Redundant capacity means that the production line will keep more products than it should, so it has the ability to respond to disruptions. This method is effective because more capacity will prevent the performance of the supply chain network from deteriorating and allow it to return to normal quickly [7]. The supply chain under the problematic plant will continue to run because there is excess capacity [14]. This strategy cannot solve the problem as a whole but only prevents and reduces the impact caused by disruptions in the supply chain network below. The existence of excess capacity means the opposite of the lean manufacturing strategy, so if used in the long term, redundant capacity strategies will be detrimental [14].

Backup plants are also one of the strategies to create a supply chain network that has good resilience. This strategy is a reactive one to maintain production when disruptions occur [15]. This strategy is very effective because if a plant in the supply chain network experiences a disruption, the backup plant will take over so that the supply chain network continues to run normally. Companies have to pay more when operating a backup plant [16]. It is said to be more expensive because companies have to bring in additional workers to operate the plant to meet existing demand [7].

In implementing several existing strategies, it is necessary to know in advance which plants have a high critical level. The purpose of a high critical level is that when there is a disturbance at the plant, two or more supply chain circuits will be disrupted. Of the several existing strategies, one needs to be assessed so that it can be compared to see which one is the best to implement. Not only that, simulation and analysis of the structure of the supply chain network are also required.

2.2. Analysis Based on Simulation of Supply Chain Resilience

In the second steps, we develop simulation frame work for supply chain resilience. Simulation can provide valuable insights in preventing and mitigating disruptions in supply chain networks [5]. There are several simulations for supply chain resilience from the existing literature.

There are several differences in the complexity of the simulated supply chain network, such as three-stage supply chain Network (SCN), where there are three levels of plant and material to produce finished goods [17, 8, 18, 7], and four-stage SCN [5,19]. Apart from three-stage and four-stage SCN, there are hierarchical network methods [20], and complex network methods [21]. Fig. 1. shows the supply chain structure, which has three stages. The first stages in the supply chain in Fig. 1 are plants one, two, three, four, and six. The plant acts as a supplier of raw materials to be processed at the next stage. The second stage in the supply chain network is at plants five and seven. The plant in the second stage will process the goods received from the first stage. The last stage is at plants eight and nine, where the product produced will enter material eight, and at that point the product is already in its final stages.

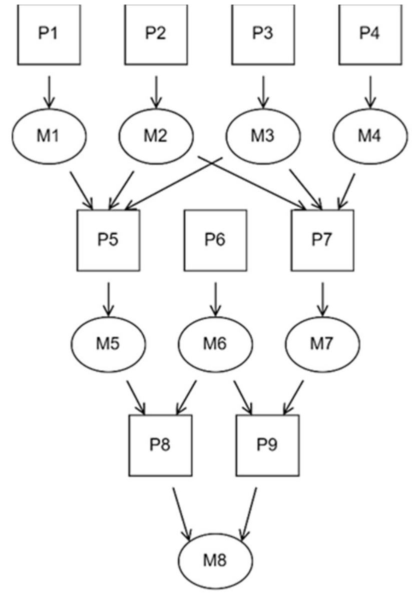

Fig. 1. Supply chain network

Distractions can be imitated using some scenarios in simulations [17, 8, 18, 5, 19,7]. In this paper discrete event simulation is developed to mimic scenarios in real systems. There are some research have been conducted using discrete event simulation such as simulation for evaluating performance of port terminal [22], optimizing assembly line [23], flexible job shop scheduling [24] and validating actuation conflict management in IoT system [25] However, in the scenario, there is also a stochastic disruption length as a simulated disturbance [20], random and targeted disruption [21]. Disruption like the one above was used by some previous researchers to run simulations of their research.

There are several kinds of mitigation and backup strategies used by several previous researchers. The mitigation strategy used generally uses a safety stock strategy where the supply chain network will keep more goods produced than requested [17, 18, 21, 20,7]. Not only safety stock is used for mitigation strategies, but a combination of safety stock and facility fortification is also carried out [5]. The backup strategy used varies, including backup plants [8],21], flexible sourcing [19], backup sourcing [5], coordinated production ordering [18], and a combination of backup plants and backup supply chains [7].

Supply chain performance measured in the simulation varies widely such as fulfillment rate [17], fill rate and cost [8, 21], fulfillment quantity and delivery distance [19], service level, sales, lead time, and inventory are used as a measure of supply chain performance [5], dynamic, profit tardiness, and time to recover [20], service level and cost are used by [18], and total cost and time to recover are used as measurements in running the simulation [7].

