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A supply chain disruption recovery strategy considering product change under COVID-19

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ABSTRACT

A recent global outbreak of Corona Virus Disease 2019 (COVID-19) has led to massive supply chain disruption, resulting in difficulties for manufacturers on recovering their supply chains in a short term. This paper presents a supply chain disruption recovery strategy with the motivation of changing the original product type to cope with that. In order to maximize the total profit from product changes, a mixed integer linear programming (MILP) model is developed with combining emergency procurement on the supply side and product changes by the manufacturer as well as backorder price compensation on the demand side. The model uses a heuristic algorithm based on ILOG CPLEX toolbox. Experimental results show that the proposed disruption recovery strategy can effectively reduce the profit loss of manufacturer due to late delivery and order cancellation. It is observed that the impact of supply chain disruptions is reduced. The proposed model can offer a potentially useful tool to help the manufacturers decide on the optimal recovery strategy whenever the supply chain system experiences a sudden massive disruption.

1. Introduction

Supply chain refers to the entire process of making and selling commercial goods, including every stage from the supply of materials and the manufacture of the goods through to their distribution and sale [1,2]. Over the past few decades, large-scale disruptions of supply chain have been caused by natural and man-made disasters, such as 2004 Indian Ocean earthquake, 2008 U.S. subprime mortgage crisis, 2011 Japan tsunami and so on [3]. With specialization and concentration in manufacturing industry, disruptions at one or a few entities can affect almost all ones in supply chain [4]. Once such disruptions occur, the whole supply chain has to face a lot of problems, such as supply disruption [5], production disturbance [6] or demand change [7]. Therefore, it is very important to design resilient supply chains so as to cope with different disruptive events effectively [8,9].

Supply chain resilience management usually starts with risk prediction or risk identification, that is, to predict possible risks and to develop different strategies for identifiable risks [10]. This approach can effectively deal with those disruptions that have occurred before and can be expected. For unexpected disruptions that are difficult to predict, an important issue for building resilience of supply chain is to develop the effective recovery strategies so that the system can respond and recover quickly from the disruptions [11,12]. In the case of the Volkswagen Group, for example, the COVID-19 pandemic that outbreak from December 2019 has affected the supply of chips related to ESP (Electronic Stability Program System) and ECU (Electronic Control Unit). During COVID-19 pandemic, many chip suppliers have been reducing their production capacity or shutting down their factories, which would lead to the disruption risk of supply chain in the production of some Volkswagen vehicles. According to statistics, 938 of Fortune's 1000 largest companies suffered the serious influences of raw material supply and production due to the disruptions in global supply chains caused by this epidemic outbreak[1] . Queiroz et al. [13] systematically analyzed the impact of the COVID-19 pandemic upon supply chain through a structured literature review. The large-scale disruptions of supply chain system could result in such high economic losses due to the following three distinctive characteristics: 1) the unpredictability of the disruption over time and its magnitude; 2) the simultaneous spread of the disruption through both the system (i.e., ripple effect) and the population (i.e., pandemic spread); 3) the partial or total simultaneous disruption of supply, production, demand, and logistics infrastructure [14,15]. Compared with previous epidemics (e.g., SARS, H1N1), COVID-19

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[1] https://fortune.com/2020/02/21/fortune-1000-coronavirus-china-supply-chain-impact/

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would last longer and spread more widely, which causes more severe disruptions and increase the recovery difficulty for supply chain greatly [16,17].

Ivanov et al. [18] categorized the schemes of dealing with the disruption risk of supply chain as proactive and reactive. The former emphasized identifying and anticipating the existing vulnerabilities and the potential disruptions of supply chain [19–21], while the latter focused on developing the recovery strategies for different disruptions [22–24]. However, the existing proactive or reactive strategies cannot cope with the prolonged disruption caused by COVID-19 effectively. For one thing, the disruption degree of supply chain could hardly be identified in the proactive context. For other, the supply capacity could not be recovered quickly in the context of reactive strategies due to such sudden outbreak cause a large-scale disruption of the original or alternate suppliers for a longer period. Therefore, a new recovery strategy will be developed with consideration of product change [25,26] to mitigate the disruption impact of supply chain under the COVID-19 pandemic in this paper. A mixed integer programming model with minimizing the total cost of recovering from the disruption of supply chain will be developed. From the numerical results, we will identify how the cost factors, that is, product change duration, new supplier selection and allocation, and customer sensitivity, play the different roles in the product change scheme.

The remainder of the paper is organized as follows. Section 2 provides an overview on relevant literature. The problem definition, the symbolic representation and the underlying assumptions are given in Section 3. Section 4 presents the mathematical model and its solution method. Numerical experiments and the discussion of results are given in Section 5. Section 6 gives management insights and the final section summarizes this paper and provides a perspective for future work.

2. Literature review

Disruptions can occur in any part of supply chain, including the upstream supply side, the intermediate manufacture processes, and the downstream demand side. As an interdependent and interconnected whole, local disruption can propagate through supply chain and wreak havoc on the entire supply chain [27]. Ivanov et al. [28] referred to this phenomenon as a ripple effect. Unlike the bullwhip effect triggered by small demand vulnerability [29], the disruption in the ripple effect could either originate at the supply side and propagate positively along the logistics direction, or originate at the demand side and propagate negatively upstream, which would affect more enterprises in the supply chain [30]. Li et al. [31] distinguished the forward and backward propagation of disruptions and gave a detailed analysis on the factors affecting the propagation of disruptions. Zhang et al. [32] explored the propagation of disruption risk in the automotive supply chain by surveying 31 Chinese automotive-related firms.

