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SUPPLY CHAIN DISRUPTION RECOVERY STRATEGIES FOR MEASURING PROFITABILITY AND RESILIENCE IN SUPPLY AND DEMAND DISRUPTION SCENARIOS

Yaru Li and Yanhong Yuan*

Abstract. This paper examines the recovery of a three-level manufacturing supply chain under supply and demand disruptions. The paper proposes new combined recovery strategies, which aim to cope with interruption by adjusting the supply chain structure and material flows. This study integrates both supply chain performance and supply chain capability dimensions. We develop a bi-criteria mixed integer linear programming model with profit and resilience maximization as the objective. The model combines supply-side supply expansion, manufacturer capacity impairment, and demand regulation on the demand side. In a numerical example, we find that a "reciprocal disruption overlay" occurs when supply and demand disruptions, but the supply chain still loses some profit. The results suggest that the combined recovery strategies reduce profit loss and increase supply chain resilience. Furthermore, the strategies are also the optimal recovery strategies under unilateral disruptions. This model facilitates the coordination of a disrupted supply chain and can help managers decide on the best recovery plan.

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1. Introduction

Supply chains experience disruptions from a variety of unexpected events. For example, COVID-19 caused supply and demand disruptions in the supply chain [28]. Disruptions in the supply of components due to supplier insolvency, resulted in production stoppages in many automotive manufacturing industries, leading to customer dissatisfaction and loss of profits [23]. The danger of demand-side disruptions could not be ignored, as the drop in demand caused by COVID-19 caused China's auto exports to plummet to a financial record of 80%. However, most companies do not pay enough attention to supply chain disruptions. According to the American Supply Management Association, 75% of companies suffered supply chain disruptions due to the COVID-19 pandemic, and 44% did not make disruption recovery plans. Therefore, it is necessary to examine supply and demand disruptions recovery strategies to help managers deal with disruptions.

In terms of mitigating the risk of supply and demand disruptions in the supply chain, several supply chain management theories are often used to mitigate supply disruptions: (1) Setting up safety stocks and inventory management to act as a buffer for production after disruptions [15, 30, 33, 47]. (2) Making product structure

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Keywords. Supply chain disruption, recovery strategy, bi-criteria, resilient supply chain, mixed integer programming.

College of Economics and Management, Taiyuan University of Technology, Taiyuan 030024, P.R. China.
*Corresponding author: `yuanyanhong2020@126.com`

adjustments or changing product composition to mitigate the impact of raw material shortages [10, 11, 41, 55]. (3) Multi-source or contingency sourcing, applying multiple sources to avoid supply failures caused by single sourcing [20,32]. (4) Setting up backup suppliers to function after the disruption of the original supplier [2, 53]. In addition, some studies combine the two strategies to cope with disruptions better. For example, Chen and Wang [9] combined setting up safety stocks and product composition changes to cope with long-term disruptions in manufacturing. For disruptions on the demand side, it is more effective to modify the production plan after the disruption than to predict it in advance [43]. Research has shown that managing demand disruptions can improve business performance [14]. In response to demand disruptions, existing research focuses on stabilizing demand to coordinate supply chains. Demand disruptions can be mitigated through external financing [58], information management [54], government subsidies [38], contracting, and flexible allocation [5]. The impact of the recent pandemic shows that both supply disruptions and demand disruptions occur in the supply chain [28]. However, most studies in the nearest literature have only considered disruption interference at one end of the spectrum. In this study, we both consider supply-side and demand-side disruptions when identifying the type of disruption to study disruption recovery in a supply-and-demand disruption scenario.

The structure of the supply chain largely determines the extent of the effect of disruptions [25]. Basole *et al.* [3] also highlight the importance of network structure and its impact on performance. After an unexpected event, it is essential to be agile and react to changes to maintain a sustainable supply chain by adjusting capacity and demand [27]. It requires coordination across the supply chain network and adjusting plans to sustain industry flows to increase financial performance by adjusting to the desired state, defining this capability as supply chain resilience [22]. A resilient supply chain that can respond to unexpected disruptions and adjust quickly to resume regular activity to achieve pre-disruption performance levels [29]. At the firm level, resilience can develop through capacity and inventory management and improving business development capabilities [8]; at the supply chain network level, resilience can improve through supplier development, optimized network structures [50], and digital technologies [17]. The constantly fluctuating environment suggests that it is imperative to develop effective recovery strategies to minimize disruption losses and increase supply chain resilience.

This study integrates the above two components to deal with supply chain disruptions. We propose a new set of combined recovery strategies to minimize the loss of profit due to supply and demand disruptions. Moreover, considering the supply chain performance after disruption recovery, the supply chain structure and material flows are adjusted to increase resilience. To this end, we develop a mathematical model of supply chain disruption recovery that maximizes the profit and resilience of the supply chain after disruption recovery, providing decision support for a three-level supply chain consisting of suppliers, manufacturers, and retailers.

The rest of the paper is structured as follows: Section 2 provides an overview of the relevant literature. Section 3 gives the problem definition, assumptions, and symbolic description. Then, in Section 4, develop a disruption recovery model and provide the solution method. Section 5 illustrates the application of the model and applies numerical examples to evaluate the performance of the recovery strategy. Section 7 lists some management recommendations and practical insights. The final section concludes the text and discusses directions for future research.

2. Literature review

Research on supply chain disruption recovery has received extensive attention in recent years. As research on supply chain disruptions deepens, scholars realize that disruption risk is dynamic to change [6]. The difficulty of predicting disruptions and the complexity of the disruption types suggest that the post-disruption management process is as important as predetermining the pre-disruption strategy [39]. Therefore, it is essential to develop an effective management strategy based on the disruption after an interruption [56]. Strategies such as setting up safety stocks [46,47], standby supply [37], and multi-source sourcing [20,32] are often employed to mitigate supply chain disruption risks. An effective post-disruption recovery strategy will directly affect the practical ability to recover from sudden and severe disruptions. Current research on disruption strategies focuses on the supply disruption perspective. Li *et al.* [33] compared and analyzed three inventory decisions: non-stockpiling, gradual stockpiling, and instantaneous stockpiling, to find the optimal inventory strategy after a supply disruption; and developed a decision model to optimize procurement time and quantity to provide recommendations for disruptions with different disruption scenarios. Combinations of various strategies were also applied to mitigate supply disruptions. Chen and Wang [9] proposed a combination strategy of product variation and setting up safety stock to cope with prolonged supply disruptions such as those caused by COVID-19. Shi *et al.* [48] formulate the recovery plan as a mixed integer linear programming model in the context of a significant supply disruption; and introduce outsourcing and capacity expansion strategies to improve supply chain service levels after a supply disruption. Sun *et al.* [49] propose a pricing and transshipment strategy for perishable goods during supply shortages; and analyze the effectiveness of the application of the solution according to different external supply scenarios, which facilitates retailers to make decisions based on external situations. COVID-19 exposes the supply chain to prolonged supply disruptions. To prevent manufacturers from suffering losses, Chen *et al.* [11] suggested changing the original product type and combining it with emergency sourcing strategies; the study found that the combination strategy effectively reduced manufacturers' losses due to late delivery and order cancellation. On this basis, Chen *et al.* [10] analyzed the interruption recovery strategies from the perspective of product changes. They also considered the timing of product life cycles and design changes to help manufacturers determine the best strategy in the face of supply disruptions.