The supply chain resilience index is generally aggregated, averaged, and sampled and used in certain studies such as aggregated performance loss [17, 7], average performance within recovery time [19], performance effect index [5], and a sample of average supply chain performance [20].

The company intends to carry out recovery due to disruptions as quickly as possible. However, at that time, the company must keep satisfying the needs of its customers. When the commodities produced have high market competition, disturbances in the supply chain network may lead customers to become less loyal [10]. When customer behavior changes because of disturbances in the company's supply chain system, supply chain performance will alter. The time required by the company to recover, as well as the total cost, will alter depending on how long the disruption occurs until the supply chain's performance returns to its ideal level. This background can be used to explain why customer behavior might be seen as a factor influencing supply chain performance.

Time is an important measure of whether an existing supply chain can be said to be resilient or not. Time-to-recover is the time from when the disturbance starts to occur until the system returns to its normal position after the disturbance is over. Supply chain performance will show a similar behavior as shown in Fig. 2.

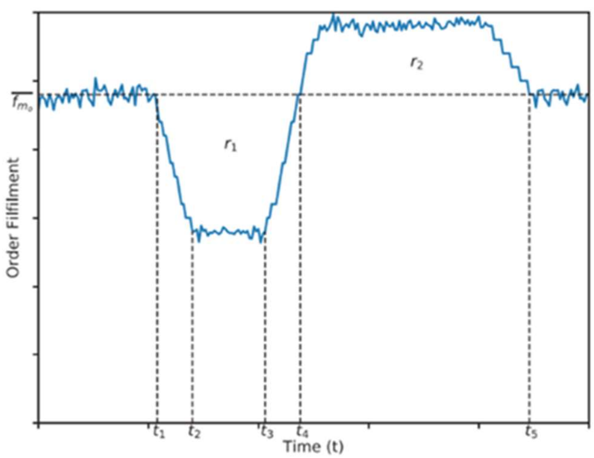

Fig. 2. Disruption and recovery in an SCN [8]

In Fig. 2, t_1 is the starting point for disruption in the supply chain network. SCN performance will continue to fall until position t_2, where the biggest impact of disruption is at positions t_2 to t_3. Recovery starts at t_3 and will return to the initial SCN performance, namely t_4. When a disturbance occurs, the most important thing is to have additional capacity after a disaster or disturbance [30] and t_5 is a condition where the SCN has returned to its initial performance.

Average Order fulfillment is a normal condition that is used to measure SCN performance. When there is a disturbance, the demand that can be fulfilled will decrease from t_1 to t_4. The area under f_{m0} is r_1, where the area is orders that cannot be fulfilled by the company (performance loss) [31]. To close backorders (r_1), at t_4 to t_5, the company must increase its capacity (area is r_2). On t_5, once all backorders have been delivered, the company may return to its original SCN performance. To determine when the recovery ends, the performance recovery must equal the performance loss. Time-to-recover is the time from the start of the disturbance (t_2) until the SCN performance returns to its original state when the backorders are fulfilled (t_5) [7].

The economic impact felt due to disruption can be influenced by mitigation and reserve strategies implemented by the company. According to [7], there are several variations that affect the economic impact of companies, including (1) Excess storage costs that aim to mitigate the impact of disruptions can be interpreted as inventory costs. (2) Production price per unit of material to produce goods (3) For backup plants for reserve capacity, the company usually pays higher than its actual capacity (risk sharing), so the costs for production are also different. (4) the cost of ordering from various suppliers. (5), and lastly, the cost of backorders that must be incurred by the company to fulfill customer satisfaction.

The above variances will be added together, and the entire cost that the company must bear when a disruption occurs will be known. The evaluation is carried out with the assumption that there is no effect from the company's customers in terms of time-to-recovery and total cost. In reality, when businesses fail to satisfy customer expectations, customer behavior might shift [10].

Customers are a very important part of companies, both customers who cooperate and those who do not. Customer satisfaction will determine the success of the company. Customers are not always the last part of a product. In the industrial world, customers are part of other companies that will use these products in their production processes [28]. Disruption that occurs in the company can disrupt the production activities of customers below.

Customer behavior can change when there is a disruption in the company's SC and customer satisfaction cannot be fulfilled. In a short span of time, customer needs that are not met will result in backorders or delays in ordering. When customer satisfaction is not fulfilled, the company will experience losses in the form of (1) loss of temporary order opportunities, (2) complete loss of customers, and (3) penalties caused because the company cannot fulfill contracts according to schedule [10]. Of these three points, there are those that affect the company's SC performance directly or indirectly, as can be seen in Fig. 3.