In the work of Ivanov et al. [18], two major categories of strategies, that is, proactive and reactive, were used to deal with the disruption risk of supply chain. Proactive strategies are referred to those that are in action before a disruption occurs. Knemeyer et al. [33] developed a process for proactive planning of catastrophic risk events by integrating the different strategy streams of risk management. In order to reduce the generated disruption costs by purchasing raw materials in advance, Pal et al. [34] proposed a three-level supply chain model based on an economic production quantity inventory model, which was termed as EPQ in [35]. Torabi et al. [36] presented a bi-objective hybrid two-stage stochastic planning model to reduce the impact of supply-side disruptions with consideration of using alternate suppliers or developing a supplier continuity plan. Islam et al. [21] presented an inventory model considering random inventory, reliability of suppliers, and delivery capacity to optimize the inventory plans of manufacturers. Although system resilience can be enhanced by building redundancy or flexibility, such built-in resilience increases costs, and these proactive mitigation strategies may not be appropriate for dealing with unexpected supply chain disruptions [37].

The reactive strategies are more effective to enable supply chain to quickly return to the normal state after a disruption happens to the system [38]. Xia et al. [39] developed a two-stage generic production and inventory disruption recovery model, which take into account the cost of deviation from the normal schedule after recovery, and introduced the concept of disruption recovery time window. Hishamuddin et al. [40] extended the model of Xia et al. [39] and proposed an economic batch model based on disruption recovery method by determining the optimal manufacturing batch size and the optimal recovery duration for a production run in the recovery time window to minimize the expected total cost of ownership. Paul et al. [41] proposed the concepts of backorders and lost sales respectively to develop a two-stage supplier-manufacturer supply chain recovery model under disruption risk. Kaur et al. [42] presented an independent production and procurement integration model, where both the changes of market demand and the uncertainty of manufacturers, suppliers, and transporters were considered. Malik et al. [43] developed a disruption recovery model for a multi-product, single-stage manufacture system in order to obtain the optimal procurement lot size for multiple materials under the budget and storage space constraints in the given recovery time window. Ivanov et al. [44] observed that disruptions in production capacity create a risk of product shortages, and developed a coordinated contingency policy for production order in the supply chain during and after disruptions. Gupta et al. [45] developed an analytical game-theoretic model to cope with supply disruptions by considering optimal pricing strategies and sourcing levels.

The existing studies have made significant contributions in developing recovery strategies after disruptions occur in supply chain system. However, these strategies do not consider the occurrence of disruptions in special circumstances, such as the supply chain disruptions caused by the global COVID-19 outbreak, which is characterized by longer duration and wider spread than the previous epidemics or abnormal events that have occurred. Due to the large-scale impact of global supply chain during the COVID-19 pandemic, the manufacture enterprises have begun to consider utilizing the current production devices or purchasing the special devices certified by testing agencies to produce the high-demand products (masks, hand sanitizers, disinfectants and etc.) or the emergency personal protective equipment (PPE) [46,47]. In this paper, we investigate this special situation in that some or all of the original suppliers are unable to recover in the short term after a supply disruption during a pandemic, and develop a disruption recovery strategy with consideration of changing product design, in order to decrease the economic loss due to the special disruption of supply chain as possible.

3. Problem statement

In this section, the definition of the problem is presented firstly, which shows the main motivation of this research. After that, the notation and basic assumptions of the mathematical model are given.

3.1. Problem definition

In order to stop the spread of the COVID-19 pandemic, many countries adopt a lot of embargo policies that cause a large-scale reduction in the supply of raw material in the global range. As a result, many manufacture enterprises are unable to obtain sufficient raw materials and then fall into the production standstill.

In this paper, we consider a three-stage supply chain consisting of multiple suppliers of the same raw material, a manufacturing firm producing one product, and multiple retailers, as shown in Fig. 1. Suppliers in some areas affected by the outbreak may not be able to recover in the short term after a supply disruption. In addition, some suppliers may experience short-term supply disruptions or reduced supply capacity due to national embargo policies and a shrinking transportation

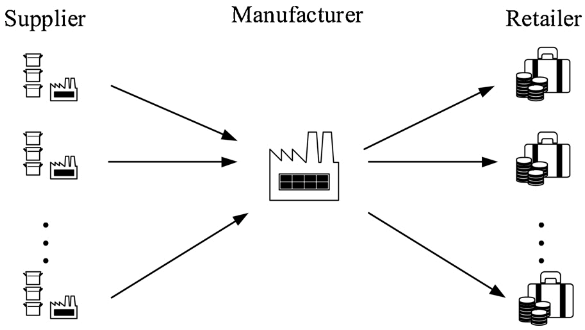

Fig. 1. Three-stage supply chain model.

industry. When a supply disruption occurs, if no action is taken, the company's capacity will drop, and out-of-stocks will occur for customer orders arriving at any given time. In this case, the customer may choose to backorder or abandon the order depending on the delivery time and will incur backorder costs or lost sales.