Demand disruption is a particular factor affecting supply chain operations, resulting in a mismatch between actual demand and production plans [51]. This situation will impose additional costs on the supply chain. In addition, demand disruptions may lead to financial deterioration [21], efficiency losses, and reputational damage. Therefore, demand disruptions also require the attention of managers. Ali *et al.* [1] show that market demand disruptions significantly affect prices and service level investments. Therefore, as demand disruptions increase, supply chains should adopt aggressive pricing strategies [51]. Behzadi *et al.* [5], on the other hand, demonstrate that allocation flexibility can effectively reduce the risk of market demand disruptions. In addition, it is possible to mitigate the pressure of disruptions with external financial support. In the context of demand disruption, Ma [38] mitigates the impact of disruption through government subsidies and constructs six models of government subsidies. The model helps supply chain members adjust their decisions to changes in demand. Zhao *et al.* [58] discuss firm recovery strategies under demand disruption, propose a two-stage combination of bank financing strategies before and after demand, and analyze the impact of each financing combination on retailers' regret, risk, and profit to provide a basis for decision-making. Xiao *et al.* [52] consider a quantity discount coordination mechanism in which manufacturers offer retailers a lower unit wholesale price to incentivize retailers to order more products.

Supply chains are exposed to unpredictable and uncontrollable events and challenges, requiring them to develop the ability to adapt to the changing environment [34]. This ability to adapt and adjust quickly is called supply chain resilience and can measure by robustness and recoverability [19]. Many studies on supply chain resilience have been based primarily on the firm level [59]. As supply chains develop and grow, firms gradually lose visibility of the supply chain network structure. Therefore, it is necessary to study the ability of the entire supply chain network to cope with disruptions. Choi *et al.* [12] extend this research of category by looking at supply networks as complex adaptive systems. Taking the entire supply chain as the main body allows for the clever integration of relationships between supply chain combinations after disruptions [45]. The importance of this extension led an increasing number of scholars to emphasize resilience at the network level of supply chains. Network theory is the primary framework for analyzing supply chain disruptions and resilience [31]. To improve supply chain resilience, previous research has adopted a complex network approach from the perspective of network structure. It can help managers allocate resources or restructure the supply chain to cope with disruptions [57]. According to complex network theory, consider the supply chain as a complex network, where the nodes in the network represent the firms in the supply chain and the interactions between firms as links [42]. Supply chain resilience can measure through network characteristics like network type, the density of the network, path length, and clustering coefficient [7,18,35,36]. Dixit *et al.* [18] calculated supply chain network resilience by network density, centrality, connectivity, and network scale to assess whether a supply chain network can face severe disruptions. Manupati *et al.* [40] considered risk propagation and used final delivery under disruption scenarios as a resilience indicator. Li *et al.* [34] developed a multidimensional quantitative framework for measuring resilience along three dimensions: robustness, recovery time, and average functionality. The study better describes the complexity of supply chain network resilience and provides decision support to improve resilience. While supply chain disruptions can cause damage to the network, resilience can effectively respond to disruptions and deliver an assessment of performance [13]. Therefore, having supply chain network resilience is becoming imperative. At the network level, resilience can improve by developing suppliers, optimizing structures, and digital technologies [4, 17, 44].

Existing research provides essential contributions to recovery from supply chain disruptions. However, most studies on recovery strategies consider only supply-side disruptions, a few literature consider demand-side interruptions and limited studies consider both types of disruption. Considering the impact of a pandemic such as COVID-19 on the supply and demand side of the supply chain, this paper extends such research by integrating supply-side and demand-side disruptions. In addition, it is worth noting that most evaluations of the effectiveness of disruption recovery strategies are according to improvements in economic outcomes, most commonly profit indicators. For example, Chen *et al.* [11] showed that a recovery strategy that changes product types reduces manufacturers' lost profits due to disruptions. However, the complexity of the market environment forces managers to consider multiple objectives in their decision-making process. Therefore, we build our model using two indicators: supply chain profit and resilience.

The main contributions of this study are summarized as follows:

First, we address the problem of supply chain disruption recovery under the risk of simultaneous supply-side and demand-side disruptions. To this end, we propose a combined strategy of expanding the supply base and product allocation management. Furthermore, we analyze the effectiveness of this strategy in improving profit levels in supply and demand disruption scenarios.

Secondly, we introduce a description of a supply chain attribute – resilience – to measure the ability of a supply chain to maintain continuous supply and quickly resume operations in the event of a partial failure. Using resilience as an optimization objective extends the study of supply chain disruption recovery.

Finally, we use a multi-objective decision model to fit the problem as a bi-criteria mixed integer linear programming model. To maximize profit and resilience after supply chain disruption recovery and to provide managers with a basis for decision-making to solve real-world problems.

3. PROBLEM DESCRIPTION

This section first describes the problem to be solved and then illustrates the model assumptions as well as the required parameters and notation.

3.1. Problem description and hypothesis

In this paper, we consider a three-level manufacturing supply chain. This supply chain consists of suppliers, manufacturers, and retailers. As shown in Figure 1, there are multiple suppliers and retailers in this supply chain network. There are two types of suppliers: primary suppliers and backup suppliers. Determine the number of orders from retailers before production. The manufacturer works on an order-production basis. Under normal circumstances, the manufacturer purchases raw materials from the primary supplier. Production completes and delivers to the retailer in the quantity ordered. When an unexpected event occurs, the supply from the main supplier is disrupted, resulting in a shortage of raw materials. And the impact of the unexpected event on the demand side may cause product delivery to fail. The supply chain either loses potential sales or increases stranded costs, resulting in direct or indirect loss of profit.

To reduce the damage of unexpected events and mitigate supply and demand disruptions. This paper proposes the combined recovery strategy: first, the expansion of the supply strategy. Manufacturers can make emergency purchases from the un-disrupted primary suppliers, or activate the backup supplier. Second, the product distribution management strategy. Fulfill orders from non-disrupted retailers first and adopt a price discount strategy to dig deeper into user demand and incentivize retailers to reorder. At the same time, it

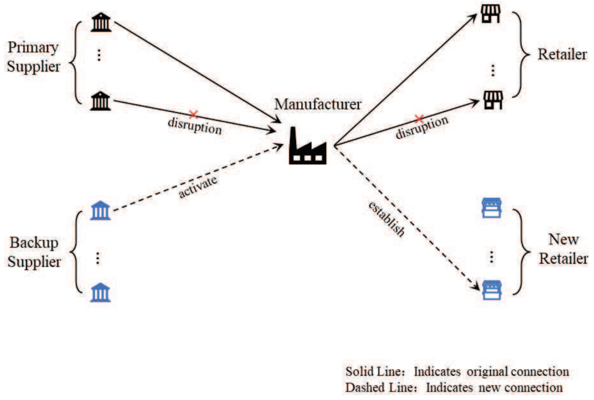

Figure 1. Three-level supply chain element network.

can develop new retailers in the market, broaden the channel, deliver products to new retailers, and promote product distribution. After a disruption occurs, managers determine the delivery of materials between suppliers and manufacturers based on supply disruptions and activate the number of backup suppliers. Determine the number of products to be delivered and develop new retailers based on demand disruptions.