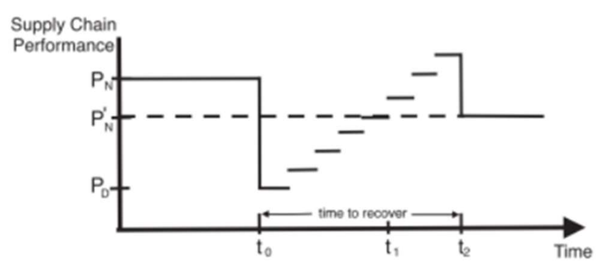

Fig. 3. Supply chain performance [10]

PN is the initial condition of the company's SC, when there is a disturbance, the performance of the SC will be at the *PD* point. When there is a disturbance and customer behavior is affected, there will be a change in the company's SC performance in the future. SC's performance after being affected by customer behavior is *P'N*. In the end, customer behavior will affect the time-to-recovery and total cost.

Companies can easily lose customers when there is competition in the market for a final product [29]. Customers will choose similar products from other companies if there is no significant difference in price and quality. Companies that apply single sourcing techniques and just-in-time deliveries for production will be vulnerable to being affected by this customer behavior [13]. In fact, customers do not want to know about the conditions that occur in the company so that no reason will be accepted by customers if there are still other similar products on the market. Companies must be aware of customer behavior by implementing several strategies so that customer satisfaction can be realized.

2.3. Simulation development

The material agent model is an inventory system for material *M* in the supply chain network structure. On the material side, there are two connected plants, namely a plant that produces material (upstream plant) and a plant that receives material (downstream plant). The downstream plant will receive material from the existing inventory in material (*M*), so material (*M*) will receive orders from the plant below it. In order to make it easier to do modelling based on customer requests, a constant number of orders will be used at a certain time for the final product (*M8*). Fulfilment of material orders depends on inventory availability, and inventory will decrease along with order fulfilment.

Backorders may occur when inventory is unable to meet downstream plant demand. The upstream plant needs to produce material requisitions (*M*) and maintain cycle stock. The average demand will be calculated according to the production lead time and within a certain time frame. There are various types of lead times in the process, namely production lead times and delivery lead times. To simplify the inventory simulation, it will be reviewed over a certain period of time so that orders that come in afterwards will be entered into the next step. The total lead time is the sum of production time and delivery time. If there are several plants that produce material (*M*), then the demand will be divided equally between each plant.

The plant agent models the information and production flow from the plant (*P*) to the plant (*P*). Material that enters the plant (*P*) from material (*M*) will be processed and produce output product. On the plant agent (P), the recourses that enter the plant are called upstream recourse, and those that receive products from the plant are called downstream recourse. The plant will receive orders from downstream recourse, and these orders will continue to be sent to upstream recourse as suppliers for Plan P. The plant will process input recourse within the production lead time, so the production rate is determined from several points: (i) the amount of input recourse, (ii) ongoing production, (iii) production capacity, and (iv) current inventory capacity.

It is assumed that each output product requires one input material, and the upstream recourse serves each downstream material evenly. The amount of input recourse depends on the number of downstream plants and the needs of each downstream plant. The production rate is determined by the four considerations in the previous paragraph. The production rate will be determined at any given time and will be added to the current inventory capacity (work-in-process). The plant will complete production within a certain time and produce material output. Inventory at that time will decrease, as will orders, because the plant has met demand. The finished product will be sent to downstream materials after a certain total lead time.

Disturbance scenarios will be simulated using a case study from a real-world supply chain network [30]. The purpose of the simulation is to determine the level of effectiveness of various supply chain resilience strategies. Disruption scenarios will be carried out at each plant for a certain period of 5 days, as shown in Fig. 4. There are three stages in the structure of a supply chain network. The total plant in the system is nine, the material in the system is eight, and the final product is *M8*.

Redundant capacity will be tested with a range of variations between 20% and 100%, with a multiple of 20%. Redundant capacity will be applied to every plant in the supply chain network system with the initial strategy. This strategy allows the same plant to produce more products than before. The number of plants did not increase, but production did. Details can be seen in Fig. 4.