In order to reduce the loss of the manufacture enterprise and alleviate the disruption of supply from some or all of the original suppliers, we consider two ways at the same time in the disruption recovery strategy: one is to make an emergency purchase from the undisrupted supplier, that is, to increase the purchase quantities to keep producing the original product; the other is to change the product composition, that is, to adjust the raw materials required for the changed product, replace the original raw materials with new ones, and then select a new supplier to replace the supplier without changing the main design of product and still using the current production equipment. When the first approach is taken, the cost of emergency procurement and the quantity of raw materials that can be obtained by emergency procurement need to be considered in the model; when the second approach is taken, the cost of product change, including the procurement cost of alternative suppliers and the cost of lost sales after the product change compared with the original product, requires to be considered. Finally, an integrated decision on product change and supplier selection is conducted to establish a disruption recovery model.

Therefore, manufacturer need consider the following three important questions during the production cycle after a supply chain disruption occurs: (1) How much raw material to obtain through emergency procurement? (2) How many products to make changes and how to choose alternative suppliers? (3) How to meet the demand of different customer orders to minimize losses in case of supply-demand imbalance?

3.2. Assumptions

In order to make the study more relevant and feasible, the following basic assumptions are made.

(1) Each supplier may face two types of disruptions, that is, long-term disruptions due to the prolonged duration of the outbreak and short-term disruptions due to the embargo policy. The occurrence of disruptions at each supplier is independent each other and only related to the presence of an outbreak in that area.
(2) After the outbreak, large-scale supply disruptions occur at time 0, where the long-term disruptions are not recoverable throughout the production horizon and the short-term supply disruptions due to the embargo policy can be recovered in l cycle after the outbreak is controlled, but cause the capacity reducing.
(3) The manufacturer needs one necessary raw material to produce its product, and may choose alternative raw materials for production by changing the product design. However, there is a price difference between the changed product and the original one, which incurs a loss in cost of sales.
(4) After supply disruptions occur, taking emergency procurement requires to consider additional procurement costs, but production delay due to emergency procurement does not be taken into count, while taking product design changes requires consideration of product change costs and product change time.
(5) For all retailers, the quantity of product required for an order is determined prior to disruption and does not change during the production horizon. Retailer's order will be produced in one period and shipped immediately after production. Products in period t are delivered in period $t+1$ regardless of product transit storage.
(6) Supply shortages can result in orders not being delivered on schedule due to the forward propagation of supply disruptions. Exceeding the retailer's latest delivery date T_j requires compensation to the retailer and results in backorder costs, and exceeding the retailer's latest order cancellation time U_j can result in lost sales costs.
(7) Both transportation time and cost of raw materials and products among suppliers, manufacturers and retailers are not considered.

3.3. Notation

In order to understand the model developed in this paper, we will give the meaning of the symbols used in the model as follows.

List of indices :

i	Index for original suppliers
j	Index for retailers
k	Index for alternative suppliers
t	Index for periods
s	Index for disruption types

List of decision variables:

Y_{ti}^s	Quantity to be procured in t^{th} period for s^{th} disruption type from i^{th} supplier
x_{tk}^s	Quantity to be procured in t^{th} period for s^{th} disruption type from k^{th} alternative supplier after product change
I_t^s	The quantity of raw materials inventory in t^{th} period for s^{th} disruption type
w_{jt}^s	1 if j^{th} retailer's order is produced for s^{th} disruption type in t^{th} period, else 0

List of parameters

X_{ti}	Quantity to be procured in t^{th} period for normal production conditions from i^{th} supplier
v_i^s	1 if i^{th} supplier for s^{th} disruption type has not been disrupted, else 0
u_i^s	1 if i^{th} supplier for s^{th} disruption type has been disrupted due to blocking policy, else 0
O_i	Cost of ordering from i^{th} supplier
C_i	Unit procurement cost of raw materials from i^{th} supplier
E_i	Emergency unit procurement cost of raw materials from i^{th} supplier
e_k	Unit procurement cost of alternative raw materials from k^{th} alternative supplier
m_{ti}	Maximum quantity of raw material that can be supplied by i^{th} supplier in t^{th} period
n_{tk}	Maximum quantity of alternative raw material that can be supplied by k^{th} alternative supplier in t^{th} period
b_i	Loss of production capacity coefficient of i^{th} supplier
f_i	Resilience coefficient of i^{th} supplier
H	Unit holding inventory cost of raw materials
Re	Unit revenue of production
Q_t	Maximum quantity to be produced in t^{th} period
Pc	Unit cost of production
d_j	Quantity of order demand from j^{th} retailer
T_j	Last lead time for j^{th} retailer's order
U_j	Last period for j^{th} retailer to cancel the order
B_j	Unit cost of backorder for j^{th} retailer's order after delayed delivery
L_j	Unit cost of lost sales for j^{th} retailer's order after order cancellation
g	Unit cost of lost sales after product change

4. Problem model and algorithm

4.1. Mathematical representation

In this section, we propose a recovery strategy in this paper to model supplier disruption recovery targeted at minimizing the manufacturer's total cost in the event of supply disruption. We present in detail the various cost functions in recovering supply chain disruption subject to the various constraints that need to be satisfied. In addition, only the costs in the recovery window are considered due to the limited time horizon for our particular model.

