



# Data driven flexible supplier network of selfcare essentials during disruptions in supply chain

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## Abstract

During disruptive events, supply chains struggle to meet the demand due to limitations posed by logistics, transportation and supply side failures. In the present study, a flexible supplier network of personal protective equipment (PPEs), such as face masks, hand sanitizers, gloves, and face shields, has been modelled using an extensive risk enabled data driven decision making for addressing disruptions in the supply chain. This paper studies various risks which exists in PPE supply chain and evaluates the total supplier risk based on them. Furthermore, the paper proposes a Multi-objective Mixed Integer Linear Program (MOMILP) to optimally select suppliers and the sustainable allocation of orders under various risks, namely disruption, delay, receivables, inventory, and capacity. The proposed MOMILP model is also extended to promptly revise the orders to other suppliers under a disruption scenario enabling an effective response resulting in minimization of stockouts. The criteria-risk matrix is developed with the help of supply chain experts from industry and academia. Conclusively, the numerical case study and its computational analysis is conducted on the PPE data received from distributors to demonstrate the applicability of the proposed model. The findings suggest that the proposed flexible MOMILP can optimally revise allocations during disruptions to drastically reduce the stockouts and minimize overall cost of procurement in the PPE supply network.

**Keywords** Personal protective equipment (PPE) · Disruptions · Sustainable order allocation · MOMILP · Supplier risk · Pandemic COVID-19

## 1 Introduction

World has witnessed the huge demand–supply gap and unpredictably soaring prices of Oil and gas, food grains and healthcare essentials with a multiplier effect of pandemic COVID-19 and Ukraine–Russia war. Unexpected casualties and spread of infections bring the infrastructure

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and healthcare resources at the verge of collapsing with deep hopelessness. The sudden spike in corona cases has exposed the existing cracks in the healthcare infrastructure of emerging economies such as India (Biswas, 2021; Sinha, 2021). People have been exposed to numerous challenges such as losing employment, availability of medicines and PPE, and food security of underprivileged due to the supply chain disruptions (Belhadi et al., 2021; Ivanov & Dolgui, 2021; Nikolopoulos et al., 2021).

Majority of the countries worldwide encountered typical challenges in streamlining the inadequate supply of life saving items like oxygen cylinders and concentrators, oximeter, and hospital beds during pandemic (Aljadede et al., 2021; Chowdhury et al., 2021; Krishnan, 2021). The disrupted supply chains of preventive care items like vaccines, triple layer face masks, hand gloves, face shield, head cap, hand sanitizer, and PPE kits were overburdened by exponential surge in COVID-19 cases during disruptions (Alam et al., 2021; Ishida, 2020). The inadequate availability of PPE items with pharmaceutical suppliers has resulted into the spread of COVID-19 infection to caregivers involved in the care of patients. This has been observed that the absence of an order allocation algorithm with pharmaceutical suppliers has also contributed to insufficient availability of life saving items (Butt, 2021; Choi, 2021; Chowdhury et al., 2021; Ivanov, 2020a, 2020b; Ivanov & Dolgui, 2021; Nikolopoulos et al., 2021; Sharma et al., 2020a, 2020b).

Technological developments such as big data, simulation, industry 4.0, block chain technology, 3D printing and artificial intelligence helps in data driven decision making during disastrous events (Dubey et al., 2021; Queiroz & Wamba, 2021). Few researchers argued in their work for implementing data driven decision making models to effectively tackle the disruptions in supply chains during COVID-19 (Ivanov, 2020a; Queiroz & Wamba, 2021). The huge information and data processing through digital technologies using optimization and analytical modelling approaches assist in sustainable allocation of medical supplies during the risk posing disruptive events like pandemic COVID-19 (Talwar et al., 2021). Hence, in the present study an order allocation model has been proposed so that the sufficient levels of PPE items can be maintained at pharmaceutical stores in any unfortunate event like pandemic COVID-19.

Motivated by a lack of theoretical studies into the pandemic environment, this paper has been developed to address the following research questions such as What are the different risks in PPE supply chains and how these risk factors are interrelated? How to evaluate the total supplier risk in PPE supply chains? How to allocate orders to the suppliers to mitigate the risk of disruption? How to re-allocate orders in case of pandemic caused disruptions to avoid shortages of PPE items?

In order to answer the proposed research questions, the research objectives such as, Identification of different kinds of risks existing in PPE supply chains and establish linkages between these risk factors has been formulated and addressed. To develop a methodology to evaluate the supplier risk in PPE supply chains. To propose a mathematical model to optimally select the suppliers and allocate orders minimizing the total operational cost and risk of disruption. To propose the mathematical model to reallocate the supplier orders in case of any demand or supply side disruptions to minimize the shortages and total operational costs.

The key contribution of this paper is to address the global concern of supply chain disruptions during pandemic by redesigning supply networks considering different risks. It integrated the qualitative and quantitative methods to study the risks involved in PPE supply chains and then to design the supply network minimizing these risks. This study of supply chain risk can help in computation of overall supplier risk. The paper contributes a multi objective flexible model which can help an organization in supplier selection and order allocation minimizing the risk of disruption in current pandemic situation along with keeping

the cost of operations low. The proposed MOMILP contributes to the literature by proposing a model which can simultaneously handle the demand and supply side failures caused by the pandemic and re-allocates the orders to minimize the shortages of PPE.

The organization of rest of the paper is as follows. Section 2 provides the literature review. Section 3 presents research methodology with average supplier-risk matrix and proposes MOMILP for supplier selection and order allocation in a pandemic environment. The proposed methodology and mathematical model are illustrated using a case study of PPE in a pandemic model in Sect. 4 which highlights the robustness of the proposed MOMILP under different disruption scenarios. Section 5 presents theoretical contributions and managerial implications of this study. The paper is concluded and the future scope of work is discussed in Sect. 6.