To make the study more relevant, the following assumptions are made:

- Both suppliers provide the same raw material.
- The manufacturer produces only one product and uses one unit of raw material to produce one unit of the product.
- Unfilled retailer orders incur out-of-stock costs. In addition, enabling a backup supplier and developing a new retailer both add additional costs.
- Disruptions may occur at any primary supplier and retailer. Backup suppliers and newly developed retailers are completely reliable and unaffected by disruption events.
- Once a disruption occurs, it is a complete disruption and cannot recover for the entire study cycle.

3.2. Symbols and parameters description

To understand the model developed in this paper, the meaning of the symbols used in the model are shown in Tables 1 and 2.

4. Bi-criteria disruption recovery model

4.1. Model construction

This section presents the proposed bi-criteria disruption recovery model with profit and resilience maximization as the objective. The objectives of the model are: (1) to determine the number of emergency purchases at non-disrupted primary suppliers, (2) to determine whether to activate backup suppliers, and (3) to determine the number of products delivers to retailers and whether to incorporate new retailers. The goal of the model is to maximize supply chain profit and resilience.

The manufacturer's revenue over the cycle is the number of products finally delivered to all retailers multiplied by the unit price of product sales.

$$REV = \left(\sum_{j \in J} y_j \times b_j + \sum_{m \in M} D_m \times w_m \right) \times P. \tag{1}$$

Table 1. List of parameters.

Parameters	Meaning
PS	Primary supplier
R	Retailer
BS	Backup supplier
NR	New retailer
i	Index of primary suppliers
j	Index of retailers
k	Index of backup suppliers
m	Index of new retailers
Z_i	Quantity of raw materials that can be procured from primary supplier i under normal conditions
$Z_i^{\max}$	Maximum quantity of raw materials that can be procured from primary supplier i under normal conditions
$Z_i^{\min}$	Minimum quantity of raw materials that can be procured from primary supplier i under normal conditions
$\varphi_i^{\max}$	Maximum quantity of raw materials that can be supplied by primary supplier i after disruption
p_i	Unit procurement cost of raw materials from primary supplier i
e_i	Emergency procurement unit cost from primary supplier i
q_k	Quantity of raw materials that can be supplied by backup supplier k
p_k	Unit procurement cost of raw materials from backup supplier k
I_k	Cost of activating backup supplier k
B_j	Quantity of orders demanded from retailer j
$r_j^{\max}$	Maximum quantity of products demanded from retailer j
α	Price discount rate
D_m	Quantity of demand from new retailer m
A_m	Cost of effort to develop new retailer m
Q	Maximum quantity to be produced by manufacturer
τ	Loss of capacity coefficient of manufacturer
P	Unit price of product sales
O	Unit cost of order
M	Unit cost of production
S	Unit cost of out-of-stock
H	Unit inventory cost of stranded products
c_i	Cost of transporting a unit of raw material from primary supplier i to manufacturer
c_k	Cost of transporting a unit of raw material from backup supplier k to manufacturer
c_j	Cost of transporting a unit of product from manufacturer to retailer j
c_m	Cost of transporting a unit of product from manufacturer to new retailer m
tr_i	Distance from primary supplier i to manufacturer
tr_k	Distance from backup supplier k to manufacturer
tr_j	Distance from manufacturer to retailer j
tr_m	Distance from manufacturer to new retailer m
n	Number of nodes in a given supply chain
n_d	Number of disrupted nodes in a given supply chain
a_i	1 if primary supplier i is not disrupted, 0 otherwise
b_j	1 if the retailer j is not disrupted, 0 otherwise

Table 2. List of decision variables.

Decision variables	Variable description
x_i	Quantity of raw materials procured from primary supplier i
y_j	Quantity of products delivered to retailer$j$
u_k	1 if backup supplier k is activated, 0 otherwise
w_m	1 if the manufacturer sells to a new retailer m, 0 otherwise

(1) Ordering cost (OC)

Ordering cost is the cost paid for the entire process involved in placing an order until receipt of the raw material. It is calculated by multiplying the sum of raw material quantities supplied by all suppliers by the unit cost of the order.

$$OC = O \times \left(\sum_{i \in I} x_i \times a_i + \sum_{k \in K} q_k \times u_k \right). \tag{2}$$

(2) Procurement cost (PC)

Raw material procurement costs consist of three sub-costs: (i) the cost of procuring raw materials from the primary supplier, (ii) additional costs incurred for emergency purchases from undisrupted primary suppliers, and (iii) the cost of procuring raw materials from backup suppliers.

$$PC = \sum_{i \in I} x_i \times a_i \times p + \sum_{i \in I} e_i \times \Big(x_i \times a_i - Z_i \times a_i \Big) + \sum_{k \in K} p_k \times q_k \times u_k. \tag{3}$$

(2) Manufacturing costs (MC)

The model assumes that a product requires only one unit of raw material, so the quantity of the product is equal to the quantity of raw material purchased. So, manufacturing cost is measured as the sum of raw material quantities purchased multiplied by the unit cost of production.

$$MC = M \times \Big(\sum_{i \in I} x_i \times a_i + \sum_{k \in K} q_k \times u_k \Big). \tag{4}$$

(3) Transportation cost (TC)

Transport costs are the transport expenses to complete the transport of goods. Transport costs arise when transporting raw materials from suppliers to manufacturers and passing products from manufacturers to retailers. Transport costs are calculated by multiplying the quantity of goods by the cost of transporting a unit of goods.

$$TC = \sum_{i \in I} x_i \times c_i + \sum_{j \in J} y_j \times c_j + \sum_{k \in K} q_k \times u_k \times c_k + \sum_{m \in M} D_m \times w_m \times c_m. \tag{5}$$

(5) Backup supplier start-up costs (C_1)

There is an additional cost for activating a backup supplier. It can be expressed as the sum of the costs of activation of all backup suppliers that have been activated.

$$C_1 = \sum_{k \in K} I_k \times u_k. \tag{6}$$

(6) Inventory costs of stranded products (IC)

Inventory resulting from slow or stagnant product sales increases costs, known as stranded product inventory costs. The quantity of stranded products multiplied by the unit inventory cost of the stranded product is the inventory cost of stranded products. The quantity of stranded product is the amount of product produced minus the amount of product delivered.

$$IC = \left(\sum_{i\in I} x_i \times a_i + \sum_{k\in K} q_k \times u_k - \sum_{j\in J} y_j \times b_j - \sum_{m\in M} D_m \times w_m \right) \times H. \tag{7}$$

(7) Cost of discounts (DC)