The supply chain disruption in the proposed model is divided into two categories, including long-term disruptions that are not recoverable in the time horizon, and short-term disruptions that are able to recover a limited capacity after l production cycles. The set of undisrupted suppliers is I_n, the set of long-term disrupted suppliers is I_l, and the set of short-term disrupted suppliers is I_s.

The manufacturer's revenue is calculated as selling price per unit multiplied by the retailers' demand quantity and orders delivery status.

$$Rev = \sum_{t\in T}\sum_{j\in J} w_{tj}^{s} d_j Re \tag{1}$$

All the costs involved in the total cost of the production system TC per item are derived as follows:

(1) Fixed order cost (FOC): FOC is the cost of raw materials ordered by the manufacturer from suppliers in advance of the production schedule, independent of the number of orders and the quantity ordered, which can be expressed as the sum of the ordering costs O_i from different suppliers.

$$\text{FOC} = \sum_{i\in I} O_i \tag{2}$$

(2) Raw material inventory cost (RIC): A manufacturer's raw material inventory includes a certain amount of safety stock held before a supply disruption occurs, which will be consumed after the disruption, and production to order, which may result in a backlog of raw materials. RIC can be calculated as the unit inventory cost H of raw materials multiplied by the quantity I_t^s of raw material inventory per production cycle, which can be denoted as follows:

$$\text{RIC} = \sum_{t\in T} H I_t^s \tag{3}$$

(3) Production cost (PC): Considering that each product takes up a certain amount of resources when it is produced, PC is defined as the cost Pc per unit of production for each product multiplied by the total quantity $d_j w_{jt}^s$ of that product produced.

$$\text{PC} = \sum_{t\in T}\sum_{j\in J} Pc * d_j w_{jt}^s \tag{4}$$

(4) Original supplier procurement cost (OPC): In case of disruptions due to the pandemic, the cost of raw materials purchased by the manufacturer from the original supplier will contain the three potential sub costs, i.e. normal procurement costs C_i from those suppliers who did not experience the disruption, emergency procurement costs E_i for additional quantities ordered after the disruption, and procurement costs C_i for suppliers who experience short-term disruptions and are able to restore supply after l production cycles. Then, OPC can be calculated by multipling the unit procurement cost of the raw materials by the purchase quantity.

$$\text{OPC} = \sum_{t\in T}\sum_{i\in I} C_i Y_{ti}^s + \sum_{t\in T}\sum_{i\in I} E_i\left(Y_{ti}^s - X_{ti} v_i^s\right) + \sum_{t\in T:t\geq l}\sum_{i\in I} b_i C_i X_{ti}^s u_i^s \tag{5}$$

(5) Product change cost (PCC): Manufacturers consider design changes to some products after a supply disruption occurs, and seek new suppliers to replace original disrupted suppliers to produce new products after the product change. Product design changes require consideration of product change time p and change costs. PCC includes the cost e_k of procuring from the alternative supplier and the cost g of lost sales resulting from price differences between changed products and original products, which can be expressed as follows:

$$\text{PCC} = \sum_{t\in T:t\geq p}\sum_{k\in K} (e_k + g) x_{tk}^s \tag{6}$$

(6) Backorder cost (BC): The impact of supply disruptions will propagate positively through the supply chain, ultimately causing demand-side orders not to be delivered on schedule. The backorder is an order that is not met at the time of the agreed delivery period, but can be deferred after the quantity of product produced meets the requirements. Delayed delivery requires price compensation to the customer and will incur backorder cost. BC can be calculated as the backorder cost per unit multiplied by the backordered number of units.

$$\text{BC} = \sum_{j\in J} B_j d_j \left(\sum_{t\in T} w_{jt}^s - \sum_{t\in T:t\leq T_j-1} w_{jt}^s\right) \tag{7}$$

(7) Lost sales cost (LSC): When the order backorder delivery time exceeds the customer's latest waiting time, the customer will cancel the order, which will result in lost sales costs. LSC is the unit lost sales cost multiplied by the lost sales units, which can be denoted as follows:

$$\text{LSC} = \sum_{j\in J} L_j d_j \left(1 - \sum_{t\in T:t\leq U_j-1} w_{jt}^s\right) \tag{8}$$

The total cost of a manufacturing company's supply chain is the sum of the seven costs listed above, including FOC, RIC, PC, OPC, PCC, BC and LSC, which can be expressed as follows:

$$\begin{aligned} \text{TC} = {} & \text{FOC} + \text{RIC} + \text{PC} + \text{OPC} + \text{PCC} + \text{BC} + \text{LSC} \\ = {} & \sum_{i\in I} O_i + \sum_{t\in T} H I_t^s + \sum_{t\in T}\sum_{j\in J} Pc * d_j w_{jt}^s + \\ & + \sum_{t\in T}\sum_{i\in I} C_i Y_{ti}^s + \sum_{t\in T}\sum_{i\in I} E_i\left(Y_{ti}^s - X_{ti} v_i^s\right) + \sum_{t\in T:t\geq l}\sum_{i\in I} b_i C_i X_{ti} u_i^s \\ & + \sum_{t\in T:t\geq p}\sum_{k\in K} (e_k + g) x_{tk}^s + \sum_{j\in J} B_j d_j \left(\sum_{t\in T} w_{jt}^s - \sum_{t\in T:t\leq T_j-1} w_{jt}^s\right) \\ & + \sum_{j\in J} L_j d_j \left(1 - \sum_{t\in T:t\leq U_j-1} w_{jt}^s\right) \end{aligned} \tag{9}$$

