A multi-stage supply chain disruption mitigation strategy considering product life cycle during COVID-19

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Abstract

The global pandemic of COVID-19 has caused severe damage to the supply chain such that manufacturers may face long-term supply disruptions. In this paper, a disruption recovery strategy of a supply chain system is investigated from the perspective of product change, in which the life cycle and design change time of a new product are both considered in order to minimize the losses of manufacturer after disruptions. A mixed-integer linear programming (MILP) model is presented to address the disruption recovery problem for this multi-period, multi-supplier, and multi-stage supply chain system. A two-stage heuristic algorithm is designed to solve the problem. Experimental results show that the proposed disruption mitigation strategy can effectively reduce the profit loss of manufacturer due to supply disruption, and demonstrate the impact of product life cycle in the selection of new product design planning. A sensitivity analysis is performed to ensure the applicability of the model in the actual environment, which illustrates the effect of different parameter changes on the results. This work can help manufacturers establish an optimal recovery strategy whenever the supply chain system experiences supply disruptions.

Keywords COVID-19 · Supply chain · Mitigation strategy · Product design change · Product life cycle

Introduction

Global supply, transportation, and manufacturing face numerous challenges that reduce their capacities during the COVID-19 pandemic (Chowdhury et al. 2021). These challenges include raw material shortages due to declining supplier supply capacity, disruptions in global transportation and international trade, labor shortages due to complete nationwide lockdowns, and the maintaining of physical distance in manufacturing facilities (Amankwah-Amoah 2020). Such massive disruptions in the supply chain can result in high losses and additional recovery costs (Ivanov 2020). Therefore, it is necessary to improve supply chain

resilience in order to enable to take timely measures against unpredictable events, such as COVID-19 (Ivanov and Dolgui 2020; Paul et al. 2021).

The concept of resilience of in the context of general network manufacturing systems, in particular with respect to the similar concepts such as robustness and reliability, can be found in Zhang and Lin (2010) and Zhang and Luttermelt (2011), and the concept of resilience in the context of supply chain network systems is referred to Wang et al. (2016) and Wang et al. (2018). Um and Han (2020) believe that different mitigation strategies can be used to improve the resilience of the supply chain more effectively in different risk environments, and the use of hybrid strategies can achieve better results. Considering the long duration and wide coverage of disruptions caused by COVID-19, as well as the unpredictability of epidemic outbreaks and the ripple effect in the spread of supply chain disruptions (Ivanov 2020), it is difficult to develop effective prevention strategies. Thus, the development of an effective disruption recovery strategy becomes the key to the study of resilience mitigation strategies.

For upstream supply-side disruptions, existing studies focus on reducing the impact of supply disruptions through

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strategies such as emergency purchase, reserving spare capacity at suppliers, delaying deliveries, supply reconfiguration, goods flow re-planning and re-scheduling, and price compensation (Shao 2012; Paul and Rahman 2018; Wang et al. 2019). The manufacturer can maintain safety stock and revise the production plan in time after production disruptions to maximize the total profit within the recovery time window (Paul et al. 2015a, b). In order to deal with demand fluctuations and demand uncertainty caused by unexpected events, some scholars have proposed measures such as supply contract mechanisms, inventory, and reserve capacity strategies (Asian and Nie 2014; Lückner et al. 2019). Chen et al. (2021) adopted a combined recovery strategy of emergency procurement and product design changes to cope with supply disruptions in the three-stage supply chain caused by the pandemic. Different from previous studies, the product change strategy is introduced in the disruption recovery strategy, and its effectiveness was illustrated.

Product design change refers to the act of adapting or changing the product itself and the materials or components that make up the product, and may change the product requirement (Wright 1997; Fan et al. 2015; Zhang and Wang 2016). Reasons for changes may include customer requirements for product improvement, replacement of certain parts for better functions or safety, and failure of original parts due to supply reasons (Jarratt et al. 2011). The product design change process needs to consider the impact of the product change on other components as well (Chen et al. 2015). In addition, product changes can also affect raw material purchases and product sales. Therefore, the impact of the life cycle of the changed product on the supply chain after product design change is supposed to be considered (Asl-Najafi and Yaghoubi 2021). In other words, supply chain operations and decisions are influenced by the product life cycle (Hsueh 2011). Gallego-García and García-García (2020) analyzed the impact of product changes in the product life cycle and supplier inventory levels in the event of supply chain disruption.

This paper extends the work on supply chain disruption recovery strategy in Chen et al. (2021) considering the impact of product life cycle on supply chain disruption recovery after product design changes, and further introduces distribution centers in the supply chain system. The problem is formulated as a mixed integer linear programming (MILP) model aimed at maximizing the profit of the manufacturer in the supply chain under capacity constraints in terms of production, inventory, and transportation. The length of the time period in the production recovery cycle is defined as constant in our model. Our study not only identifies how product design change cost and time factors play different roles during the design of mitigation strategies, but also examines the impact of the changed product life cycle on the design of product change options, the selection of

alternative suppliers, the allocation of order quantities, and inventory planning.