The manufacturer promotes by discount, and the reduced benefit due to the discount can be considered as increased cost. The cost of a discount is the sales revenue before the discount minus the sales revenue after the discount. Sales revenue after discount is calculated by multiplying the price discount rate by the unit price of the product sales multiplied by the quantity.

$$DC = P(1-\alpha) \times \sum_{j\in J} (y_j - B_j) \times b_j. \tag{8}$$

(8) Cost of effort to develop new retailers (C_2)

Costs incurred during the period from development to product distribution represent effort costs. The effort cost of developing new retailers can be calculated as the sum of the cost of effort to develop new retailers.

$$C_2 = \sum_{m\in M} w_m \times A_m. \tag{9}$$

(9) Stock-out costs (SC)

Stock-out costs are losses due to disruptions that prevent delivery of orders from uninterrupted retailers. The stock-out quantity is the retailer's pre-order quantity minus the number of products delivered. The stock-out quantity multiplied by the unit cost of the stock-out is the stock-out cost.

$$SC = S \times \left(\sum_{j\in J} B_j \times b_j - \sum_{j\in J} y_j \times b_j \right). \tag{10}$$

The manufacturer's total cost (TC) is the sum of equations (2)–(10), see equation (11).

$$TC = OC + PC + MC + TC + C_1 + IC + DC + C_2 + SC. \tag{11}$$

Then, translate the problem into a mixed integer linear programming model with supply chain profit and resilience as the optimization objectives. The objective function of the model is as follows:

(1) Objective 1: Maximizing the supply chain profit (PRO)

Total supply chain profit equals total supply chain revenue minus total costs.

$$\max PRO = REV - TC. \tag{12}$$

(2) Objective 2: Maximizing the supply chain network resilience (R)

Resilience is calculated based on connectivity (CV) and network density (D). Network connectivity determines by the number of paths from all supply nodes to all demand nodes in the network [24]. It is a topological property of the network that determines the ability of the supply chain system to maintain its plan in the presence of perturbations. Network connectivity calculated the number of all effectively connected edges (paths) from upstream to downstream. These edges undertake the delivery of the supply chain product flows and information flows. Network density is the number of nodes per unit distance [16]. It is a crucial metric for analyzing supply chain resilience to determine how to connect the network for a well-functioning supply chain. Network density shows the relationship between the nodes in a given supply chain. It can as calculated by dividing the total number of nodes by the average node spacing, *i.e.* $\frac{(n-n_d)}{\frac{\sum_{i\in I} a_i\times tr_i+\sum_{j\in J} b_j\times tr_j+\sum_{k\in K} u_k\times tr_k+\sum_{m\in M} w_m\times tr_m}{\sum_{i\in I} a_i+\sum_{j\in J} b_j+\sum_{k\in K} u_k+\sum_{m\in M} w_m}}$. The calculation formula for each of the two indicators is as follows:

$$CV = \sum_{i\in I} a_i + \sum_{j\in J} b_j + \sum_{k\in K} u_k + \sum_{m\in M} w_m \tag{13}$$

$$D = \frac{\left(n-n_d\right)\times\left(\sum_{i\in I} a_i+\sum_{j\in J} b_j+\sum_{k\in K} u_k+\sum_{m\in M} w_m\right)}{\sum_{i\in I} a_i\times tr_i+\sum_{j\in J} b_j\times tr_j+\sum_{k\in K} u_k\times tr_k+\sum_{m\in M} w_m\times tr_m}\cdot \tag{14}$$

From the perspective of a supply chain network, a disruption to a firm in the supply chain equates to removing a node from the network and can result in unreachability between nodes. High network connectivity means that when nodes are unreachable, managers can coordinate alternate edges (paths) or create new edges (paths) to mitigate the effects of upstream and downstream disconnections. So, network connectivity is usually proportional to resilience. Higher network density indicates a relative concentration of nodes and closer connections between them. When there is a local disruption in the supply chain, nodes close are more susceptible to disruption propagation due to the ripple effect. It is detrimental to disruption recovery, so network density is inversely proportional to resilience. Therefore, this study expresses supply chain resilience as a network connectivity (CV) to network density (D) ratio. Objective 2 is to maximize supply chain resilience:

$$\max R = \frac{CV}{D}\cdot \tag{15}$$

The model satisfies the following constraints:

s.t.

$$\sum_{j\in J} B_j = \sum_{i\in I} Z_i \tag{16}$$

$$\sum_{i\in I} Z_i \le Q \tag{17}$$

$$Z_i \le Z_i^{\max} \tag{18}$$

$$Z_i^{\min} \le Z_i \tag{19}$$

$$\sum_{j\in J} B_j \le \sum_{i\in I} x_i\times a_i + \sum_{k\in K} q_k\times u_k \tag{20}$$

$$\sum_{i\in I} x_i\times a_i + \sum_{k\in K} q_k\times u_k \le Q(1-\tau) \tag{21}$$

$$\sum_{j\in J} y_j\times b_j + \sum_{m\in M} D_m\times w_m \le \sum_{i\in I} x_i\times a_i + \sum_{k\in K} q_k\times u_k \tag{22}$$

$$x_i \le \varphi_i^{\max} \tag{23}$$

$$Z_i\times a_i \le x_i\times a_i + Z_i\times(1-a_i) \tag{24}$$

$$B_j\times b_j \le y_j\times b_j \tag{25}$$

$$y_j \le r_j^{\max} \tag{26}$$

$$0 \le x_i \le N\times a_i \tag{27}$$

$$0 \le y_j \le N\times b_j \tag{28}$$

$$a_i, b_j, u_k, w_m \in \{0,1\} \tag{29}$$

$$x_i, y_j \in Z_0^{+}. \tag{30}$$

Constraints (1) to (30) together define the optimization objectives and constraints of the model. Equation (16) states that in normal conditions, the purchase volume from the primary supplier is equal to the retailer's pre-order volume. Equation (17) constrains the manufacturer's capacity in the normal case. Equations (18) and (19) bound the upper and lower bounds on the manufacturer's purchasing volume under normal conditions. Equation (20) states that the manufacturer's raw material purchases after the disruption are not less than the retailer's pre-order quantity. Equation (21) constrains the manufacturer's capacity after disruption. Equation (22) constrains the final product delivery not exceeding the manufacturer's production capacity. Equation (23) constrains the supply capacity of the primary supplier after the disruption. Equation (24) states that the procurement volume from the non-disrupted supplier is not less than what it would be under normal circumstances. Equation (25) indicates that if the retailer j does not disrupt, its product deliveries are not less than the order quantity. Equation (26) ensures that the amount of product delivered to the retailer j does not exceed the retailer j's maximum demand. Equations (27) and (28) show that the purchased quantity is zero if the supplier disrupts and the delivery quantity is zero if the retailer disrupts, respectively, where N is a large number. Equation (29) constrain the binary nature of the variables a_i, b_j, u_k, w_m. Equation (30) constrains the non-negative variables.