## 2 Literature review and research gaps

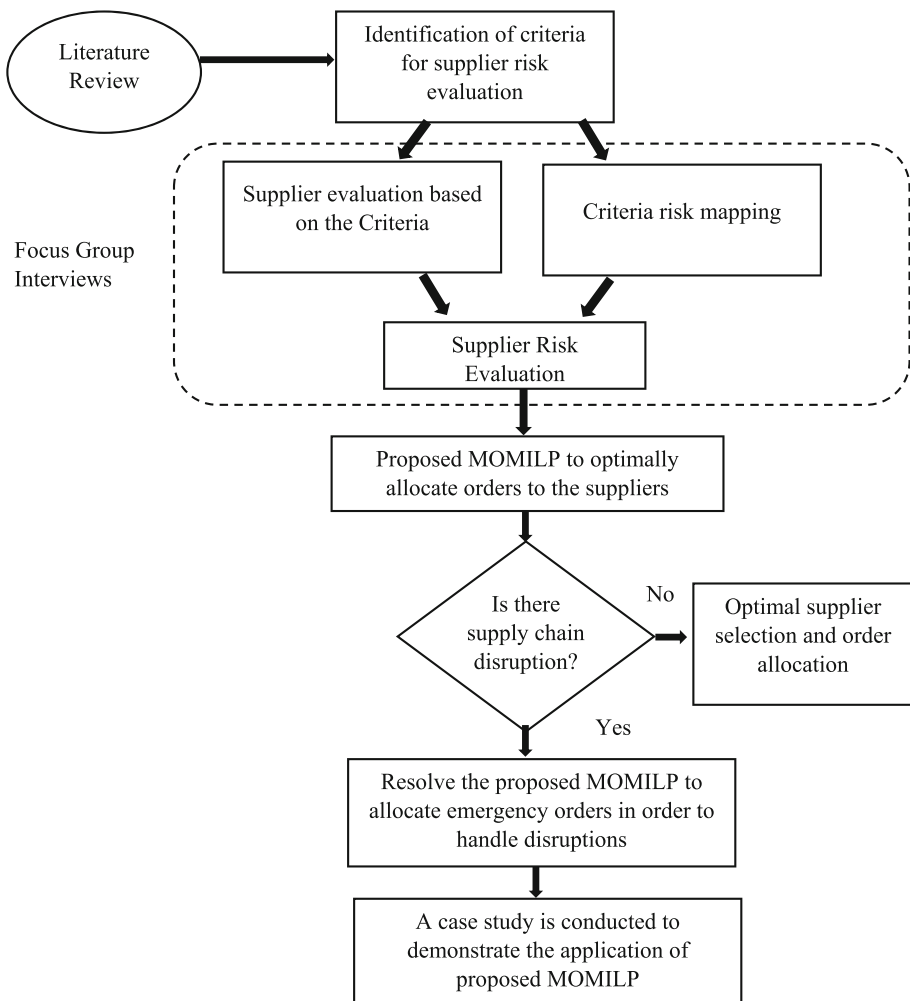
Dubey and Gunasekaran (2016) emphasized on the role of data driven decision making in supply chain and logistics operations impacting the timely delivery of medical supplies and food to the affected people. Similarly, various studies suggest that the impact of data driven decision making based on digital technologies such as big data, simulation, Industry 4.0, artificial intelligence, and block chain technology among others, has a huge impact in operations and supply chain management decisions during disruptive events (Dubey et al., 2021; Queiroz & Wamba, 2021; Talwar et al., 2021; Wamba & Queiroz, 2022). However, Modgil et al. (2021) revealed in their work that in spite of huge availability of data the application of artificial intelligence has been very limited in tackling pandemic COVID-19 and better resilience to supply chains in future is needed.

Mollenkopf et al. (2020) studied the role of supply chain ecosystem in ensuring the health safety of employees and customers during COVID-19. Research works such as, predicting the impact of COVID-19 disruptions, risks, and resilience on socio-economic wellbeing of global supply chains (El Baz & Ruel, 2021; Ivanov, 2020b; Karmaker et al., 2021), a mathematical model for demonstrating the strategies to ensure the sufficient service levels of COVID-19 vaccines (Sinha et al., 2021)), suggesting forecasting models based on real-time data of infections for timely policy making (Nikolopoulos et al., 2021)), developing a conceptual framework for redesigning supply chains through block chain technology in the pandemic environment (Nandi et al., 2021), and a study on twitter data of several firms concluding the demand–supply mismatch are few to mention (Sharma et al., 2020a, 2020b).

Rosales et al. (2019) carried out a study on dual sourcing and joint supplies of hospital items with suggestions for future studies to include more parameters for modelling to curb the risk of procurement in joint replenishment. Sharma et al. (2020a, 2020b) found an urgent attention to deal with the lack of resilience in supply chains during pandemic times. Choi (2021) conducted a review study and found the need of studying risk for managing logistics under COVID-19 outbreak. Chowdhury et al. (2021) explored through their review to conduct a study under various scenarios of a disruptive event in a real-world situation which may include inputs from exploratory studies and focused group discussions. In addition to this, few more studies revealed the lack of researches using real-time or simulation-based data driven decision making during disruptions of pandemic crisis (Majumdar et al., 2020; Queiroz & Wamba, 2021; Queiroz et al., 2020). Hence, this study has been carried out to bridge the important gap with our supplier network model considering risk enabled supply chain disruptions scenario with real-world qualitative and quantitative data of a pandemic.

### 3 Research methodology

In this study, a data driven optimization model (Talwar et al., 2021) is formulated and implemented for allocating the optimal quantities to different suppliers to keep the service levels high and minimize costs. This has been pictorially presented in Fig. 1. The criteria-risk mapping has been done to calculate the risk associate with each supplier (Chopra & Sodhi, 2004; Kaur & Singh, 2021); and used as an input to MOMILP model to incorporate the impact of both qualitative and quantitative data which has been a prime concern of Chauhan et al. (2022), Chowdhury et al. (2021), Pamucar et al. (2022) for studies during pandemic crisis. The detailed stepwise research methodology has been provided in the sub-sections below.



**Fig. 1** The proposed research methodology

### 3.1 Potential risk and their significance

#### 3.1.1 Criteria-risk mapping (Kaur & Singh, 2021)

Since, the criteria identified for selecting suppliers also help in tackling one or more supply chain risks associated to them. These supply chain risks are classified based on the work of Chopra and Sodhi (2004). Based on the nature of the criteria in this study, it has been found that the disruption risk, delays risk, receivables risk, inventory risk, and capacity risk are the one which can be mitigated with one or more criteria during the selection of a supplier in a pandemic situation. A brief explanation of these risks are as follows.

*Disruption risk:* This is a risk posed due to a natural-manmade disaster, pandemic and epidemics, and labour disputes, etc.

*Delays risk:* The risk which occurs as a result of logistics and transportation issues, border crossings, and high capacity utilization of supply sources.

*Receivables risk:* This risk is an outcome of customer base for a product and their financial condition for buying products when available for purchase.

*Inventory risk:* This risk is an outcome of uncertainties in demand and supply, inventory holding cost, and rate of product obsolesce.

*Capacity risk:* This risk is related to the expansion and contraction of a facility i.e. capacity flexibility and cost of capacity.

#### 3.1.2 Supplier risk calculation

The calculation of supplier-risk has been done with help of the work of Kaur and Singh (2021). They have suggested a six steps procedure for calculating the supplier risk. These steps are as follows.

*Step 1:*

The risk mitigation link is identified through criteria-risk matrix. It shows that which criteria helps in mitigating which particular risk. The binary values are put up in the matrix for binary variable  $w_{ki}$ . It assumes value as 1 if a criterion covers the particular risk  $k$  for an organization (distributor in our case); else 0. Therefore, the matrix  $W$  can be shown as given in Eq. (1).

$$W = \begin{vmatrix} w_{11} & w_{21} & w_{k1} \\ w_{12} & w_{22} & w_{k2} \\ w_{1i} & w_{2i} & w_{ki} \end{vmatrix} \quad w_{ki} \in \{0, 1\} \forall k, i \quad (1)$$

We can also calculate the column sum ( $\sum_i w_{ki}, \forall k$ ) as it helps in determining that how many criteria covers the risk of each kind for the company.