In summary, we propose a mixed integer linear programming (MILP) model as follow:

$$\text{Max Rev - TC} \tag{10}$$

$$\sum_{t\in T}\sum_{i\in I} X_{ti} \leq \sum_{t\in T} Q_t \tag{11}$$

$$\sum_{t\in T}\sum_{i\in I} Y_{ti}^s + \sum_{t\in T:t\geq l}\sum_{i\in I} b X_{ti} u_i^s + \sum_{t\in T:t\geq p}\sum_{k\in K} x_{tk}^s \leq \sum_{t\in T} Q_t, \forall s \in S \tag{12}$$

$$I_{t-1}^s + \sum_{i\in I} Y_{ti}^s + \sum_{i\in I} b_i X_{ti} u_i^s + \sum_{k\in K} x_{tk}^s - I_t^s = \sum_{j\in J} d_j w_{jt}^s \quad \forall t \in T, s \in S \tag{13}$$

$$X_{ti}(1 + f_i) \leq m_{ti} \quad \forall t \in T, i \in I \tag{14}$$

$$Y_{ti}^s \leq X_{ti} v_i^s (1 + f_i) \quad \forall t \in T, i \in I, s \in S \tag{15}$$

$$Y_{ti}^s \geq X_{ti} v_i^s \quad \forall t \in T, i \in I, s \in S \tag{16}$$

$$x_{tk}^s \leq n_{tk} \quad \forall t \in T, k \in K, s \in S \tag{17}$$

$$\sum_{t\in T} w_{jt}^s \leq 1 \quad \forall j \in J, s \in S \tag{18}$$

$$\sum_{j\in J} d_j w_{jt}^s \leq Q_t \quad \forall t \in T, s \in S \tag{19}$$

$$\sum_{t^{'} \in T: t^{'} \leq t} \sum_{j \in J} d_j w_{jt}^s \leq \sum_{t^{'} \in T: t^{'} \leq t-1} \left(\sum_{i \in I} Y_{ti}^s + \sum_{k \in K} x_{tk}^s + \sum_{i \in I} b X_{ti} u_i^s \right) \tag{20}$$

$$w_{jt}^s \in \{0,1\} \quad \forall t \in T, j \in J, s \in S \tag{21}$$

$$Y_{ti}^s, I_t^s, x_{tk}^s \text{ are positive integers}, \quad \forall i \in I, j \in J, k \in K, s \in S, t \in T \tag{22}$$

Eq. (10) defines the objective function to maximize the manufacturer's total profit, along with Eqs. (1) and (9). Eqs. (11) and (12) constrain the maximum procurement quantity within the production schedule, both before and after the disruption, to not exceed the manufacturer's production capacity. Eq. (13) balances the manufacturer's procurement, product change procurement, actual production, and raw material inventories with the order requirements for each cycle after the disruption occurs. Eqs. (14)–(16) constrain the supply capacity of the original supplier before and after the disruption. Eq. (17) constrains the supply capacity of the alternative supplier chosen after the product change. Eqs. (18) and (19) constrain that each customer's order can only be produced at most once, and that the quantity of products produced for that order during the production cycle does not exceed the manufacturer's maximum capacity. Eq. (20) constrains the total quantity of products produced to not exceed the quantity of raw materials purchased from suppliers within the production schedule. Eq. (21) constrains the binary nature of the decision variable w_{jt}^s. Eq. (22) defines the decision variables Y_{ti}^s, I_t^s and x_{tk}^s as positive integers.

4.2. Solution approach

In the existing literature, various optimization tools have been widely used to solve small and medium-sized problems. Considering that the model developed in this paper is a mixed-integer linear programming (MILP) model, we propose a heuristic algorithm for solving the model. we will use IBM ILOG CPLEX 12.10.0 and matlab2018b Optimization Toolbox as the solution approach. With its integrated development environment, descriptive modeling language, and built-in tools, ILOG CPLEX can solve mixed-integer linear programming problems quickly and reliably.

In the solving process, we firstly solve for the raw material procurement and production under normal production conditions with the goal of maximizing the manufacturer's total profit; and then we classify the types of disruptions faced by suppliers; and later on, we solve to minimize the manufacturer's total cost without any recovery strategy after a supply disruption occurs; and finally we solve the model developed by the combined recovery strategy proposed in this paper.

The main steps of the proposed solution algorithm are presented as follows:

Step 1: Input all parameters on the production system and get X_{ti};

Step 2: Classify the disruption types of suppliers and assign values to u_i^s, v_i^s according to the classification results;

Step 3: Set $s = 1$ for the first disruption type and input disruption scenario;

Step 4: Put $s = 1, 2, 3\ldots$ for disruption for all suppliers;

Step 5: Solve the mathematical model under the updated disruption scenario;

Step 6: Update the values of Y_{ti}^s and x_{tk}^s as the revised procurement lot size from Step 5 and record the revised production plan;

Step 7: Output the final results.