4.2. Solution approach

The bi-criteria disruption recovery model developed in this paper is a mixed integer linear programming model. We use the NNC (normalized normal constraint) method to solve it. Using IBM ILOG CPLEX Optimization Studio V12.8.0 and MATLAB 2018a as solving tools, modeled by the YALMIP toolkit and invoked the CPLEX solver to solve. The resulting solution provides decision support for managers. CPLEX supports the rapid development and deployment of decision optimization models using mathematical and constraint planning and is well suited for solving the mixed integer linear programming model presented in this paper.

For ease of illustration, we describe the bi-criteria disruption recovery model as a general form.

$$\max\Big(f_1(x), f_2(x)\Big)$$

$$\text{s.t.}$$

$$g_i(x) = 0$$

$$y_i(x) \leq 0$$

where x represents the decision variables, f_1 and f_2 represent the profit objective and the resilience objective, respectively, g_i represents the equation constraint, and y_i represents the inequality constraint. The process of solving the bi-criteria disruption recovery model is as follows:

Step 1. Initialize the model parameters.
Step 2. Input the parameters of the supply chain under normal conditions, and solve the optimal procurement solution Z_i when there is no disruption.
Step 3. Assign values to the relevant parameters according to the disruption situation; input the value of a_i, b_j according to the disruption scenario.
Step 4. Solve the model and output the results.

5. NUMERICAL EXPERIMENTS

This section focuses on verifying the feasibility of the bi-criteria disruption recovery model by numerical examples to provide reference examples for managers. Firstly, we assign random values to the parameters required by the model. Then, with supply chain profit and resilience as the optimization objectives, we consider the capacity constraints of each supply chain firm and make decisions on the procurement, production, and

Table 3. Primary supplier parameters.

Primary supplier	p_i	e_i	$Z_i^{\max}$	$\varphi_i^{\max}$	c_i	tr_i
PS_1	11	2	670	820	1	1300
PS_2	10	1	630	790	3	2250
PS_3	12	3	660	820	2	2970
PS_4	12	2	680	880	2	2700
PS_5	11	1	700	850	3	2250
PS_6	13	3	630	800	1	2520

Table 4. Backup supplier parameters.

Backup supplier	p_k	q_k	I_k	c_k	tr_k
BS_1	13	565	3250	3	2196
BS_2	14	505	3128	1	2280
BS_3	17	520	1508	2	3235
BS_4	13	470	2540	1	2737
BS_5	15	490	2720	1	3550

delivery plans after disruptions. In addition, we also compare and analyze the disruption recovery strategies under unilateral disruption scenarios and perform sensitivity analysis for different parameters.

5.1. Parameter settings

It is assumed that under normal conditions, the supply chain network has six master suppliers and one manufacturer. The manufacturer schedules production based on pre-orders from retailers and delivers the product to eight retailers. After a risk event, the manufacturer's upstream and downstream master suppliers and retailers disrupt randomly. There are five backup suppliers and six potential new retailers for the manufacturer selection. Risk event results in the disruption of primary suppliers PS_3 and PS_5. Retailers R_1, R_3, and R_5 are unable to complete product deliveries.

According to the model determine the parameters of firms in the supply chain and randomly assign values within the range of values. Table 3 shows the relevant parameters for the primary supplier. Allowing the manufacturer to make emergency purchases from the master supplier, but emergency purchases entail additional emergency purchase costs. In addition, the minimum quantity that the manufacturer can purchase from primary suppliers is 300 under normal production conditions.

Table 4 describes the information on the parameters of the backup supplier. According to product demand and market supply, backup suppliers are usually unavailable. However, they can be made active in case of supply shortage, and this decision requires the payment of start-up capital. This format is present in the market and therefore does not lose its generality.

Table 5 shows the parameters for retailers and Table 6 for potential new retailers. Retail demand is limited. For stranded products, the manufacturer can use price incentive strategies to induce retailers to reorder or develop new retailers.

The other parameters of the model are as follows: unit cost of order $O = 5$, unit cost of production $M = 10$, unit price of product sales $P = 70$, unit inventory cost of stranded products $H = 20$, unit cost of out-of-stock $S = 50$, price discount rate for the undisrupted retailer j, $\alpha = 0.98$, maximum quantity to be produced by manufacturer of 6000. Due to interruption of propagation, loss of capacity coefficient of the manufacturer $\tau = 0.2$.

Table 5. Retailer parameters.

Retailer	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
B_j	460	500	530	515	530	440	510	450
$r_j^{\max}$	565	654	580	730	660	775	785	577
c_j	3	3	1	3	2	1	2	1
tr_j	3300	3500	3400	2500	3300	3000	2500	2800

Table 6. New retailer parameters.

New retailer	NR_1	NR_2	NR_3	NR_4	NR_5	NR_6
D_m	572	670	598	570	594	500
A_m	1348	3522	2980	3051	3195	3155
c_m	4	1	2	3	2	2
tr_m	2460	2500	2560	3900	3750	3300

Table 7. Procurement plan under normal conditions.

Quantity of raw materials that can be procured from primary supplier						Profit
Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	
670	630	660	680	700	595	\$171 240

5.2. Calculation results

Following the solution steps, calculate the optimal sourcing solution without disruption first. Under normal production conditions, the manufacturer's source of raw material supply is the primary supplier. The manufacturer organizes its production activities by the retailer's pre-order quantities and delivers them to the retailer at the end of production. See Table 7 for the manufacturer's optimal sourcing plan resulting from the model solution, at which point the supply chain makes a profit of \$171 240.

After the disruption event, suppliers and retailers disrupt randomly. If no recovery measures are taken, the manufacturer can only purchase from uninterrupted primary suppliers. The manufactured product are delivered to the retailer that is operating normally. Table 8 illustrates the sourcing and delivery scenario at this point. Combining disruption scenarios and Table 8, we can see a disruption overlay when both the supply side and the demand side disruption. Disruption overlay results from the magnifying or mitigating effect of interactions in the supply chain. An overlay occurs when the negative consequences of changes in the supply chain structure due to disruptions in magnified or mitigated by changes in the operating environment. This overlay can be reciprocal (*i.e.* complementary or mitigating) or aggravating (*i.e.* concurrent or enhancing)[26]. We observed a reciprocal overlay in this scenario: the manufacturer fails to meet the retailer's order due to a partial supply disruption (*i.e.* supply $\sum_{i=1}^{6} Z_i \times a_i < \sum_{j=1}^{8} B_j$), negatively impacting the supply chain, yet the total demand decreases due to the retailer's disruption or bankruptcy (*i.e.* $\sum_{j=1}^{8} B_j \times b_j < \sum_{j=1}^{8} B_j$). In other words, supply decreases at the same time that demand falls instead. The fall in demand mitigates the impact of the supply shortfall. Thus, there is a reciprocal overlay in this scenario. Although, the effect of supply shortfall is tempered by the effect of demand disruptions. However, the upstream and downstream interruptions still result in a supply chain loss of \$83 050 due to the loss of potential sales. Measures to mitigate the risk of disruption are necessary.