*Step 2:*

In this step, we calculate the supplier non-compliance values based on the aggregated ratings for all products. Afterwards, a non-compliance risk percentage is calculated for each supplier against each criterion using the expression given in Eq. (2).

$$R_{ij} = \frac{(\max \text{ rating} - x_{11})}{\max \text{ rating}} * 100 \quad \forall s, i \quad (2)$$

With the help of Eq. (2), the supplier-criteria risk matrix is developed as given in Eq. (3).

$$R_{ij} = \begin{vmatrix} N_{11} & N_{21} & N_{i1} \\ N_{12} & N_{22} & N_{i2} \\ N_{1j} & N_{2j} & N_{ij} \end{vmatrix} \quad (3)$$

*Step 3:*

We achieve a total-risk matrix in this step which is  $TNR_{kj}$ . This is obtained by the multiplication of  $w_{ki}$  and  $NR_{ij}$ .

$$TR_{kj} = [w_{ki}] * [R_{ij}] \quad (4)$$

*Step 4:*

Total risk matrix is normalized by dividing the values of matrix by the corresponding column sum which results into a normalized matrix  $NR_{kj}$  given in Eq. (5).

$$NR_{kj} = \begin{vmatrix} TR_{11}/\sum_i w_{1i} & TR_{21}/\sum_i w_{2i} & TR_{k1}/\sum_i w_{ki} \\ TR_{12}/\sum_i w_{1i} & TR_{22}/\sum_i w_{2i} & TR_{k2}/\sum_i w_{ki} \\ TR_{ij}/\sum_i w_{1i} & TR_{2j}/\sum_i w_{2i} & TR_{kj}/\sum_i w_{ki} \end{vmatrix} \quad (5)$$

*Step 5:*

Average risk associated with each supplier is calculated in this step. This is computed by taking the average of each row, here  $k$  denotes the risk type (given in column) and  $j$  represents the suppliers (rows). The formula for calculating average risk against each alternative (supplier) is given in Eq. (6).

$$Risk A_j = NR_{ik}/k \forall j \quad (6)$$

Finally, we obtained an average-risk which is associated with each supplier. This average risk for each supplier would be used as an input in the mixed integer linear program.

### 3.2 Multi objective mixed integer linear programming model (MOMILP) formulation

Sherif et al. (2021) recommended in his recent work on integrated optimization of transportation, routing, and inventory issues that multi-objective mathematical programming helps in incorporating qualitative dimensions of sustainability, risks, etc. for various supply chains. In this study, an MOMILP model has been formulated to sustainably allocate the PPE to pharmacies so that better service level can be maintained at their end and society can be benefitted at the fullest during and post-pandemic times.

## 4 Assumptions of model

- The nature of demand for PPE is stochastic with changing mean and variance due to the rapid spread of pandemic COVID-19.
- Suppliers supplying PPE receives a certain demand from distributors. Suppliers have a limited supplying capacity. However, for meeting the exigencies posed during the lockdown ending dates, a supplier maintains an additional 40% back up capacity for such emergency.
- Late delivery of PPE poses a threat of increasing coronavirus spread; therefore, the late deliveries are not allowed strictly. Additionally, a penalty cost is imposed for any shortages.

- The execution of emergency orders helps in containing the spread of COVID-19 among hospital staff.

**Model parameters**

$Q_{pst}$  Quantity of a PPE product ordered from supplier  $s$  in time period  $t$ .

$Q'_{pst}$  Quantity of a PPE product ordered for product  $p$  from supplier  $s$  in time period  $t$  during the emergency of lockdown.

$B_{pst}$  Binary variable which takes value 1 if PPE product is ordered from supplier  $s$  in time period  $t$  otherwise 0.

$J_{pst}$  Binary variable which assumes value 1 if the order is placed for a PPE product  $p$  from supplier  $s$  in time period  $t$  during the emergency surfaced from lockdown relaxation otherwise 0.

$Inv_{pt}$  Inventory carried for a PPE product  $p$  during time period  $t$ .

$SO_{pt}$  Stock-out of a PPE product  $p$  occurred in  $t$  time period.

**Notations**

$TPC_{pst}$  Unit price of a PPE product  $p$  ordered from supplier  $s$  in time period  $t$ .

$TPC'_{pst}$  Increased unit price for emergency orders of a PPE product  $p$  ordered from supplier  $s$  during lockdown relaxation period  $t$ .

$RCOV_s$  Risk associated with a supplier  $s$  due to the spread of pandemic.

$RCos_s$  Risk cost associated with supplier  $s$  during pandemic.

$CO_{pst}$  Cost of ordering PPE product  $p$  from supplier  $s$  in time period  $t$ .

$LTC_{pst}$  Logistics and transportation cost incurred in accepting the delivery of a PPE product  $p$  from supplier  $s$  in time period  $t$ .

$CH_{pt}$  Unit holding cost of a PPE product  $p$  in time period  $t$ .

$CA_{pst}$  Additional capacity offered for a PPE product  $p$  by a supplier in time period  $t$ .

$BC_{pst}$  Back up suppliers made available by a PPE supplier  $s$  for product  $p$  in time period  $t$ .

$F_{Dpt}^{-1}$  Constant inverse demand function for given mean, standard deviation, and probability of meeting the demand.

$\alpha_{pt}$  Service level i.e. probability of meeting the demand for product  $p$  in time period  $t$ .

$Pe_{pt}$  Cost for penalty due to shortages incurred in time period  $t$ .

Hence, the supplier selection and order allocation model during a pandemic situation can be formulated as a multi objective mixed integer linear program (MOMILP) which is as follows:

$$\begin{aligned}
 Z_{min} = & \sum_p \sum_s \sum_t (TPC_{pst} * Q_{pst} + TPC'_{pst} * Q'_{pst}) \\
 & + \sum_p \sum_s \sum_t CO_{pst} * (B_{pst} + J_{pst}) + \sum_p \sum_s \sum_t LTC_{pst} * (Q_{pst} + Q'_{pst}) \\
 & + \sum_p \sum_t CH_{pt} * Inv_{pt} \\
 & + \sum_p \sum_t Pe_{pt} * SO_{pt} + \sum_p \sum_s \sum_t RCOV_s * RCos_s (B_{pst} + J_{pst}) \tag{7}
 \end{aligned}$$