The remainder of the paper is organized as follows. The “Literature review” section provides an overview on relevant literature. The problem definition, the notations, and the underlying assumptions are given in the “Problem statement” section. The “Mathematical model” section presents the mathematical model and its solution method. Numerical experiments and the discussion of results are given in the “Numerical experiments” section. The “Managerial and practical insights” section gives managerial and practical insights. The “Conclusions” section summarizes the paper and provides directions for future research.

Literature review

Product complexity and globally dispersed product design activities pose challenges for today’s companies. These challenges affect the entire product lifecycle, and are exacerbated by the disruptions to the global supply chain caused by the COVID-19 pandemic. This section reviews research on supply chain disruption recovery, product design changes, and product lifecycle.

Supply chain disruption recovery

In recent years, the study of supply chain disruption risk has received extensive attention (Govindan et al. 2020; Sawik 2019). A number of scholars have proposed recovery strategies for supply chain disruptions (Ivanov et al. 2017). Ahmed et al. (2017) developed an inventory model for sourcing from multiple suppliers considering the uncertainty of supply time as well as supply capacity in case of supply disruption. Xia et al. (2010) proposed a two-stage generic production and inventory disruption recovery model, which takes into account the cost of deviation from the normal schedule after recovery and introduces the concept of disruption recovery time window. Hishamuddin et al. (2012) extended the model proposed by Xia et al. (2010) and developed an economic batch model disruption recovery method that takes into account four costs of manufacturer production by determining the optimal manufacturing batch size and optimal recovery duration for a production run in the recovery time window to minimize the expected total cost of ownership, which yields a real-time revision schedule within a specified time frame. Kaur et al. (2020) proposed an independent and integrated production and sourcing model for a resilient supply chain considering sustainability and uncertainty in the supply chain, such as changing market demands and uncertainty in the capabilities of manufacturers, suppliers, and transporters. Paul et al. (2019a) studied a lean two-stage supplier-manufacturer supply chain system.

In this system, when the transportation network is suddenly disrupted, this will result in delivery delays and out-of-stock losses. The authors modeled a recovery plan after a sudden disruption and evaluated its efficiency in terms of performance impact. Paul et al. (2019b) developed a three-stage supply chain production recovery model considering one or more combinations of demand uncertainty, production disruptions, or raw material supply disruptions. Malik and Sarkar (2020) developed a disruption recovery model for a multi-product, single-stage production system, taking into account the main costs, budget, and storage space constraints to obtain the optimal manufacturing lot size for multiple materials within the recovery time window, thus reducing the losses due to disruptions.

In order to respond to the disruptions caused by the COVID-19 pandemic, Paul and Chowdhury (2021) developed a production recovery model for high-demand products during COVID-19, taking into account increased demand, limited production capacity, and insufficient supply of raw materials. The model is capable of modifying production schedules in the event of demand and supply disruptions, and takes into account emergency purchasing costs and the increased labor costs of increased production capacity, resulting in higher profits for manufacturers. Islam et al. (2020) developed the disruption inventory model by considering a combination of supplier and retailer disruptions as well as stochastic capacity and reliability. Shahed et al. (2021) developed an inventory model using the update reward theory to mitigate the supply chain network disruption in the three stages affected by natural disasters such as the COVID-19 pandemic, which maximizes the profit of the manufacturer. Rahman et al. (2021) used the facemask supply chain as an example to propose a primary recovery strategy for establishing emergency supply and additional manufacturing capacity to mitigate the impact of supply chain disruptions on manufacturers' production. Nagurney (2021) considered the uncertainty of product demand and the impact of the COVID-19 pandemic on the workforce and developed a supply chain network optimization model to cope with supply chain disruptions.

Product design change

Product components may change throughout the product life cycle due to emergencies or product upgrades to increase profits. Changes in product components directly affect the manufacturer's production and order delivery. Product change refers to the behavior of making some adjustments or changes to the product itself and the components that constitute the product, focusing on the functional design of the product (Chen et al. 2015). Changes to some parts of a product may trigger a series of changes to other parts, posing a potential risk of compromising the integrity of the entire

product. To correctly predict the risk of change propagation based on the impact of the change, researchers have proposed various product models to analyze the change (Zhang et al. 1993; Chandrasegaran et al. 2013). Wang and Che (2008) developed a part change relationship analysis and an evaluation model for part and supplier selection, using a TFT-LCD module as an example. Cheng and Chu (2012) proposed three variability metrics (degree variability, reachability variability, and inter-variability) to assess the impact of part changes on product production in complex products. Zhang et al. (2017) proposed a design change model to systematically analyze and search for change propagation paths in complex product systems to cope with demand changes. Yin et al. (2021) proposed a deterministic simulation model to evaluate change propagation scenarios and to efficiently assess the change time as well as the risk before design changes. Product changes require the selection of new suppliers based on the design solution and consideration of the product life cycle impact on new product production.