The disruption will be simulated for 5 days, and the disturbance scenario will start on the fifth or tenth day. The five strategies above will be simulated using Anylogic software, and the results will be compared in one table with time-to-recovery and total cost under the influence of different customer behaviors with the help of visual charts. This comparison will show which strategy has the best performance (time-to-recovery) or the lowest cost given the conditions of customer behavior.

Disturbance scenarios will be applied randomly to each plan, with five repetitions for each scenario. Scenarios are applied to one plan at a time. The simulation will be carried out in each scenario five times with random disruption for a period of five days. The parameters for carrying out the simulation are taken from existing data sets [30], namely production lead time and production capacity. The order quantity on *M8* is 24 units per day, and each material has an inventory buffer time (production lead time).

Parameters that are not available in the dataset will be determined: holding cost 1/unit, production cost 1/unit, backup capacity 2.5/unit, ordering cost 20/plant, backorder cost 1/unit, partial lost sales 1/unit, lost sales cost 3/unit, penalty cost 1.5/unit. The data are based on simulations in previous studies [27, 7].

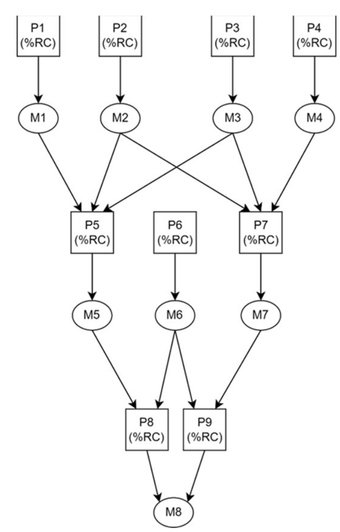

Fig. 4. Supply chain network

2.4. Simulation result analysis

In the last steps, analysis is conducted from the simulation results. Indexing for time-to-recover (TTR) and total cost (TC) is only done for critical plants. The critical plant level must be determined in advance in the existing supply chain network. If the results of the critical plant level are <1 then it is said not to be included in the critical plant criteria. The critical plant level is determined by dividing the number of plants in the supply chain by the number of supply chains. After knowing which plants are critical, the supply chain resilience index can be calculated. Equation (1) is the supply chain resilience index for time-to-recover.

$$SCRES\ ttr = \frac{1}{Total\ Plant} \times CP \times TTR \quad (1)$$

Equation (2) is the supply chain resilience index for total cost, can be calculated using a formula that is almost the same as the formula for calculating the supply chain resilience index for time-to-recover.

$$SCRES\ tc = \frac{1}{Total\ Plant} \times CP \times TC \quad (2)$$

2.5. Relative Cost-Effectife Strategy

Equation (3) is the relative total cost (RTC). When the indexing results have been obtained and compared in graphical form, the relative total cost can be known. When the result of the relative strategy cost (RCS) is less than 0, the strategy being implemented is more cost-effective than the default strategy cost (RCD). The default strategy adds 20% more production than it should to cover production shortfalls that occur due to disruptions.

$$RTC = \left(\frac{RCS-RCD}{RCD}\right) \quad (3)$$

III. Result and Discussion

Fig. 5 shows the result of the simulation using Anylogic software, showing that the default strategy takes 25 days after the disturbance ends on day 10 to return to its initial performance. Meanwhile, the backup capacity strategy with a percentage of 100% takes 5 days after the disruption ends. The increase in production capacity goes the same way as the speed of recovery that has occurred.

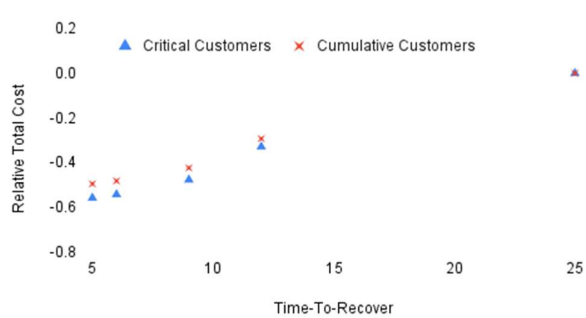

Fig. 5. Comparisons of SCRES strategies using SCRES indexes

Critical consumers have a bigger economic impact on the organization. Losing orders will cost the company more than the penalty fees that must be borne by the company when orders are not fulfilled on time. Figure 5 indicates that the faster the corporation can return to its initial performance, the smaller the losses will be. This is possible since the cost of backup capacity is less than the cost of lost sale.