Subject to,

$$Inv_{p(t-1)} + \sum_s Q_{pst} + \sum_s Q'_{pst} - F_{Dpt}^{-1}(\alpha_{pt}) - Inv_{pt} + SO_{pt} = 0 \quad \forall p, t \tag{8}$$

$$Q'_{pst} \leq ((CA_{pst} - Q_{pst}) + BC_{pst}) * J_{pst} \quad \forall p, s, t \tag{9}$$

$$RCOV_s * J_{pst} \leq 0.5 \quad \forall p, t \quad (10)$$

$$Q_{pst}, Q'_{pst}, Inv_{pt}, CH_{pt} \text{ are integers} \quad \forall p, s, t \quad (11)$$

$$B_{pst} \in \{0, 1\} \text{ and } J_{pst} \in \{0, 1\} \quad \forall p, s, t \quad (12)$$

The objective function of our mixed integer linear program which is given by Eq. (7) minimizes the total cost of procuring PPE from suppliers, this total cost includes purchasing cost, cost of transporting the regular and pandemic influenced orders, holding cost of PPE, costs due to stock-out penalties, and risk cost associated with the spread of pandemic to suppliers. Equation (8) shows the constraint on balancing inventory on hand with regular and emergency orders due to pandemic, current inventory and stockouts. Equation (9) represents the capacity constraint for emergency orders received due to pandemic spread. This has been found that the suppliers of PPE are very flexible in their capacity expansion and contraction; therefore, they are able to provide 40% extended capacity for tackling orders during pandemic time. The surged orders due to pandemic can be placed with existing regular suppliers as well as backup suppliers available in the market. Since, the pandemic situation is extremely difficult, therefore, the risk associated with orders during pandemic is considered to be working if it falls within the range of 50% i.e. it should be less than 50% as given in Eq. (10). The variables for regular and emergency orders during pandemic, inventory, and stockouts are integer in nature which is denoted by Eq. (11). Lastly, the binary integers for regular and emergency orders during pandemic orders' supplier selection are given in Eq. (12).

## 5 Case study

The proposed MOMILP is used for to optimize supplier selection and order allocation for PPE by a government hospital and medical institute in Jalandhar, Punjab. This government hospital has a pool of suppliers which are mostly MSME units from Ludhiana, Delhi-NCR and Coimbatore. The hospital needs a continuous supply of PPE throughout the year, however, during certain unexpected events such as a pandemic demand of these products increase manifold. In other cases, such as lockdowns or travel restrictions, procurement of these products becomes quite challenging and is often delayed which leads to dissatisfaction among the hospital staff. The hospital management is keen to identify the evaluate the set of suppliers on their risk and optimize the order allocation in order to jointly minimize the procurement cost and the risk while procuring. In addition, the management would like to have a flexibility and visibility in the order allocation plan to efficiently handle both supply and demand side disruptions by issuing emergency orders. Therefore, to evaluate the suppliers on their ability to minimize the risk of disruption in case of any unforeseen and optimally allocate orders, models discussed in Sects. 3.1 and 3.2 are used and results are discussed in Sect. 4.1.

## 6 Results and discussion

With the help of experts such as supply chain consultants and distributors dealing with medical supplies, the criteria-risk matrix is prepared which is shown in Table 1. The matrix provides the understanding of how various criteria can influences a particular type of risk for the organization. If the value is "1" then criteria influences the risk type. In case of no influence, it is shown by "0". In order to evaluate supplier performance of different criteria, suppliers



**Table 1** Criteria-risk mapping

Criteria	Disruptions risk (R1)	Delays risk (R2)	Receivables risk (R3)	Inventory risk (R4)	Capacity risk (R5)
Lead Time of PPE (Chiu et al., 2020; Dasaklis et al., 2012) (C1)	1	1	0	1	1
Quality of PPE supplied (Qin et al., 2017) (C2)	0	1	1	1	0
Cost of PPE (Chauhan & Singh, 2021) (C3)	0	0	1	1	0
Social conscience of PPE (Kellner et al., 2019) (C4)	0	1	1	0	0
Response of panic buying of PPE (Sim et al., 2020) (C5)	1	1	0	1	0
logistics Network (Sherif et al., 2021) (C6)	1	1	0	1	0
Disinfection of vehicles (Vasilakis, 2020) (C7)	1	1	0	0	0
Brand of PPE (Xu et al., 2020) (C8)	0	0	1	1	1

are rated on the Likert scale (1 to 5) and cost values for three main PPE items i.e. face masks, hand sanitizers, and hand wash, are given. The ratings are provided for suppliers against each of the criterion for face masks in Table 4, hand sanitizers in Table 5, and hand wash in Table 6, respectively. Table 7 provides the ideal and negative ideal values of criteria against all the suppliers for all type of PPE. Table 8 shows the supplier-criteria common matrix for all PPE suppliers. Furthermore, the computations for Supplier-Criteria Risk Matrix, Total risk matrix with respect to criteria, Supplier-risk evaluation, Average supplier-risk matrix, and Supplier Average Risk Calculation, are given in Tables 2, 9, 10, 11, and 12, respectively. Tables 1 and 2 are given below wherein Tables 4, 5, 6, 7, 8, 9, 10, 11, and 12 which majorly contains the computational steps are appended in the Appendix 1.

The proposed MOMILP is used to optimize the multi-period, multi-item supplier selection and order allocation for PPE items in the hospital. In last two years, hospital has witnessed disruptions both from demand as well as supply side. The data considered to solve the model is benchmarked with the data provided by the hospital, However, the actual data has been masked to protect the organization's data. The model is first solved using the normal demand characteristics to optimally allocate orders to the selected suppliers simultaneously minimizing cost and risk associated with the procurement. The model is then solved under various disruption scenarios simulated using circumstances faced by the hospital administration during COVID 19 pandemic. In some cases, if demand is normal, the supplier side disruptions

**Table 2** Supplier average risk calculation

	R1 (%)	R2 (%)	R3 (%)	R4 (%)	R5 (%)	Average risk (%)
S1	34.51	24.12	12.75	28.18	51.25	30.16
S2	38.06	30.93	21.67	34.26	58.33	36.65
S3	45.00	44.44	41.75	41.17	50.00	44.47
S4	56.25	49.72	36.67	44.17	51.39	47.64
S5	56.88	50.14	41.33	52.14	69.58	54.01
S6	61.74	58.94	56.72	58.97	48.47	56.97

are observed due to manpower shortage or production halts as a result of lockdown. In other cases, the supplier capacity is there, however sudden increase in demand is observed due to rise in COVID cases coming to the hospital. For some extreme cases, both demand side and supply side disruptions are simultaneously observed. The proposed MOMILP can be extended for order allocation and emergency order allocation under different scenarios to minimize the cost and risk. Each scenario is solved on a same problem i.e. for six period planning horizon and for eight different products and six suppliers. The model is coded and solved in Lingo\_10. The problem is initially solved without any disruption for the purpose of comparison with different disruption scenarios.