Product life cycle management

Product life cycle management (PLM) is an integrated, information-driven approach consisting of people, processes, and technologies that address all aspects of a product's life by exchanging product information throughout the organization and supply chain. Companies need to consider PLM to help with operations management to reduce the complexity of the design process for new product development. Life cycle assessment is a widely used method in industry to quantify and compare the environmental impact of products, taking into account the entire life cycle of the product (Martí and Seifert 2013). Chiang and Trappey (2007) proposed a conceptual architecture of PLM for LCD collaborative product commerce and listed the important modules of PLM that support the key activities of the LCD industry value system. Chen and Chang (2013) proposed a pricing strategy based on the different stages of the product life cycle, the cost of new products and the substitutability factor, and an analytical model using Lagrangian relaxation and dynamic programming schemes. Oh et al. (2015) proposed a hybrid collaborative model integrating product lifecycle management and supply chain management to cope with the uncertainty of product development and demand forecasting. Labbi et al. (2015) investigated the role of PLM in supply chain optimization and proposed a mixed-integer linear programming formulation to simultaneously determine the best alternative design solution and the selection of the optimal upstream supplier. Gallego-García and García-García (2020) developed a model for inventory and purchasing planning model in the case of supply chain disruptions by simulating a system dynamics approach, considering the product life cycle. Singh et al.

(2021) studied personal protective equipment (PPE) supply chain management during the COVID-19 pandemic from a product life cycle perspective and proposed corresponding measures. More recently, a so-called semantic data modeling framework was developed, which captures social and cultural information in the global manufacturing and service context (Yu et al. 2021). This framework captures various ways that data are represented, i.e., structural data, semi-structural data, and un-structural data, which can improve the manufacturing system.

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.

Problem descriptions

Supply chain disruptions caused by COVID-19 pandemic often occur first on the supply side due to embargo policies in raw material supply areas, or reduced transportation capacity, and then spread downstream along the supply chain due to ripple effects. Supplier disruptions are highly random due to COVID-19, making it difficult to predict the scale of the disruption and the supplier where the disruption occurs. COVID-19 pandemic risks may also act simultaneously on other nodes in the supply chain, such as manufacturers' limited production capacity due to labor shortages, or reduced transportation capacity. The combined effect of the two causes a manufacturer's capacity to drop, shaping the risk of stock-outs. In addition,

disruptions caused by the pandemic often have long-term effects on the supply chain and are difficult to recover from in a short period of time.

This paper considers a multi-tier supply chain consisting of multiple suppliers, a manufacturer, multiple distribution centers, and multiple clients, as shown in Fig. 1. The manufacturer produces a product that requires a key component from multiple suppliers. The products are produced during the production cycle based on the quantity and delivery time of the product required by the order. Once production is complete, the products are first shipped to a distribution center, which then delivers the product to customers in their respective regions based on the order. There are multiple customers in each distribution center area and there is no overlap between them. Distribution centers can store a certain number of products, but will incur inventory costs. Exceeding the delivery time of an order requires compensation to the customer, which will result in backorder costs, and exceeding the latest delivery time of an order will result in cancelation of the order, incurring lost sales costs. Therefore, the manufacturer needs to rationalize production schedule, the number of products shipped to each distribution center at each time period, and the order delivery time.

After disruptions occur on the supply side, the manufacturer first maintains production by holding safety stock while making emergency purchases from suppliers that have not experienced disruptions. When these strategies are still unable to meet orders, manufacturers can use product design changes to make changes to parts while maintaining product performance. Different types of product design changes result in different design costs and change times. When purchasing raw materials for the changed product, the life cycle of the changed product needs to be considered. The product life cycle can be generally divided into 4 stages,

Fig. 1 Multi-tier supply chain model

Fig. 2 Change in production quantity over time after product change

including introduction, growth, maturity, and decline, and in each stage, there are its own characteristics (Anderson and Zeithaml 1984). The decline period of the product will not be considered in the production time window of the disruption recovery model proposed in this paper. Experimental production is first carried out, with a small number of products produced. Subsequently, production will enter a period of rapid development and the demand for raw materials will increase rapidly. After a period of production, considering the order situation, production capacity, and supply capacity, the production of the changed product enters the maturity period. The number of products produced in the production cycle after the change is shown in Fig. 2. We define the recovery time window as n normal production cycle times from the start of a disruption. During the recovery period, the production schedule is modified such that the length of n cycles in the recovery schedule is equal to n cycles in the original schedule. In addition, only the costs in the recovery window are considered due to the limited time horizon for our particular model.