To verify the feasibility of the combined strategy, after the disruption occurred, using the combined recovery strategy proposed in this paper, *i.e.* the expanded supply strategy and the product allocation management

Table 8. Scenarios without any recovery strategies under disruption.

Purchase volume						Delivery volume								Profit	Resilience
x_1	x_2	x_3	x_4	x_5	x_6	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8		
670	630	0	680	0	595	0	500	0	515	0	440	510	450	$88 190	1098.57

Table 9. Summary of solution results.

Solutions	Profit	Resilience	Solutions	Profit	Resilience
1	162 063.80	2303.90	18	166 790.40	2023.95
2	162 283.60	2299.14	19	166 944.60	2006.76
3	162 755.60	2263.90	20	167 248.80	1988.71
4	162 758.00	2242.48	21	167 477.60	1985.86
5	163 193.60	2235.33	22	167 708.40	1966.76
6	163 346.40	2232.48	23	167 845.60	1957.29
7	163 523.80	2195.33	24	168 149.80	1924.43
8	164 001.40	2190.57	25	168 421.40	1917.29
9	164 209.40	2182.00	26	168 517.80	1895.88
10	164 857.80	2146.76	27	168 830.00	1860.62
11	165 086.60	2143.90	28	168 960.00	1849.62
12	165 454.60	2115.33	29	168 971.60	1804.14
13	165 758.80	2082.48	30	169 412.60	1800.14
14	165 989.60	2078.19	31	169 661.60	1789.14
15	166 126.80	2053.90	32	169 718.00	1743.48
16	166 317.80	2038.19	33	169 886.20	1732.48
17	166 576.60	2035.33			

strategy. We use the NNC method to solve the bi-criteria disruption recovery model. In contrast to single objective optimization, bi-criteria optimization results in a set of non-dominated solutions (the Pareto optimal set). Table 9 shows the profit and resilience of each option. In the order of the solution scenarios, the profit of the Pareto optimal solution increases while the supply chain resilience decreases. It indicates that there is a balance between the total profit objective and the resilience objective in the supply chain disruption recovery model. Single-objective optimization is more one-sided, where the solution is better for one objective but worse for the other and cannot balance. The bi-criteria model, however, achieves a trade-off between the profit and resilience objectives of decision-making and better meets the requirements of business managers.

Figure 2 shows the distribution of the generated Pareto points. Each Pareto point represents an optimized solution, and the points on the Pareto front can be chosen as decision plans. In practice, managers can choose the appropriate recovery solution for their situation. The points on the Pareto front have no advantages or disadvantages, and managers can choose according to the disruption and their preferences: managers with profit preferences will select the lower-cost recovery solution, while managers with resilience preferences will sacrifice some profits to improve supply chain resilience.

We assume that the manager selects a solution from the alternatives in Table 9 using the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution), a classical multi-criteria decision-making method for determining the most desirable solution from alternatives. Table 10 presents the selected backup suppliers, new retailers, and the material flows in the supply chain. As can be observed, when the primary supplier PS_3, PS_5 and retailers R_1, R_3, and R_5 disrupt, the manufacturer uses backup suppliers BS_1, BS_4, and BS_5, based on cost, distance, and supply quantity, to avoid any loss of profit due to unmet demand. Given the costs, demand, and transport distances, selecting deliveries to new retailers NR_2 and NR_3 to fully unleash

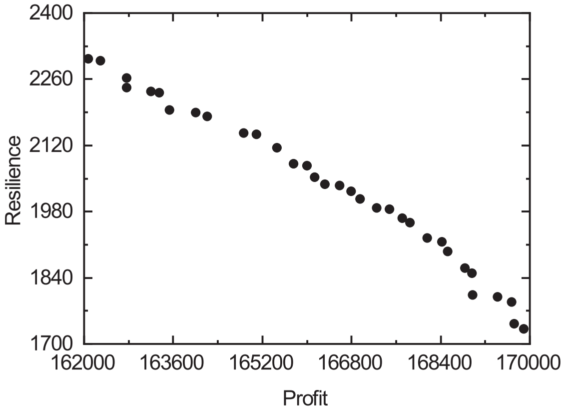

Figure 2. Pareto Frontier.

Table 10. Optimal solution under combined recovery strategies.

Purchase volume								Backup supplier activation						Profit	Resilience
x_1	x_2	x_3		x_4	x_5	x_6		u_1	u_2	u_3	u_4	u_5			
820	790	0		860	0	793		1	0	0	1	1		$169 718	1743.48
Delivery volume								New retailer selection							
y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	w_m	w_2	w_3	w_4	w_5	w_6		
0	653	0	730	0	775	785	577	0	1	1	0	0	0		

capacity after the disruption. Compared to when no measures are taken, using the combined recovery strategies increased supply chain profits to $169 718, helping the supply chain recover 98% of lost profits. In addition, due to linking new businesses, the network structure gets strengthened, and supply chain resilience increases. That shows the strategy is feasible.

5.3. Analysis of supply chain disruption recovery strategies in a unilateral disruption scenario

In the previous section, we demonstrated the feasibility of combined recovery strategies to solve supply and demand dual-side disruption problems. To analyze in more depth the ability of the bi-criteria disruption recovery model to solve real-world problems so that it still works in different environments. We set up a unilateral disruption scenario to further explore whether the strategy is feasible and advantageous for application under one-sided disruption. To this end, this section first sets up six different disruption scenes, representing various risk events. Then, we compare and analyze the mitigation effects of the strategies in each scenario. Table 11 gives six disruption scenarios, which describe the disruptions of each enterprise in the supply chain: among them, scenarios 1, 2, and 3 represent the supply-side disruption scenarios, while scenarios 4, 5, and 6 stand for the demand-side disruption scenarios.

5.3.1. Supply-side disruption scenarios

Supply disruptions are common supply chain disruptions. Relying on only a single-source supply increases the vulnerability of the network. To prevent supply disruptions, manufacturers often contract to establish standby supplies. Consider the proposed strategies, where the manufacturer can make emergency purchases or invoke the backup supply after supply disruptions. That is, using the expanded supply strategy. To verify the advantages of applying the combined recovery strategies, Table 12 compares the use of the expanded supply strategy with the

Table 11. Different disruption scenarios.

Disruption scenarios	Disrupted nodes
1	S$_2$, S$_5$
2	S$_1$, S$_4$
3	S$_5$
4	R$_1$, R$_3$, R$_5$
5	R$_3$, R$_5$, R$_7$, R$_8$
6	R$_2$, R$_6$, R$_7$

Table 12. Comparison of different strategies in supply-side disruption scenarios.