### 6.1 Scenario I: When COVID-19 leads to no disruption in supplier selection process

In this scenario, it is assumed that COVID-19 caused no disruption in supply or demand side of the supplier selection and order allocation process i.e. all suppliers are working with the same capacity and demand is also same as before. The model is solved and the complete supplier selection and order allocation for the entire planning horizon is provided in Table 13. It can be noted that at this stage all the orders are the regular planned orders which suppliers will be able to supply without any disruption. The buffer capacity available with suppliers has not been used. The total cost of procurement at this stage is INR 6,110,588. The cost obtained is the combination of ordering, purchasing and holding. There are no shortages observed in this case. It is also observed from the Table 13, given in Appendix 2, that dynamic lot-sizing is used to fulfil the stochastic demand.

### 6.2 Scenario II: When COVID-19 leads to demand disruptions

In this scenario, it is assumed that the distributor faces the demand side disruptions due to significant increase in demand of healthcare products. In this scenario, supplies capacity is limited, however, suppliers tend to offer the buffer capacity which is a certain proportion of their initial projected capacity. Therefore, if supplier capacity is not sufficient, emergency orders are issued to the supplies along with the regular orders to meet the demand disruptions and minimize the stockouts as much as possible. On solving the proposed MOMILP, it is observed that the total cost of procurement is INR 18,703,640. The results also show that emergency orders are also allocated in addition to regular orders to cater to the amplified demand for almost all of the products. Therefore, total cost of procurement includes cost of ordering, prices and holding for regular as well as emergency orders along with the penalty

cost on unmet demand. The total shortages are estimated to be 900 units. The increased demand, the regular and emergency orders issued and the complete supplier selection is shown in the Table 14, given in Appendix 2.

### 6.3 Scenario III: When COVID-19 leads to supplier capacity failure

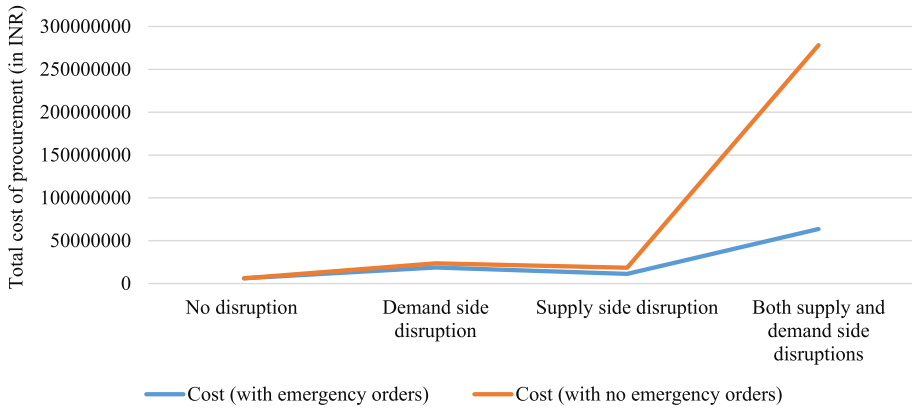
In this case, it is assumed that the distributor is facing disruptions from the supply side. Some suppliers are not operating due to the restrictions or lockdown imposed by the government in view of COVID-19. In this scenario, it may happen that the remaining supplier capacity is not sufficient to meet the demand. In such case the remaining suppliers tend to offer some buffer capacity. In this scenario, it is observed that the supplier S4 and S5 are disrupted and will not be able to supply the regular orders allocated to them, failing which will result in stockouts. To prevent it from happening, proposed MOMILP allocates emergency orders to suppliers with remaining or backup capacity left to close the gap between demand and supply as much as possible. The total cost of procurement in this case is observed to be INR 11,343,320 which includes the cost of ordering, holding and unit cost for regular as well as emergency orders along with penalty cost on shortages. The number of stockouts observed is 2890 and the cost stockouts is INR 1,445,000. The regular and emergency orders along with complete supplier selection is provided in Table 15, given in Appendix 2.

### 6.4 Scenario IV: When COVID-19 leads to both demand disruptions and supplier failures simultaneously

In scenario IV, it is assumed that the distributor is facing the disruptions from both the sides. The demand is significantly increased due to COVID-19 and the suppliers S4 and S5 are disrupted because of the lockdown and inability of the suppliers to function. Again, it is assumed that the undisrupted suppliers are offering a buffer capacity which is 20% of their initial projected capacity. However, in this case due to the scale of disruptions it can happen that stockouts are huge. Upon solving the proposed MOMILP for this scenario, it is observed that total cost of procurement including the cost of stockouts is INR 63,674,810. The total cost includes the total cost of procurement for regular and emergency orders and the penalty cost on the stockouts. The number of stockouts are 86,456. The ordering pattern and supplier selection for both regular and emergency orders is provided in Table 16, given in Appendix 2.

It is observed from all four scenarios that demand and supply side disruptions affects the ability of the hospital to meet the demand. However, the proposed MOMILP minimizes the stockouts of the critical PPE by responding quickly and issuing emergency orders to the suppliers which are not disrupted. Figure 2 compares the cost if the MOMILP when emergency orders are issued to traditional and rigid mathematical solution when only fixed regular orders are issued. It is seen that if the order allocation decisions are not flexible and no emergency orders are issued, there will be huge shortages and hence penalty on these shortages will be huge. However, when emergency orders are issued as per the proposed MOMILP, the shortages are less and hence total cost is also less.

Table 3 also explains the cost comparison when proposed MOMILP is used to handle disruptions efficiently and effectively by allocating emergency orders to undisrupted suppliers with the case when no proactive measure is in place to handle disruptions. From the table, it is evident that the total cost of procurement will increase when emergency orders are used to meet demand or supply disruptions. However, it can also be seen from the table that when



**Fig. 2** Cost comparison for the different scenarios using proposed MOMILP and when no emergency orders are issued

**Table 3** Cost comparison under different disruption scenarios with traditional approach

	Cost (with emergency orders) (INR)	Cost (with no emergency orders) (INR)	Extra cost incurred if no emergency orders are issued
No disruption	6,110,588	6,110,588	
Demand side disruption	18,703,640	4,956,948	27%
Supply side disruption	11,343,320	7,043,268	62%
Both supply and demand side disruptions	63,674,810	214,604,778	337%

proactive measures are not used the total cost can be even higher ranging from 27 to 337% depending upon the extend of disruption.

## 7 Implications of the study

### 7.1 Managerial implications

The large and complex qualitative and quantitative data collected and analysed using the proposed network model for flexible supplier selection enables the hospital administration for data driven decision making in future. The digital technologies application in collecting the real-time error-free data and information brings a double advantage in terms of modelling and execution for the practitioner's purpose (Dubey et al., 2021). The proposed model to compute overall supplier risk can help companies in assessing the risk in their supplier networks. The proposed risk-enabled MOMILP model can help companies in maintaining a flexible supplier network approach towards supplier selection and order allocation especially during the time

of pandemic. The managers will be able to minimize overall cost of operations along with the risks under disruptions in selecting suppliers and allocating orders. The proposed model proactively mitigates the risk of disruption by selecting the suppliers with low risk and handles supply or demand side disruptions by reallocating the orders to minimize the shortages and total operational costs. Hence, companies can maintain business continuity by reacting to the disruptions and close the gap between demand and supply in the most cost-efficient manner.