In the optimization process of supply chain disruption recovery, the manufacturer needs to decide on the following issues: (1) How much raw material to obtain through emergency procurement. (2) How to select product change options and alternative suppliers based on disruptions and product life cycles. (3) The quantity of products shipped from the manufacturer to each distribution center in each time period, as well as the delivery time of orders within the distribution center area, need to be determined.

Notations

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 orders
- k Index for distribution centers
- m Index for alternative suppliers
- t Index for production periods

List of decision variables:

- y_i 1 if i th original supplier makes an emergency procurement, else 0
- z_m 1 if m th alternative supplier is selected, else 0
- z_{mt} Quantity to be procured in t th period from m th alternative supplier considering product life cycle after product design change
- I_t Quantity of raw materials inventory in t th period
- Q_{kt} Quantities of products shipped from the manufacturer to the k th distribution center in t th period, else 0
- I_{qkt} Quantity of products inventory for the k th distribution center in t th period
- w_{jt} 1 if j th order is delivered in t th period, else 0

List of parameters:

- X_i Quantity to be procured in a period for normal production conditions from i th supplier
- $z_{i,max}$ Maximum quantity of raw material that can be supplied by i th supplier in a period
- u_i 1 if i th supplier has not been disrupted, else 0
- C_i Unit procurement cost of raw materials from i th supplier
- E_i Emergency procurement cost of raw materials from i th supplier
- A_m Unit procurement cost of alternative raw materials from m th alternative supplier
- e_m Change cost of choosing the raw materials from m th alternative supplier
- $Z_{m,t,max}$ Maximum quantity of alternative raw material to be procured from m th alternative supplier in t th period
- $P_{p,max}$ Maximum quantity to be produced in t th period
- α Production capacity change rate after disruption
- L Length of production period
- l_m Product design change time of choosing the raw materials from m th alternative supplier
- τ_k Transportation time from the manufacturer to the k th distribution center
- f_i Resilience coefficient of i th supplier
- H Unit holding inventory cost of raw materials
- h_k Unit holding inventory cost of products at the distribution center
- I_s Quantity of safety stock of raw materials held by the manufacturer before the disruption occurred quantity

P_c	Unit cost of production
v_{kj}	1 if j th order is supplied by the k th distribution center, else 0
Q_{min}	Minimum quantity for a single shipment from manufacturer to distribution center
Q_{max}	Maximum quantity for a single shipment from manufacturer to distribution center
β_k	Transportation capacity change rate of the k th distribution center after disruption
U_j	Last time for cancelation of the j th order
B_j	Unit cost of backorder for j th order after delayed delivery
L_j	Unit cost of lost sales for j th order after order cancelation

Assumptions

In order to make the study more relevant and feasible, the main assumptions used in the type of supply chain environment considered are as follows:

- (1) The manufacturer starts the production recovery cycle after the disruption, and the orders that need to be delivered have been determined before the disruption. In addition, the supplier where the disruption occurred does not resume supply at the given production recovery cycle and does not consider the creation of new disruptions.
- (2) Since COVID-19 has spread globally for a long time, manufacturers can prepare for possible disruptions in advance by maintaining safety stocks before actual disruptions occur.
- (3) Emergency procurement requires additional costs, but production delays caused by emergency procurement are not considered.
- (4) Product design changes need to ensure the performance of the product, taking into account the change time l_m , the change cost e_m , and the life cycle of the raw materials purchased after the product change.
- (5) The quantity of product shipped from the manufacturer to distribution center k in a production time period cannot be less than Q_{min} or it will not be shipped. Client order needs to be shipped by the distribution center in a single shipment.
- (6) Exceeding the order's latest delivery period T_j will result in backorder costs, and exceeding the order's latest cancelation period U_j will result in lost sales costs.
- (7) Transportation costs of raw materials and products among suppliers, manufacturers, distribution centers, and clients are not considered.

Mathematical model

In this section, a disruption recovery model is developed for the supply chain system described earlier firstly. Furthermore, an effective heuristic is developed as a solution to determine the optimal value of the recovery model.

Mathematical representation

According to the above notations and variable definitions, the total cost function of the supply chain can be established as follows:

$$TC = C_s + C_m + C_c + C_d + C_b + C_u \quad (1)$$

C_s is the cost of raw materials purchased by the manufacturer from the original supplier, including the cost of the original planned purchase from the undisrupted supplier and the cost of the emergency purchase after the disruption.

$$C_s = \sum_{i \in I} Tu_i [C_i X_i + y_i E_i f_i X_i] \quad (2)$$

C_m is the manufacturer's production cost, including the storage costs of raw materials and the production cost of products.

$$C_m = \sum_{t \in T} HI_t + \sum_{k \in K} \sum_{t \in T} P_c * Q_{kt} \quad (3)$$

C_c is the cost of product design changes made by the manufacturer, including the cost of design and the cost of purchasing alternative raw materials from alternative supplier after the product change. The design change time is considered.