5. Numerical experiments

In this section, detailed numerical examples are conducted to verify the feasibility of the proposed model. Firstly, we use a randomly generated data-set with values assigned to each parameter of suppliers, manufacturers and retailers. Next, the proposed MILP model simultaneously optimize product and procurement plan considering all resource constraints related to suppliers, manufacturers and retailers, where the objective is maximizing total profit for the manufacturer under different recovery strategies. Finally, some numerical experiments are conducted and the experiment results of lost manufacturer revenue due to disruptions are compared. In addition, we perform a sensitivity analysis on the different parameters to characterize the effect of their changes on the results. It is assumed that 6 suppliers provide raw materials before the disruption occurs that the products produced by the manufacturer will be supplied to each of the 8 customers, and that the production horizon for the recovery period after the disruption consists of 10 time periods. There are 3 alternative suppliers to choose from after a product design change, and the product design change time p is $2T$.

The supply side may face long-term disruptions due to large-scale spread of the epidemic or short-term disruptions due to the embargo policy. It is assumed a random value between $2T$ and $4T$ for the recovery time l after a short-term disruption. To demonstrate the proposed model, two supply disruption types that a manufacturer may face are discussed, including long-term disruption that cannot be recovered within a production recovery plan, and both long-term disruption and short-term disruption that are considered simultaneously. Therefore, it is assumed that suppliers 1,3,4, and 5 have long-term disruptions in illustration 1, where $I_n = \{2,6\}$, $I_l = \{1,3,4,5\}$, $s = 1$, and suppliers 1 and 2 experience long-term disruptions and suppliers 4 and 6 face short-term disruptions in illustration 2, where $I_n = \{3,5\}$, $I_l = \{1,2\}$, $I_s = \{4,6\}$, $s = 1$.

5.1. Computational results

The supplier parameter information is shown in Table 1, which describes the values of maximum supply quantity m_{ti}, loss of production capacity coefficient b_i, resilience coefficient of supply capacity f_i, fixed order cost O_i, unit procurement cost C_i, and emergency procurement cost E_i.

Parameters related to product changes are shown in Table 2, which describes the values of maximum supply quantity n_{tk}, unit procurement cost e_i, and the cost of lost sales g. In addition, product change time $p = 2T$.

The retailer's parameter information is shown in Table 3, which describes the order quantity d_j, the latest delivery cycle T_j for the retailer's order, the latest cycle U_j for the retailer's order cancellation, the unit backorder cost B_j, and the cost of lost sales L_j, where $3T$ represents the third time period of the production schedule.

We give the values of the other parameters in the model, including the manufacturer's production capacity $Q_t = 3000$, the manufacturing unit cost $Pc = 6$, the raw material inventory cost $H = 2$, and the product revenue per unit $Re = 30$.

Under normal production conditions, the raw material procurement from the original supplier is calculated to maximize the manufacturer's total profit, and the results are shown in Table 4.

In the case of different types of disruptions to suppliers, when the manufacturer does not adopt any recovery strategy, the raw material procurement from the original suppliers is calculated to maximize the manufacturer's total profit, and the results of illustration 1 and illustration 2 are shown in Table 5. In case of supply disruptions, an emergency procurement strategy will be implemented immediately, and the

Table 1
Supplier parameters.

Supplier	m_{ti}	b_i	f_i	O_i	C_i	E_i
S1	500	0.75	0.25	2000	12	5
S2	400	0.8	0.25	1800	11	4
S3	400	0.8	0.2	1800	10	4
S4	500	0.75	0.2	2000	11	3
S5	600	0.8	0.3	2100	12	4
S6	500	0.7	0.25	2000	11	5

Table 2
Product design change parameters.

Supplier	n_{tk}	e_i	g
A1	400	10	5
A2	450	9	5
A3	500	11	5

Table 3
Retailer parameters.

Retailer	d_j	B_j	L_j	T_j	U_j
R1	2100	4	8	3 T	4 T
R2	2300	3	6	3 T	5T
R3	2400	5	10	5T	6T
R4	2500	5	10	5T	7T
R5	2500	4	8	6T	7T
R6	2400	4	8	8T	9T
R7	2100	3	6	8T	10T
R8	2300	3	6	9T	10T

Table 4
Manufacturer's procurement of raw materials and maximum total profit.

X_{t1}	X_{t2}	X_{t3}	X_{t4}	X_{t5}	X_{t6}	Total Profit
400	320	333	416	198	400	220,812

Table 5
Manufacturer's maximum profit without any measures.

s	X_{t1}	X_{t2}	X_{t3}	X_{t4}	X_{t5}	X_{t6}	Total Profit
1	0	320	0	0	0	400	−227118
2	0	0	333	$0(t \leq 3T)$ $312(t > 3T)$	198	$0(t \leq 3T)$ $280(t > 3T)$	−161452

corresponding results are shown in Table 6.

It can be seen that when suppliers have supply disruptions, the manufacturer's total profit will decrease as the number of disrupted suppliers increases, and the manufacturer will suffer a significant loss if it does not take timely recovery measures. As can be seen from Table 5, without any recovery strategy, the supply disruptions in illustration 1 and 2 will result in losses to the manufacturer of 447,930 and 382,264 respectively. As can be seen from Table 5, when only an emergency sourcing strategy is adopted, it will result in losses to the manufacturer of 248,132 and 191,880 respectively.

When adopting the product design change and emergency procurement combination recovery strategy proposed in this paper, raw material procurement from original suppliers with emergency procuring strategy and the manufacturer's maximum profit are shown in Table 7, and the manufacturer's procurement at alternative suppliers after product change time $2T$ for each time period are shown in Table 8.