The relative total cost of cumulative customers is slightly worse when compared to critical customers when implementing the same strategy. It can be concluded that if a supply chain has critical customer characteristics, the percentage of backup capacity can be lower than if the supply chain has cumulative customers.

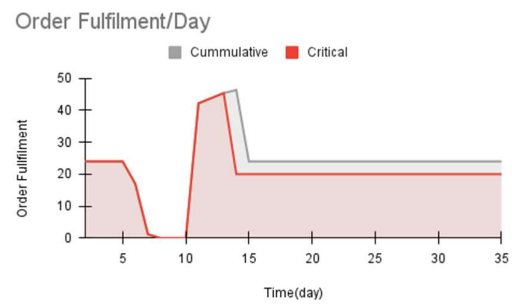

Fig. 6 Impat of disruption for 100% backup capacity

Fig. 6 illustrates the amount of production every day for the 100% backup capacity strategy with cumulative customer characters for the gray area. Fulfillment orders will begin to decline on days five to eight. Production will restart after the problematic plant starts producing goods again on day 11. Production will almost double for a few days so that backorders can be fulfilled. When the backorder has been fulfilled, production capacity will return to normal, with a capacity of 24 per day.

Critical customers are depicted in red areas. The initial stage of production has the same capacity of 24 products per day. What is different from the area of cumulative customers is the impact after backorders are fulfilled. Production capacity will decrease to 20 products per day as a result of declining demand. The decreased demand was caused by some customers who decided not to work with the company anymore. So that the greater the percentage applied, the better the relative total cost.

Fig.7 shows the relative total cost and relative time-to-recover values with the default strategy as a comparison. The best relative time-to-recovery for the cumulative customer type is the redundant capacity strategy of 100% with a value of -0.67, while for the critical type of customer there is a redundant capacity strategy of 80% and 100% with a value of -0.47. If the decision maker wants to speed up the completion of the impact of the disturbance, he can use a redundant capacity strategy of 100% for cumulative customers and 80% for critical customers. If the decision maker considers the costs due to disruption, the strategy that can be implemented is 100% redundant capacity with a value of -0.10 for cumulative customers and -0.09 for critical customers, with three strategic choices, namely 60%, 80%, and 100%.

TABLE I. Relative time-to-recover and relative total cost between defferent strategy and customers tipe

Strategi		Cumulative Customer			Critical Customer		
		TTR	Relative TTR	Relative Total Cost	TTR	Relative TTR	Relative Total Cost
Default Strategy	20%	30	0	0	19	0	0
Redundant Capacity	40%	17	-0.43	-0.07	14	-0.26	-0.06
	60%	14	-0.53	-0.09	12	-0.37	-0.09
	80%	11	-0.63	-0.09	10	-0.47	-0.09
	100%	10	-0.67	-0.10	10	-0.47	-0.09

IV. CONCLUSION

The purpose of implementing the strategy is to minimize losses in terms of time and cost by considering existing customer characteristics. Losses can be overcome by increasing fulfilment when the disturbance is over and the plant can operate again. Figure 6 shows that the more capacity there is to fulfil backorders, the shorter the overall impact caused by disruptions. A shorter time will minimize the impact that occurs, especially if the customer's character is critical.

Slow recovery times from backorders will result in reduced demand in the future. A good recovery speed will better maintain customer satisfaction. Of course, implementing a backup capacity strategy with a higher percentage will increase operational costs, but on the other hand, losses due to lost customers will be reduced. Total losses will decrease with better recovery speeds. The impact of the speed of recovery due to disruption on cumulative customer characters is not as good as if it were applied to critical customer characters. However, the strategy of increasing production capacity also reduces the impact of disruption, which is better than the default strategy.

The simulation model presented can help decision-makers in a company determine which strategy can help increase resilience in their supply chain network. The above model can be applied according to different customer characteristics so that the decisions taken can be more accurate. Strategies for critical customers can be applied to companies with intense market competition so that when a disruption occurs, the company does not lose too many customers. On the other hand, the speed of recovery can be adjusted if the competition in the market is not too heavy, in the sense that the demand is greater than the supply.

Future research can consider the investment costs required to implement the strategy. Some strategies have a very good time-to-recover performance. The total cost that must be borne by the supply chain network also varies depending on the strategy being implemented. Of course, this strategy cannot be carried out without incurring additional costs. Investment is needed to realize a resilient supply chain so that the costs incurred will be included in the total cost due to disruptions that occur. Decision makers can consider whether the investment costs that will be used to carry out the strategy can benefit the company for both cumulative and critical customer types.

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