$$C_c = \sum_{m \in M} e_m z_m + \sum_{m \in M} \sum_{t \in T: t \geq l_m} A_m Z_{mt} \quad (4)$$

C_d is the cost of inventory after the product has been shipped from the manufacturer to the distribution center.

$$C_d = \sum_{k \in K} \sum_{t \in T} h_k I_{kt} \quad (5)$$

C_b is the backorder cost. Delayed delivery requires price compensation to the customer and will incur backorder cost.

$$C_b = \sum_{j \in J} B_j D_j (\sum_{t \in T} w_{jt} - \sum_{t \in T: t \leq T_j} w_{jt}) \quad (6)$$

C_u is the cost of lost sales incurred when an order is canceled after the order's latest delivery cycle has been exceeded.

$$C_u = \sum_{j \in J} L_j D_j (1 - \sum_{t \in T: t \leq U_j} w_{jt}) \quad (7)$$

The manufacturer's revenue is related to the actual number of orders delivered and can be calculated as selling

price per unit multiplied by the orders' quantity and orders delivery status.

$$\text{Rev} = \sum_{t \in T} \sum_{j \in J} w_{jt} D_j R_e \quad (8)$$

The product life cycle of alternative parts selected for each product design change plan includes three periods of introduction, growth, and maturity. The changed product is produced in smaller quantities during the introduction period and requires fewer parts. During the growth period, production capacity increases rapidly and the number of parts required also increases rapidly. During the maturity period, the production quantity is determined for each time period and the number of parts required remains the same. The maximum number of products produced in each time period after the change can be expressed as follows:

$$Z_{mt, \max} = ae^{bt} \quad (9)$$

A mixed integer linear programming (MILP) model with the objective of maximizing the manufacturer's total profit (TP) is proposed as follow:

$$\text{MaxTP} = \text{Rev} - \text{TC} \quad (10)$$

s.t.

$$\sum_{i \in I} u_i (X_i + y_{if_i} X_i) + I_s = \sum_{k \in K} Q_{k1} + I_1 \quad (11)$$

$$I_{t-1} + \sum_{i \in I} u_i (X_i + y_{if_i} X_i) + \sum_{m \in M} Z_{mt} = \sum_{k \in K} Q_{kt} + I_t, \forall t \in T : t \geq 2 \quad (12)$$

$$\sum_{k \in K} Q_{kt} \leq \alpha P_{t, \max}, \forall t \in T \quad (13)$$

$$Q_{kt} \geq Q_{\min}, \forall k \in K, t \in T \quad (14)$$

$$Q_{kt} \leq \beta_k Q_{\max}, \forall k \in K, t \in T \quad (15)$$

$$(1 + y_{if_i}) X_i \leq X_{i, \max}, \forall i \in I \quad (16)$$

$$(1 + y_{if_i}) X_i \geq X_i u_i, \forall i \in I \quad (17)$$

$$Z_{mt} \leq z_m Z_{mt, \max}, \forall m \in M, t \in T \quad (18)$$

$$\sum_{t \in T} w_{jt} \leq 1, \forall j \in J \quad (19)$$

$$I_{q_{k(t-1)}} + Q_{kt} = \sum_{j \in J} v_{kj} D_j w_{jt} + I_{q_{kt}}, \forall k \in K, t \in T : t \geq 2 \quad (20)$$

$$\sum_{t' \in T : t' \leq t} \sum_{j \in J} v_{kj} D_j w_{jt} \leq \sum_{t' \in T : t' \leq t - \tau_k} Q_{kt}, \forall k \in K \quad (21)$$

$$\sum_{t \in T} \sum_{k \in K} Q_{kt} \leq T \sum_{i \in I} u_i (X_i + y_{if_i} X_i) + \sum_{m \in M} \sum_{t \in T} Z_{mt} + I_s \quad (22)$$

$$y_i \in \{0, 1\}, \forall i \in I \quad (23)$$

$$z_m \in \{0, 1\}, \forall m \in M \quad (24)$$

$$w_{jt} \in \{0, 1\}, \forall j \in J, t \in T \quad (25)$$

$$Z_{mt}, Q_{kt}, I_t, I_{q_{kt}} \text{ are positive integers, } \forall m \in M, k \in K, t \in T \quad (26)$$

Equation (10) is obtained from Eqs. (1) and (8), with the manufacturer's maximum profit as the objective. The constraints are shown in Eqs. (11)–(26). Equations (11)–(15) constrain the relationship between the manufacturer's raw material procurement, storage, product production, and distribution transportation. Equations (16) and (17) constrain the supply capacity of the original supplier before and after the disruption. Equation (18) constrains the supply capacity of the alternative supplier. Equation (19) constrains that each client's order can only be fulfilled once. Equations (20) and (21) constrain the relationship between storage, transportation, and order distribution of products in distribution centers. Equation (22) constrains the total quantity of products produced to not exceed the quantity of raw materials purchased from suppliers within the production schedule. Equations (23)–(25) constrain the binary nature of the decision variables y_i , z_m , and w_{jt} . Equation (26) constrains the non-negative variables.