## 7.2 Theoretical contributions

This study solidifies the fact that the findings obtained with the help of data driven optimization modelling is an outcome of the amalgamation of digital technologies with mathematical modelling; Hence, this contribution will enrich the literature of the application of digital technologies and real time data to effectively handle the unprecedented challenges of disruptive events. Additionally, this paper identifies the risks in the supply chains of PPE and establishes interlinkages among these risks. Hence, the proposed methodology to compute overall risk of dealing with a supplier under disruptive events contributes to the body of knowledge under disruptive events. Furthermore, the paper develops an MOMILP model for optimizing the supplier selection and order allocation in a pandemic environment considering both supply and demand side failures to minimize the risk of disruptions and overall operational costs.

## 8 Conclusions and future scope of work

This paper proposes a data driven flexible model for supplier selection and order allocation problem in a pandemic environment, where there are disruptions on both supply and demand side. The supplier risk is estimated using a MCDM based approach and is used to allocate orders to the suppliers. In case of disruption, the model has the flexibility to incorporate supply side failures and demand shifts and promptly revise the allocations and issue emergency orders to the existing suppliers against reserved capacity to minimize the stockouts. Through our case study, we observed that it is essential for a PPE supply chain to maintain business continuity and avoid stockouts to provide better health care support to the people. The detailed computational analysis presents different scenarios showing how the proposed MOMILP reallocates the orders of PPE under demand and supply side disruptions to minimize the shortages and overall operational cost. The findings show that the proposed flexibility in supplier selection and order allocation model can result in significant reduction in stockouts and overall cost compared to the static version to same model. The research can be extended to add lead time considerations given the criticality of certain items in health sector. This work can be further extended to incorporate joint routing activities in collaboration with other hospitals to jointly optimize the supply network and secure suppliers at the district or state level. However, with introduction of many variables the problem may not be solved using exact methods, hence, metaheuristics can be proposed for the same (See Tables 4, 5, 6, 7, 8, 9, 10, 11, 12, See Tables 13, 14, 15, 16).

## Appendix 1

See Tables 4, 5, 6, 7, 8, 9, 10, 11, 12.

**Table 4** Face Masks (SCE1)

	C1	C2	C3	C4	C5	C6	C7	C8
S1	60	5	200	5	2	10	5	5
S2	36	4	150	4	2	12	5	5
S3	24	3	100	3	2	6	2	4
S4	28	3	100	2	3	5	2	4
S5	12	2	40	4	1	7	1	1
S6	12	3	48	4	5	1	1	2

**Table 5** Hand Sanitizer (SCE2)

	C1	C2	C3	C4	C5	C6	C7	C8
S1	96	5	105	5	1	8	4	5
S2	72	4	100	5	1	7	4	5
S3	36	4	92	2	4	8	3	3
S4	36	3	95	4	3	4	2	4
S5	24	3	92	3	2	5	4	3
S6	8	2	85	2	4	2	2	3

**Table 6** Hand Wash (SCE3)

	C1	C2	C3	C4	C5	C6	C7	C8
S1	48	5	196	4	1	10	4	5
S2	36	5	170	3	2	9	4	5
S3	36	3	165	2	4	10	3	5
S4	24	4	225	3	4	7	1	4
S5	24	4	300	3	3	9	3	5
S6	8	2	105	1	5	3	2	3

**Table 7** Ideal and negative ideal value for all criteria

	C1	C2	C3	C4	C5	C6	C7	C8
Max Value	96	5	300	5	5	12	5	5
Min value	8	2	40	1	1	1	1	1

**Table 8** Supplier-Criteria Common Matrix for all PPE suppliers

	C1	C2	C3	C4	C5	C6	C7	C8
S1	68.00	5.00	167.00	4.67	1.33	9.33	4.33	5.00
S2	48.00	4.33	140.00	4.00	1.67	9.33	4.33	5.00
S3	32.00	3.33	119.00	2.33	3.33	8.00	2.67	4.00
S4	29.33	3.33	140.00	3.00	3.33	5.33	1.67	4.00
S5	20.00	3.00	144.00	3.33	2.00	7.00	2.67	3.00
S6	9.33	2.33	79.33	2.33	4.67	2.00	1.67	2.67

**Table 9** Supplier-Criteria Risk Matrix

	C1	C2	C3	C4	C5	C6	C7	C8
S1	29.17%	0.00%	44.33%	6.67%	73.33%	22.22%	13.33%	0.00%
S2	50.00%	13.33%	53.33%	20.00%	66.67%	22.22%	13.33%	0.00%
S3	66.67%	33.33%	60.33%	53.33%	33.33%	33.33%	46.67%	20.00%
S4	69.44%	33.33%	53.33%	40.00%	33.33%	55.56%	66.67%	20.00%
S5	79.17%	40.00%	52.00%	33.33%	60.00%	41.67%	46.67%	40.00%
S6	90.28%	53.33%	73.56%	53.33%	6.67%	83.33%	66.67%	46.67%

**Table 10** Total risk matrix w.r.t. criteria

	R1	R2	R3	R4	R5
C1	1	1	0	1	1
C2	0	1	1	1	0
C3	0	0	1	1	0
C4	0	1	1	0	0
C5	1	1	0	1	0
C6	1	1	0	1	0
C7	1	1	0	0	0
C8	0	0	1	1	1
Sum	4	6	4	6	2

**Table 11** Supplier-risk evaluation

	R1	R2	R3	R4	R5
S1	1.38	1.45	0.51	1.69	0.29
S2	1.52	1.86	0.87	2.06	0.50
S3	1.80	2.67	1.67	2.47	0.87
S4	2.25	2.98	1.47	2.65	0.89
S5	2.28	3.01	1.65	3.13	1.19
S6	2.47	3.54	2.27	3.54	1.37

**Table 12** Average supplier-risk matrix

	R1	R2	R3	R4	R5	Average Risk
S1	0.35	0.24	0.13	0.28	0.15	0.23
S2	0.38	0.31	0.22	0.34	0.25	0.30
S3	0.45	0.44	0.42	0.41	0.43	0.43
S4	0.56	0.50	0.37	0.44	0.45	0.46
S5	0.57	0.50	0.41	0.52	0.60	0.52
S6	0.62	0.59	0.57	0.59	0.68	0.61

## Appendix 2: Scenario wise computations and comparisons

See Tables [13](#), [14](#), [15](#), [16](#).