In the same supply disruption scenario, the manufacturer's combined recovery strategy results in losses of 99,882 and 43,450 respectively. Therefore, comparing the results obtained by manufacturers with different strategies after a supply disruption, it can be seen that a combination of emergency procuring and product design change to add alternative suppliers can effectively reduce the manufacturer's losses.

Table 6
Manufacturer's maximum profit after emergency procurement.

s	Y_{t1}	Y_{t2}	Y_{t3}	Y_{t4}	Y_{t5}	Y_{t6}	Total Profit
1	0	400	0	0	0	450	−27320
2	0	0	399	$0(t \leq 3T)$ $312(t > 3T)$	226	$0(t \leq 3T)$ $280(t > 3T)$	28,932

Table 7
Manufacturer's maximum profit after combination recovery strategy.

s	Y_{t1}	Y_{t2}	Y_{t3}	Y_{t4}	Y_{t5}	Y_{t6}	Total Profit
1	0	400	0	0	0	500	120,930
2	0	0	399	$0(t \leq 3T)312$ $(t > 3T)$	257	$0(t \leq 3T)280$ $(t > 3T)$	177,362

Table 8
Manufacturer's procurement of alternative suppliers after product change.

s	k	x_{3k}	x_{4k}	x_{5k}	x_{6k}	x_{7k}	x_{8k}	x_{9k}
	1	400	400	400	400	400	400	0
1	2	450	450	450	450	450	450	100
	3	500	500	500	500	500	500	0
	1	400	302	302	400	400	400	400
2	2	450	450	450	450	450	450	450
	3	500	500	500	390	500	500	500

5.2. Sensitivity analysis

Manufacturer's total cost after disruptions vary with different parameters. In this section, we will analyze the change in manufacturer's total cost by performing a sensitivity analysis on E_i, B_j, L_j and g for the cases of illustration 2. For characterizing the impact, the sensitivity analysis is performed different parameters, and only one parameter is changed for each analysis, and the remainder is kept the same as in Section 5.1. We will change the parameters to -50 %, -25 %, +25 %, and +50 % of the original values to solve for the results, and details are given in Table 9.

As can be seen in Table 9, the manufacturer's total profit after adopting the recovery strategy is more sensitive to the loss of sales resulting from the product change and can quickly change the resultant values with small changes in the parameter values.

Figs. 2 and 3 show the changes of a manufacturer's total profit with product change sales loss and product change design time respectively after the disruption. It can be seen that total profit decreases as product change cost and time increase, and in particular, product change design time can have a large impact on total profit. Figs. 4 and 5show the changes of a manufacturer's total profit with backorder cost and lost sales cost respectively. The backorder cost can have a large impact on total profit because of compromises in the production quantities. However, the manufacturer's profit will increase significantly when the compensation price for backorders is low. The increment in lost sales cost causes a linear decrease in overall profit for the production system.

Table 9
Sensitivity analysis regarding key parameters for illustration 2.

Parameters	Parameter change (%)	Total profit	Change in profit (%)
g	−50%	203,177	+14.55 %
	−25%	190,269	+7.28 %
	+25%	164,454	−7.28%
	+50%	151,547	−14.55%
E_i	−50%	177,612	+0.14 %
	−25%	177,487	+0.07 %
	+25%	177,237	−0.07%
	+50%	177,112	−0.44%
B_j	−50%	184,462	+4.01 %
	−25%	179,087	+0.97 %
	+25%	175,637	−0.97%
	+50%	173,912	−1.95%
L_j	−50%	184,262	+3.89 %
	−25%	180,812	+1.95 %
	+25%	173,912	−1.95%
	+50%	170,462	−3.89%

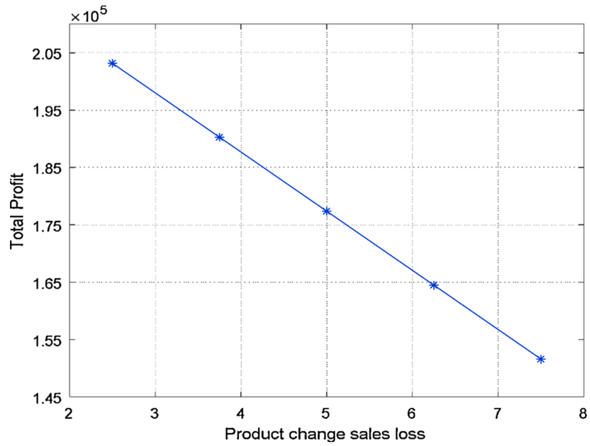

Fig. 2. Changes of total profit with product change sales loss.

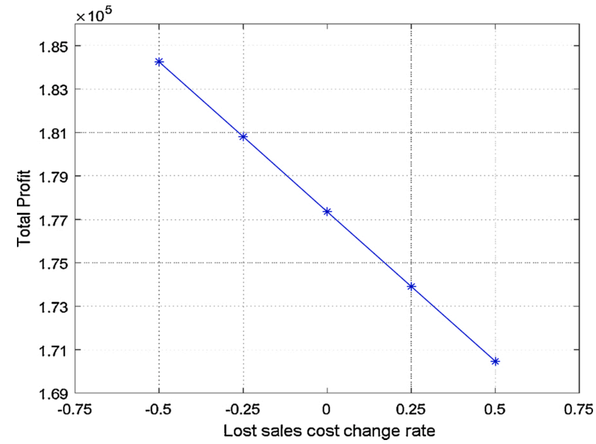

Fig. 5. Changes of total profit with lost sales cost change rate.