Solution approach

In the existing literature, various optimization tools have been widely used to solve small and medium-sized problems, such as CPLEX or Gurobi. Therefore, considering that the proposed disruption recovery model is a complex mixed integer linear programming (MILP) with constraints, an efficient heuristic combined CPLEX is developed in this paper as a solution to determine the optimal value of the recovery model. The algorithm is divided into two parts, first determine the emergency procurement plan for suppliers after the disruption, and the product design change plan, and then solve the procurement, transportation and inventory quantities, and the order delivery situation. We use the local search to improve the solving ability of the algorithm. The heuristic solution process consists of two stages. In the first stage, the raw material procurement and production under normal production conditions are solved with the objective of maximizing the manufacturer's profit to obtain the optimal X_i . In the second stage, the different types of supply disruptions faced by manufacturers are

first identified, then considering disruption characteristics, taking emergency procurement strategy, safety stock strategy, product design change strategy, or a mixture of the three strategies. Finally, a search procedure is performed by solving the model using the above strategies and the strategy with the maximum TP value is chosen as the optimal solution. The detailed procedure for the heuristic is presented as follows.

Step 1: Initialize the parameters and enter the user input for the ideal supply chain system and get the optimal X_i when no disruption.

Step 2: Classify the number of disruption suppliers and assign value to u_i according to the classification results.

Step 3: Put $s = 1$ for the first disruption type and input disruption scenario.

Step 4: Select emergency procurement plan y_i for suppliers after the disruption, and the product design change plan z_m according to the X_i obtained in step 1 and the u_i obtained in step 2.

Step 5: Solve the proposed mathematical model and get the quantities of procurement Z_{mt} after product change, the quantities of transportation Q_{kt} , the quantities of inventory I_t , I_{kt} , and the order delivery situation w_{jt} according to the y_i and z_m obtained in step 4 under the current disruption scenario.

Step 6: Record the result of the current disruption scenario and update the disruption type u_i .

Step 7: If there is any other disruption, go to step 4, and repeat steps 4–6.

Step 8: Stop and output the final results.

Numerical experiments

This section verifies the feasibility of the proposed model and the validity of the proposed heuristic algorithm through numerous examples. The parameters are determined based on the assumptions made for this model, and a value is assigned to each parameter through a randomly generated data set. In addition, we perform a sensitivity analysis on the different parameters to characterize the effect of their changes on the results.

Computational results

It is assumed that some suppliers provide raw materials before the disruption occurs that the products produced by the manufacturer will be first transported to distribution centers, which in turn distribute them to customers according to orders. Each distribution center is responsible for the delivery of five clients' order, with no overlap in the delivery area. After the

Table 1 Supplier parameters

Supplier	$X_{i,\max}$	f_i	C_i	E_i
S1-S20	(360, 420)	(0.15, 0.3)	(15, 17)	(2, 4)

Table 2 Alternative supplier parameters

Alternative supplier	$Z_{mt,\max}$	A_m	e_m
S1	$6e^{1.1t}$	17	12,000
S2	$8e^{0.8t}$	18	10,000
S3	$8e^t$	17	11,000
S4	$10e^{0.9t}$	16	12,500
S5	$10e^t$	16	12,500
S6	$12e^{0.9t}$	15	13,500

product design change, five alternative suppliers can be selected, whose maximum supply capacity needs to meet the maximum quantity limit for each time period of the product life cycle. The production horizon for the recovery period after the disruption consists of ten time periods. Such T represents the time period of the production schedule.

The epidemic will cause at least one original supplier to be disrupted. Numerical experiment assumes different supplier disruption scenarios for demonstrating the effectiveness of the proposed disruption recovery strategy model. In each disruption scenario, the number of disrupted suppliers is different, and the disrupted suppliers are generated randomly. Considering different suppliers and client sizes, and disruption scenarios, we have presented the results of 13 sample test problems to verify the proposed model and heuristic algorithm.

Parameters of each part of the supply chain are determined based on the assumptions made for the model and are generated randomly within the range of values. Table 1 presents the parameter information of the suppliers and Table 2 presents the parameter information of the alternative suppliers. The initial supply cycle of the changed product is $1T$ or $2T$, and its production capacity enters the maturity period after $3T$ or $4T$, and the corresponding raw material supply reaches the maximum. The value of $Z_{mt,\max}$ can be calculated from Eq. (9).

The range of values for the parameters related to transportation and inventory of distribution centers is shown in Table 3. Table 4 presents the parameter information of the clients' order.