Table 13 Order allocation and supplier selection when COVID-19 leads to no disruption

	T1	T2	T3	T4	T5	T6
P1						
Stochastic demand	2785	3324	3550	2262	3113	1792
Order lot size (Regular)	2785	3900	3410	2579	2360	1792
Supplier selection	$X(1, 1, 5) = 1460X(1, 1, 6) = 1140X(2, 1, 1) = 1060X(2, 1, 2) = 1460X(2, 1, 3) = 1380X(3, 1, 1) = 1090X(3, 1, 3) = 1020X(3, 1, 5) = 1300X(4, 1, 1) = 1239X(4, 1, 4) = 1340X(5, 1, 3) = 1060X(5, 1, 5) = 1300X(6, 1, 3) = 980X(6, 1, 4) = 812$					
P2						
Stochastic demand	1842	3057	3262	3617	1209	2719
Order lot size (Regular)	3026	2030	3250	3520	1390	2490
Supplier selection	$X(1, 2, 1) = 910X(1, 2, 2) = 616X(1, 2, 5) = 1500X(2, 2, 2) = 910X(2, 2, 3) = 1120X(3, 2, 2) = 860X(3, 2, 4) = 900X(3, 2, 5) = 1490X(4, 2, 1) = 1470X(4, 2, 4) = 880X(4, 2, 5) = 1170X(5, 2, 6) = 1390X(6, 2, 3) = 1270X(6, 2, 6) = 1220$					
P3						
Stochastic demand	1764	3391	3893	3341	1864	3785
Order lot size (Regular)	2840	4339	2460	2750	3129	2520
Supplier selection	$X(1, 3, 4) = 1450X(1, 3, 5) = 1390X(2, 3, 1) = 1210X(2, 3, 3) = 800X(2, 3, 4) = 859X(2, 3, 6) = 1470X(3, 3, 3) = 1230X(3, 3, 5) = 1230X(4, 3, 2) = 1420X(4, 3, 3) = 1330X(5, 3, 2) = 749X(5, 3, 5) = 1260X(5, 3, 6) = 1120X(6, 3, 4) = 1340X(6, 3, 5) = 1180$					
P4						
Stochastic demand	2187	1231	1768	2269	2460	3449
Order lot size (Regular)	2187	1231	4040	0	2457	3449
Supplier selection	$X(1, 4, 2) = 17X(1, 4, 4) = 950X(1, 4, 6) = 1220X(2, 4, 4) = 870X(2, 4, 5) = 361X(3, 4, 2) = 1500X(3, 4, 4) = 1060X(3, 4, 6) = 1480X(5, 4, 2) = 1247X(5, 4, 6) = 1210X(6, 4, 2) = 899X(6, 4, 3) = 1320X(6, 4, 5) = 1230$					
P5						
Stochastic demand	3800	2580	2742	1695	2585	3154
Order lot size (Regular)	3800	3262	2060	1695	3669	2070
Supplier selection	$X(1, 5, 2) = 960X(1, 5, 3) = 680X(1, 5, 4) = 820X(1, 5, 6) = 1340X(2, 5, 1) = 352X(2, 5, 2) = 950X(2, 5, 4) = 1130X(2, 5, 5) = 830X(3, 5, 5) = 850X(3, 5, 6) = 1210X(4, 5, 3) = 820X(4, 5, 6) = 875X(5, 5, 1) = 1310X(5, 5, 2) = 1010X(5, 5, 3) = 359X(5, 5, 6) = 990X(6, 5, 2) = 850X(6, 5, 5) = 1220$					

Table 13 (continued)

	T1	T2	T3	T4	T5	T6
P6						
Stochastic demand	3689	2703	1360	3288	2454	3726
Order lot size (Regular)	3689	3040	1751	2780	3030	2930
Supplier selection	$X(1, 6, 1) = 1070X(1, 6, 2) = 820X(1, 6, 3) = 839X(1, 6, 6) = 960X(2, 6, 1) = 850X(2, 6, 4) = 1310X(2, 6, 6) = 880X(3, 6, 4) = 1070X(3, 6, 6) = 681X(4, 6, 1) = 920X(4, 6, 4) = 1000X(4, 6, 6) = 860X(5, 6, 2) = 900X(5, 6, 3) = 910X(5, 6, 5) = 1220X(6, 6, 1) = 1020X(6, 6, 2) = 1030X(6, 6, 6) = 880$					
P7						
Stochastic demand	3400	2559	1835	1512	3707	2481
Order lot size (Regular)	3400	2559	2465	2410	4660	0
Supplier selection	$X(1, 7, 2) = 1030X(1, 7, 4) = 1180X(1, 7, 5) = 1190X(2, 7, 1) = 960X(2, 7, 5) = 369X(2, 7, 6) = 1230X(3, 7, 3) = 1055X(3, 7, 5) = 1410X(4, 7, 1) = 920X(4, 7, 2) = 1490X(5, 7, 1) = 1130X(5, 7, 3) = 1360X(5, 7, 4) = 840X(5, 7, 6) = 1330$					
P8						
Stochastic demand	1899	2179	2920	1563	3514	3374
Order lot size (Regular)	1899	2390	3400	1030	3620	3110
Supplier selection	$X(1, 8, 1) = 869X(1, 8, 3) = 1030X(2, 8, 1) = 1340X(2, 8, 6) = 1050X(3, 8, 2) = 1110X(3, 8, 3) = 1420X(3, 8, 5) = 870X(4, 8, 2) = 1030X(5, 8, 1) = 1480X(5, 8, 4) = 1090X(5, 8, 5) = 1050X(6, 8, 3) = 940X(6, 8, 4) = 1340X(6, 8, 5) = 830$					

Table 14 Order allocation and supplier selection when COVID-19 leads to demand disruptions