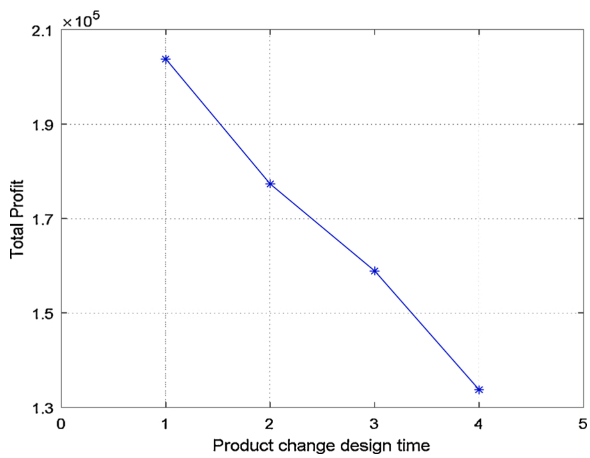

Fig. 3. Changes of total profit with product change design time.

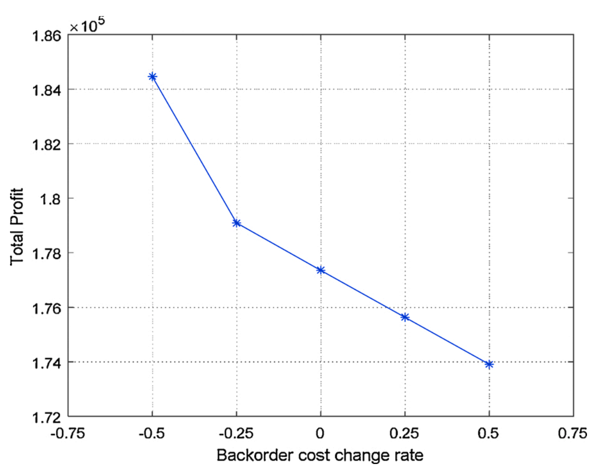

Fig. 4. Changes of total profit with backorder cost change rate.

6. Managerial insights

In this paper, we consider a three-tier supply chain system in that demand is deterministic but sensitive to both price and delivery time. When its supply chain is disrupted by the COVID-19 pandemic, the manufacturer's optimal disruption recovery strategy is analyzed by combining emergency procurement on the supply side and product changes by the manufacturer as well as backorder price compensation on the demand side. The approach of using numerical problems to develop a recovery plan after a production disruption occurs can provide managers with examples to solve disruption problems in real-world environments. Our results provide decision makers with the following insights.

(1) This paper presents a model for combined disruption recovery strategies under uncertainty during the COVID-19 pandemic. The proposed model can help managers consider factors such as market demand, machine capacity, and supply situation in the decision-making process of designing a resilient supply chain to cope with unexpected disruptions similar to those caused by a pandemic outbreak.
(2) Cost and time factors play different roles in designing an optimal disruption recovery strategy. The cost factor takes into account the additional procurement costs arising from emergency purchases, the change costs arising from product changes and their resulting lost sales, and the compensation costs to customers for backorder. How to determine raw material purchases, order production allocations and compensation levels for the recovery period essentially depends on time factors such as customer sensitivity to wait times and the duration of disruptions.
(3) When the supply interruption may exist for a long time, the manufacturer can take into account factors such as out-of-stock situation, product design change time, alternative supplier procurement cost and supply capacity, etc., to make certain degree of design changes to the products produced, in order to achieve the purpose of rapid resumption of production, reduce the disruption loss and reduce the impact on corporate reputation.
(4) For short-term disruptions, the optimal disruption recovery strategy mainly consists of emergency procurement. For long-term disruptions, a combined strategy consisting of both emergency procurement and product change is optimal for certain time periods of the production horizon.
(5) The sensitivity analysis reveals that the time of product design changes and the sales loss incurred after product changes are more likely to pose an impact upon the manufacturer's total cost. Therefore, managers should consider how to reduce time cost and sales loss in actual system.

7. Conclusions

In this paper, we develop a disruption recovery strategy for manufacturing companies in order to cope with the large-scale disruptions caused by the COVID-19 pandemic. When some or all of suppliers cannot recover quickly in a short period, the manufacturer would consider to change the product type partly and select the new suppliers that provide the raw material for the changed product in order to decrease the profit loss caused by this special disruption of supply chain. A MILP model is presented with combining emergency procurement on the supply side and product changes by the manufacturer as well as backorder price compensation on the demand side. Numerical experiments show that although changing product could incur additional procurement cost and sales profit loss, it can effectively decrease the impact of large-scale supply chain disruptions. In addition, several managerial insights are also provided for decision-makers to address the real-world disruption problems of supply chain.

Despite all these efforts, this study still has a few limitations. For instance, the influence of demand fluctuation and the transshipment cost have not been taken into count, which may often occur during the outbreak in fact. In addition, other factors exist in practice, such as multiple types of products, procurement costs of different raw materials, and so on. Thus, future studies may incorporate these factors into the present disruption recovery model.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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