In addition, the values of other parameters in the model are given, including unit production cost $Pc = 6$, raw

Table 3 Distribution center parameters

Distribution center	h_k	τ_k	Client quantity
K1-K6	(2, 4)	(1 T, 2 T)	(4, 5)

Table 4 Client parameters

Client	D_j	B_j	L_j	T_j	U_j
C1-C25	(1600, 2100)	(6, 9)	(18, 27)	(3 T, 8 T)	(5 T, 10 T)

Table 5 Manufacturer's procurement of raw materials and maximum profit

Case	Supplier	Client	Disruption quantity	Total profit	Alternative supplier options
1	6	9	2	235,137	(0, 0, 0, 0, 1, 1)
2			3	206,800	(0, 0, 0, 1, 1, 0)
3			4	168,682	(0, 0, 1, 1, 1, 1)
4			5	113,253	(0, 0, 1, 1, 1, 1)
5	10	15	4	428,737	(0, 0, 0, 0, 1, 1)
6			5	379,689	(0, 0, 0, 1, 1, 1)
7			6	338,943	(0, 0, 1, 1, 1, 1)
8			7	300,178	(0, 0, 1, 1, 1, 1)
9	15	25	6	698,463	(0, 0, 1, 1, 1, 1)
10			7	653,222	(0, 0, 1, 1, 1, 1)
11			8	636,840	(1, 0, 1, 1, 1, 1)
12			9	595,956	(1, 0, 1, 1, 1, 1)
13			10	443,141	(1, 1, 1, 1, 1, 1)

material inventory cost $H=2$, product design change time $l=T$, and product unit revenue $Re=40$.

Table 5 gives the results of the solution using the heuristic respectively after the recovery strategy adopted by the manufacturer for different supplier and customer size cases. For the selection of alternative suppliers after the design change, it is related to the number of disrupted suppliers and the life cycle of the changed product. By comparing alternative supplier selection options after product changes for different size suppliers and client orders, it can be seen that alternative suppliers 5 and 6 are often preferred in the disruption recovery strategy due to their shorter initial delivery period and larger supply quantities after entering the maturity. Figure 3 gives the change in product quantity over time for each production time period for the changed product in case 6. As the number of disruptions to the original supplier increases, so does the number of alternative suppliers choose after the product changes.

We compare the maximum profit for a supply chain size of six suppliers and nine customers, where the manufacturer does not adopt any measures after a disruption and only adopts an emergency procurement strategy, and the recovery strategy proposed in this paper. The results are shown in Table 6. It can be found that when the number of disrupted suppliers is small, the manufacturer only adopts emergency procurement strategy to ensure timely delivery of orders and obtain considerable profits. As the number of disrupted suppliers increases, only the emergency procurement strategy can no longer meet the manufacturer's production needs. When the number of disrupted suppliers is high, the manufacturer adopts a combination of emergency procurement

Fig. 3 The production quantity after product change

Table 6 Manufacturer's procurement of raw materials and maximum profit

Case	Without any measure	Total profit Emergency procurement	Proposed recovery strategy
1	65,854	115,137	235,137
2	-70,025	-10,050	206,800
3	-173,710	-157,182	168,682
4	-317,564	-317,564	113,253

and product design changes, and chooses product design changes by considering supply capacity and costs at different times in the product life cycle. The product life cycle has an impact on the selection and lead times of alternative suppliers, and is an important factor for manufacturers to consider when making product design changes.

For the delivery of customer orders, if the manufacturer does not take any measures after the disruption, the delivery situation is shown in Table 7. It can be seen that when the disruption occurs, as the number of disrupted suppliers increases, manufacturer production decreases significantly and more orders are delayed or canceled. Not only will the manufacturer's profits be reduced, but also the corporate reputation will be affected. After adopting the emergency procurement and product change strategy, the order delivery is shown in Table 8. Compared with when no recovery strategy was adopted, the order delivery situation has been greatly improved.

Sensitivity analysis

Manufacturer's total profit after disruptions vary with different parameters. In this section, a sensitivity analysis was performed to show the effect of various parameters on the total profit of the proposed model. This section gives the sensitivity analysis for P_t , e_m , H , B_j , and L_j in case 2. For characterizing the impact, the sensitivity analysis is performed in different parameters, and only one parameter is changed for each analysis, and the remainder is kept the same as in Sect. 5.1. The total effect of the parameter changes - 30%, - 20%, - 10%, + 10%, + 20%, and + 30% are calculated.

Table 7 Quantity of orders delivered without any measures

Case	Delivery on schedule	Delayed delivery	Undelivered
1	5	2	2
2	5	1	3
3	2	2	5
4	1	1	7

Table 8 Quantity of orders delivered with recovery strategy

Case	Delivery on schedule	Delayed delivery	Undelivered
1	9	0	0
2	7	2	0
3	6	3	0
4	5	4	0

Figure 4 shows the behavior of the total profit for different values of product maximum capacity varying from 2100 to 3900. It can be observed that the total profit for the system increases with an increase in maximum capacity when the other parameters are fixed. A decrease in manufacturer capacity can cause a significant drop in profits, while an increase in capacity, influenced by supply capacity as well as the number of orders, has a smaller impact on profits. When supply chain disruptions occur, manufacturers need to ensure raw material procurement on the one hand, and also to maintain capacity as stable as possible. Increasing capacity requires a combination of suppliers and orders.