The expanded supply strategy						
Disruption scenarios	Profit	Resilience	Production volume	Delivery volume	Selected backup suppliers	
1	108 674	1899.67	4590	3935	BS$_2$, BS$_3$, BS$_4$, BS$_5$	
2	108 944	1920.50	4570	3935	BS$_2$, BS$_3$, BS$_4$, BS$_5$	
3	108 022	1784.28	4700	3935	BS$_2$, BS$_4$, BS$_5$	
The combined recovery strategies						
Disruption scenarios	Profit	Resilience	Production volume	Delivery volume	Selected backup suppliers	Selected new retailers
1	170205.8	2062.17	4788	4788	BS$_2$, BS$_3$, BS$_4$, BS$_5$	NR$_4$
2	171 143.6	1959.21	4800	4800	BS$_1$, BS$_3$, BS$_5$	NR$_5$
3	166 761.2	1913.08	4800	4797	BS$_2$, BS$_4$, BS$_5$	NR$_1$, NR$_3$, NR$_4$, NR$_6$

adoption of the combined recovery strategy in the case of a supply-side disruption. The results show that using the combined recovery strategy results in higher profit and greater resilience. It is because the manufacturer takes the initiative to develop new retailers to expand sales on top of meeting existing demand. The management of the demand side resulted in a higher level of balance between supply and demand. The value of resilience also increases as creating new linkages in the supply chain. In contrast, using an expanded supply strategy can alleviate supply shortages and meet the demand of existing retailers. However, the profits gained by the supply chain are limited as the demands of retailers are less than fully adapted to the expanded supply.

5.3.2. Demand-side disruption scenarios

Risk events can also lead to disruptions or bankruptcies on the demand side, resulting in short-term stagnation of product sales. In such cases, waiting passively for the recovery of the end-user company is frequently undesirable. Managers can maintain product flow only by proactively managing product distribution based on supply and inventory. Similarly, this section assumes demand-side disruptions and contrasts the adoption of a product allocation management strategy with the combined recovery strategy. Table 13 shows that choosing combined recovery strategies to deal with disruptions results in higher profitability and resilience of the recovered supply chain. Even though adopting a product distribution management strategy can expand distribution to avoid product hold-ups. However, the profit loss recovered is less due to the limited supply of raw materials. However, manufacturers use a combined recovery strategy to fulfill retailer orders and reconfigure upstream suppliers and downstream retailers. Not only does this improve supply chain resilience, but it also increases spare supply, upstream and downstream linkage to releases capacity, resulting in higher profits.

Table 13. Comparison of different strategies in demand-side disruption scenarios.

The product distribution management strategy						
Disruption scenarios	Profit Profit	Resilience Resilience	Production volume	Delivery volume	Selected new retailers	
4	151,059.4	1341.30	3935	3932	NR_3	
5	143,705	1692.73	3935	3929	NR_4, NR_5, NR_6	
6	147,938.6	1606.09	3935	3935	NR_4, NR_5	
The combined recovery strategies						
Disruption scenarios	Profit Profit	Resilience Resilience	Production volume	Delivery volume	Selected backup suppliers	Selected new retailers
4	180,196.6	1450.00	4789	4789	NR_2, NR_3	–
5	168,605.8	2082.27	4792	4792	NR_1, NR_3, NR_4, NR_5, NR_6	BS_5
6	172,225	2015.22	4799	4797	NR_3, NR_4, NR_5, NR_6	BS_5

Table 14. Sensitivity analysis regarding key parameters.

Parameters	Parameter change (%)	Profit	Change in profit (%)	Resilience	Change in resilience (%)
P	−50%	8394.90	−95.05%	1454.62	−16.57%
	−25%	86 793.60	−48.86%	1742.71	−0.04%
	+25%	253 304.00	49.25%	1683.00	−3.47%
	+50%	336 724.40	98.40%	1683.00	−3.47%
τ	−50%	178 954.00	5.44%	2466.10	41.45%
	−25%	177 121.00	4.36%	2018.67	15.78%
	+25%	159 676.60	−5.92%	1826.29	4.75%
	+50%	154 020.60	−9.25%	1456.52	−16.46%
q_k	−50%	151 227.70	−10.89%	2286.57	31.15%
	−25%	166 914.50	−1.65%	1901.52	9.07%
	+25%	170 926.10	0.71%	1747.48	0.23%
	+50%	172 472.40	1.62%	1578.43	−9.47%
p_k	−50%	182 032.60	7.26%	1901.52	9.07%
	−25%	175 391.20	3.34%	1732.48	−0.63%
	+25%	164 752.35	−2.93%	1683.00	−3.47%
	+50%	159 621.10	−5.95%	1683.00	−3.47%
α	−50%	157 621.30	−7.13%	2303.90	32.14%
	−25%	165 298.25	−2.60%	1957.29	12.26%
	+25%	188 851.50	11.27%	1683.00	−3.47%
	+50%	167 136.30	−1.52%	2249.67	29.03%

6. SENSITIVITY ANALYSIS

Supply chain profitability varies with different parameters. In this section, we will analyze the impact of the parameters on the optimization objective by performing sensitivity analyses on P, τ, q_k, p_k, and α. Only one parameter is changed for each analysis, varying the parameters to −50%,−25%,+25% and+50% of the original values, with the remaining parameters remaining unchanged. Details of the parameter changes are given in Table 14.

As seen in Table 14, after adopting the combined strategy, supply chain profits are more sensitive to the unit price of product sales. In contrast, supply chain resilience is more sensitive to the manufacturer's capacity loss

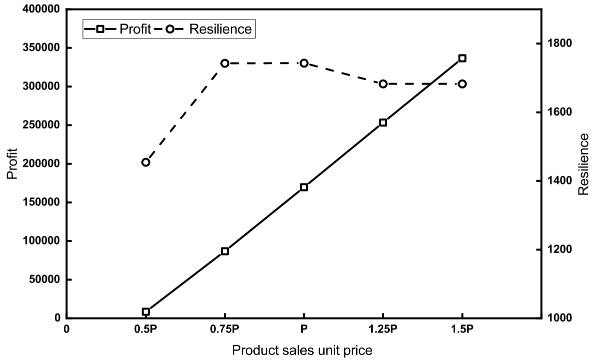

FIGURE 3. Variation of profit and resilience with unit price of product sales.

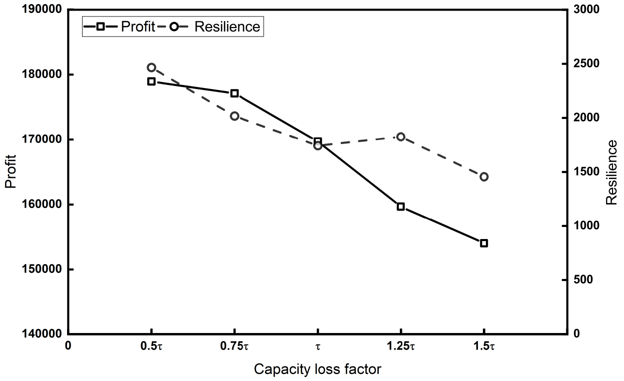

FIGURE 4. Variation of profit and resilience with loss of capacity coefficient of manufacturer.

coefficient. To compare the relationship between each parameter and the objective more visually, we plotted Figures 3–7.