Figure 5 and Fig. 6 respectively depict the impact of changes in [product design change](#) cost and inventory cost on profitability. Comparing two parameters, the manufacturer's profit is more sensitive to changes in product design change cost, and just a small change in the parameter value can quickly change the resulting value.

When the backorder cost increase, there is a similar impact on the manufacturer's profit, as shown in Fig. 7. As the cost of lost sales increases, the total cost does not change and is constant throughout the range of lost sales costs, as shown in Fig. 8. This is due to the fact that all shortages tend to. When the lost sales cost is greater than the backorder cost, all shortages are backordered. Therefore, there is no loss of sales in the system. This is due to the fact that the adoption of the recovery strategy has largely alleviated the shortage of raw materials and the number of out-of-stock orders has decreased.

Managerial and practical insights

The model developed in this paper can help managers cope with supply chain disruptions while maintaining profitability during the COVID-19 pandemic. The COVID-19 pandemic exposes suppliers to prolonged disruptions, thereby increasing the complexity of supply chain operations. The mitigation strategy proposed in this paper considers the product life cycle as well as the cost and time of change, and makes design changes to products with raw material shortages to

Fig. 4 Changes of total profit with product maximum capacity **Fig. 5** Changes of total profit with product design change cost

help manufacturers mitigate losses. Numerical experiments based on the proposed model to develop a recovery plan can provide managers with examples of solving disruption

problems in a real-world environment. The management insights of the model in the context of COVID-19 are presented below.

Fig. 6 Changes of total profit with raw material inventory cost

Fig. 7 Changes of total profit with backorder cost

Fig. 8 Changes of total profit with lost sales cost

- (1) This paper proposes a disruption mitigation strategy in the context of COVID-19 pandemic. The proposed model can help managers to consider factors such as market demand, product life cycle, machine capacity, and raw material supply in the decision-making process of designing a resilient supply chain to deal with sudden and long-term disruptions similar to the pandemic.
- (2) When the supply disruption exists for a long time, the manufacturer can consider the time and cost of product design changes and the life cycle of the changed product according to the supply capacity of raw materials after the disruption, and make design changes to the original product without affecting the overall performance of the product, while adopting an emergency procurement strategy so that the company can quickly resume production, reduce the disruption loss, and reduce the impact of not being able to deliver the order on time on the reputation of the company.
- (3) Setting strategic inventory helps manufacturers cope with the early effects of supply disruptions, but the cost of raw material inventory can have an impact on manufacturers' profitability. Thus, the quantities of strategic inventory need to be reasonably planned.
- (4) Manufacturers making product design changes need to consider the performance of the product after the change, the cost, and time of the change design. The

product life cycle has a significant impact on the selection of product change options and the procurement of raw materials after the change.

Conclusions

This paper investigates a supply chain disruption recovery problem in the context of COVID-19 pandemic with supply disruption risk and manufacturer capacity fluctuations in a four-tier supply chain with make-to-order manufacturing. A mixed-integer linear programming (MILP) model is developed based on emergency procurement and product design change strategies considering the product life cycle with the manufacturer's maximum profit as the goal. The MILP model is solved using a new heuristic that we have developed in this paper. Numerical experiments show that the proposed recovery strategy is effective in reducing manufacturers' losses in case of supply chain disruptions. Managers can choose a recovery strategy based on the degree of disruption, and when adopting product design changes, the life cycle of the changed product and the cost of the change for product change options need to be considered.

There are still issues in this paper that deserve further research and discussion. Firstly, the supply chain optimization problem studied in this paper has not considered

uncertainties, which have three types according to Cai et al. (2017), namely vague, undetermined, and missing, and may have some significant impact on the supply chain system. Therefore, uncertainties need to be incorporated in the model. Secondly, in the field of supply chain management, the impact of human factors in each link on the system cannot be ignored (Ogbeyemi et al. 2020). The influence of the game between the various parts of the supply chain on the optimization results, as well as the whole value chain considering each part of the supply chain, can be the direction of future research. Thirdly, by integration, the activities across product design, manufacturing, and whole life cycle will be considered variables to keep the supply continuity (Zhang et al. 2019).

Author contribution W. H. F. contributed to the conception of the study and contributed to manuscript preparation. C. J. Z. performed the experiment and the data analyses and wrote the manuscript. F. Y. P. helped perform the analysis with constructive discussions. All authors read and approved the final manuscript.

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Data availability All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Declarations

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