Figure 3 shows the variation in profit and resilience according to the unit price of product sales. As can be seen, profits increase with the selling price, while resilience increases first and later decrease. In addition, the impact of the selling price on profit is more pronounced. Figure 4 shows the variation of profit and resilience with the loss of capacity coefficient. As the capacity loss factor increases, profits and resilience tend to decrease overall. The reason is that the manufacturer's capacity impairment causes production constraints, resulting in lower supply chain profits. In addition, impaired capacity leads to a shortage of products to meet demand and a break in the chain upstream and downstream of the supply chain, resulting in a decrease in resilience. Figure 5 illustrates how profits and resilience vary with the number of raw materials supplied by backup suppliers. As the supply of spare suppliers increases, supply chain profits increase. Backup supply can cover supply shortfalls in supplier disruptions and meet the demand to improve profitability. And as supply decreases, the supply chain will trade with more suppliers, expanding the range of potential suppliers, so supply chain resilience increases.

Figure 6 shows how profits and resilience vary with the unit procurement cost of raw materials from backup suppliers. As the purchase unit price increases, supply chain profits and resilience tend to decrease overall. As the unit price increases, purchasing costs increase, and profits decline. Manufacturers will choose to centralize purchasing to reduce the activation costs of backup suppliers. Safety of supply is satisfied with the minimum

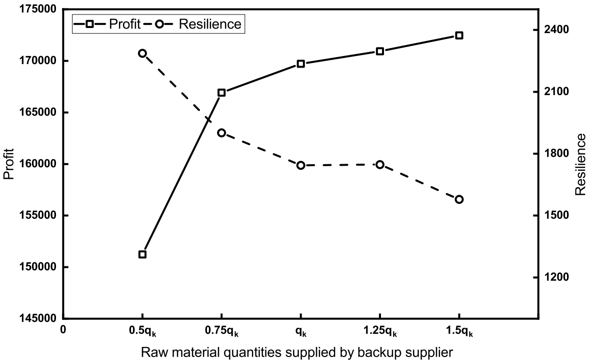

FIGURE 5. Variation of profits and resilience with raw material quantities supplied by backup supplier.

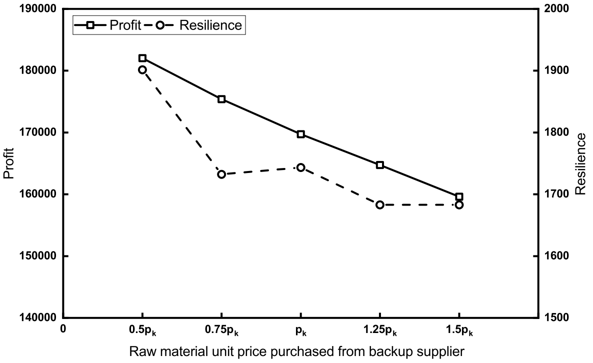

FIGURE 6. Variation of profit and resilience with unit procurement cost of raw materials from backup suppliers.

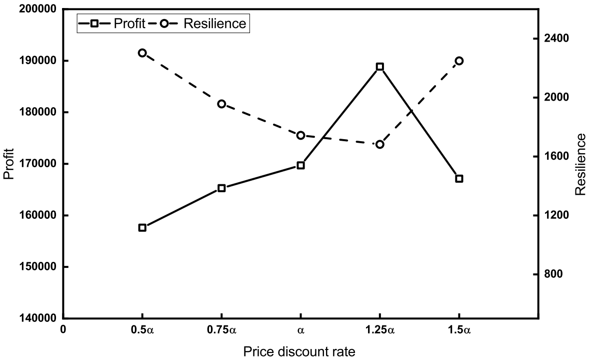

FIGURE 7. Variation of profit and resilience with price discount rate.

number of backup suppliers resulting in supply chain resilience decreases. Figure 7 shows the variation in profit and resilience with the price discount rate. The graph shows that as the discount rate increases, supply chain profit first increases and then decreases, and supply chain resilience first decreases and then increases. When the discount rate is low, the cost of taking price discounts is small, and manufacturers prefer the price discounting strategy. However, as the discount rate increases, the cost increases, and the supply chain profit decreases. As retailer demand hits an upper limit, manufacturers will elect to seek new retailers to boost sales. As a result, supply chain resilience increases.

7. Managerial insights

The model developed in this paper can help managers cope with supply chain disruptions and maintain flexibility while maintaining profitability. When supply chains are disrupted by unforeseen events, managers can apply combined recovery strategies. Adapting and reconfiguring supply chains to help supply chains mitigate the impact of disruptions. Numerical examples based on the proposed model can provide managers with examples of solving disruption problems in real-life situations. The results of the study provide managers with the following insights:

(1) The disruption or failure of a node in a supply chain can cause the entire supply chain network to malfunction while threatening the survival and growth of companies in that supply chain. Supply chain disruptions can result in severe profit losses if nothing takes to remedy the situation. Managers should be fully aware of these risks.

(2) Cost and supply chain resilience play different roles in disruption recovery strategies. The cost factor relates to the economic performance of the supply chain. Supply chain resilience relates to the functionality of the supply chain after a disruption and ensures flexibility in supply chain operations. When developing a recovery plan, combining cost and resilience is more conducive to restoring the supply chain system to normal function.

(3) Although simultaneous disruptions on the supply and demand sides can result in a "reciprocal overlap," our analysis shows that the supply chain can still lose money due to the loss of potential sales. Therefore, when supply and demand suffer shocks, managers should improve the suitability of the supply side and the demand side. Make plans based on supply fluctuations on the supply side and demand fluctuations on the demand side.

(4) When the supply side disrupts, manufacturers can make emergency purchases or activate backup supplies to quickly resume production activities, depending on factors such as disruption, market demand, and loss of capacity. When the demand side disrupts, manufacturers can use price discounting strategies or channel building to develop new retailers to avoid loss of profit due to product stagnation. Whether the disruption is unilateral or bilateral, the optimal strategy is the combined recovery strategy that enables both the supply and demand sides to synergize. Managers can apply this strategy flexibly to deal with different types of disruptions.

8. Conclusion

Recovery strategies are necessary to avoid the impact of supply chain disruptions. This study integrates cost and resilience to examine supply chain disruption recovery strategies in the context of supply and demand disruptions. We develop a new combined recovery strategy for managers. When interruptions prevent firms from recovering in the short-term, managers can expand the supply base and manage demand allocation to mitigate the impact of disruptions through reconfiguration and adjustment of the supply chain system. We combine supply and demand disruptions, emergency sourcing, impaired capacity, and price discounts to create a bi-criteria disruption recovery model. The aim is to maximize supply chain profit and resilience and to transform the sourcing, production, and delivery problem into a mixed integer linear programming problem. Numerical experiments show that the combined recovery strategy is not only effective in helping manufacturers reduce losses but also improves supply chain resilience. Furthermore, whether there is unilateral or bilateral disruption, the combined recovery strategy is the best. The strategies and models proposed in this paper also provide some insights for business managers.

Indeed, this paper has some shortcomings. Firstly, this paper analyses supply chain disruptions as static events and does not consider the effects of disruption timing or instability. Future research could consider the dynamics of disruptions when building the model. Secondly, there are other influencing factors of supply chains in practice, such as multi-product production, multiple raw materials, etc. Future research could incorporate these factors.

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