	T1	T2	T3	T4	T5	T6
P1						
Increased Demand	6236	6299	5120	5900	5349	6030
Regular order lot size	5250	5340	4660	5210	5000	4910
Emergency order lot size	991	1283	528	293	851	618
Supplier selection	$X(1, 1, 2) = 1170 X(1, 1, 3) = 1480 X(1, 1, 5) = 1460 X(1, 1, 6) = 1140 X(2, 1, 1) = 1060 X(2, 1, 2) = 1460 X(2, 1, 3) = 1380 X(2, 1, 4) = 1440 X(3, 1, 1) = 1090 X(3, 1, 3) = 1020 X(3, 1, 4) = 1250 X(3, 1, 5) = 1300 X(4, 1, 1) = 1340 X(4, 1, 4) = 1340 X(4, 1, 5) = 1360 X(4, 1, 6) = 1170 X(5, 1, 1) = 1430 X(5, 1, 3) = 1060 X(5, 1, 4) = 1210 X(5, 1, 5) = 1300 X(6, 1, 1) = 1150 X(6, 1, 3) = 980 X(6, 1, 4) = 1320 X(6, 1, 5) = 1460 E(1, 1, 1) = 51 E(1, 1, 3) = 370 E(1, 1, 4) = 205 E(1, 1, 5) = 365 E(2, 1, 1) = 265 E(2, 1, 3) = 345 E(2, 1, 4) = 360 E(2, 1, 6) = 313 E(3, 1, 1) = 273 E(3, 1, 3) = 255 E(4, 1, 6) = 293 E(5, 1, 1) = 283 E(5, 1, 3) = 265 E(5, 1, 4) = 303 E(6, 1, 1) = 288 E(6, 1, 4) = 330$					
P2						
Increased demand	5443	5720	6229	6590	5849	6436
Regular order lot size	4810	4950	4440	5040	5360	5160
Emergency order lot size	1180	1238	1063	1261	823	942
Supplier selection	$X(1, 2, 1) = 910 X(1, 2, 2) = 1240 X(1, 2, 5) = 1500 X(1, 2, 6) = 1160 X(2, 2, 1) = 1260 X(2, 2, 3) = 1120 X(2, 2, 5) = 1280 X(2, 2, 6) = 1290 X(3, 2, 1) = 1090 X(3, 2, 3) = 930 X(3, 2, 5) = 1490 X(3, 2, 6) = 930 X(4, 2, 1) = 1470 X(4, 2, 2) = 1140 X(4, 2, 5) = 1170 X(4, 2, 6) = 1260 X(5, 2, 2) = 1480 X(5, 2, 4) = 1390 X(5, 2, 5) = 1100 X(5, 2, 6) = 1390 X(6, 2, 1) = 1310 X(6, 2, 2) = 1360 X(6, 2, 3) = 1270 X(6, 2, 6) = 1220 E(1, 2, 2) = 310 E(1, 2, 3) = 205 E(1, 2, 5) = 375 E(1, 2, 6) = 290 E(2, 2, 1) = 315 E(2, 2, 3) = 280 E(2, 2, 5) = 320 E(2, 2, 6) = 323 E(3, 2, 1) = 250 E(3, 2, 2) = 215 E(3, 2, 4) = 225 E(3, 2, 5) = 373 E(4, 2, 1) = 368 E(4, 2, 2) = 285 E(4, 2, 3) = 293 E(4, 2, 6) = 315 E(5, 2, 3) = 200 E(5, 2, 5) = 275 E(5, 2, 6) = 348 E(6, 2, 1) = 328 E(6, 2, 3) = 41 E(6, 2, 5) = 268 E(6, 2, 6) = 305$					

Table 14 (continued)

	T1	T2	T3	T4	T5	T6
P3						
Increased demand	5635	5366	5251	6076	5499	5534
Regular order lot size	5600	5210	5120	5420	5010	5290
Emergency order lot size	35	303	455	308	610	0
Supplier selection	$X(1, 3, 2) = 1410 X(1, 3, 4) = 1450 X(1, 3, 5) = 1390 X(1, 3, 6) = 1350 X(2, 3, 1) = 1210 X(2, 3, 2) = 1480 X(2, 3, 4) = 1050 X(2, 3, 6) = 1470 X(3, 3, 1) = 1340 X(3, 3, 3) = 1230 X(3, 3, 4) = 1320 X(3, 3, 5) = 1230 X(4, 3, 2) = 1420 X(4, 3, 3) = 1330 X(4, 3, 4) = 1440 X(4, 3, 5) = 1230 X(5, 3, 2) = 1330 X(5, 3, 3) = 1300 X(5, 3, 5) = 1260 X(5, 3, 6) = 1120 X(6, 3, 1) = 1390 X(6, 3, 2) = 1380 X(6, 3, 4) = 1340 X(6, 3, 5) = 1180 E(1, 3, 6) = 35E(2, 3, 1) = 303E(3, 3, 1) = 147E(3, 3, 3) = 308E(4, 3, 5) = 308E(5, 3, 3) = 325E(5, 3, 4) = 285$					
P4						
Increased Demand	6600	6220	5596	5607	5198	5720
Regular order lot size	5290	4710	5280	4620	5470	5270
Emergency order lot size	1303	1139	775	528	178	0
Supplier selection	$X(1, 4, 2) = 1160 X(1, 4, 3) = 1420 X(1, 4, 5) = 1490 X(1, 4, 6) = 1220 X(2, 4, 1) = 1400 X(2, 4, 2) = 1230 X(2, 4, 5) = 990 X(2, 4, 6) = 1090 X(3, 4, 2) = 1500 X(3, 4, 3) = 1240 X(3, 4, 4) = 1060 X(3, 4, 6) = 1480 X(4, 4, 2) = 1050 X(4, 4, 3) = 1070 X(4, 4, 5) = 1170 X(4, 4, 6) = 1330 X(5, 4, 1) = 1280 X(5, 4, 2) = 1500 X(5, 4, 3) = 1480 X(5, 4, 6) = 1210 X(6, 4, 2) = 1370 X(6, 4, 3) = 1320 X(6, 4, 4) = 1350 X(6, 4, 5) = 1230 E(1, 4, 1) = 270E(1, 4, 3) = 355E(1, 4, 5) = 373E(1, 4, 6) = 305E(2, 4, 1) = 350E(2, 4, 2) = 308E(2, 4, 3) = 208E(2, 4, 6) = 273E(3, 4, 1) = 250E(3, 4, 2) = 375E(3, 4, 4) = 150E(4, 4, 3) = 268E(4, 4, 4) = 260 E(5, 4, 1) = 178$					
P5						
Increased demand	3800	5950	5644	6073	5575	5101
Regular order lot size	4340	4780	5430	4700	4800	4490
Emergency order lot size	440	534	710	900	581	438

Table 14 (continued)

	T1	T2	T3	T4	T5	T6
Supplier selection	$X(1, 5, 2) = 960 X(1, 5, 3) = 1220 X(1, 5, 4) = 820 X(1, 5, 6) = 1340X(2, 5, 1) = 1300 X(2, 5, 2) = 950 X(2, 5, 3) = 1400 X(2, 5, 4) = 1130 X(3, 5, 2) = 1380X(3, 5, 3) = 1400X(3, 5, 4) = 1440X(3, 5, 6) = 1210 X(5, 5, 1) = 1310X(5, 5, 2) = 1010X(5, 5, 3) = 1250X(5, 5, 4) = 1230 X(6, 5, 2) = 850X(6, 5, 4) = 1490X(6, 5, 5) = 1220X(6, 5, 6) = 930 E(1, 5, 1) = 235E(1, 5, 4) = 205E(2, 5, 1) = 325E(2, 5, 6) = 209E(3, 5, 3) = 350E(3, 5, 4) = 360E(4, 5, 2) = 305E(4, 5, 5) = 315E(4, 5, 6) = 280E(5, 5, 1) = 328E(5, 5, 2) = 253E(6, 5, 2) = 213E(6, 5, 3) = 225$					
P6	5335	6370	5448	6209	6733	4948
Increased demand						
Regular order lot size	4870	4830	4360	4980	4820	4870
Emergency order lot size	1198	1167	973	1246	1129	78
Supplier selection	$X(1, 6, 1) = 1070 X(1, 6, 3) = 1320 X(1, 6, 4) = 1040 X(1, 6, 5) = 1440X(2, 6, 2) = 1020 X(2, 6, 3) = 1190 X(2, 6, 4) = 1310 X(2, 6, 5) = 1310 X(3, 6, 1) = 960X(3, 6, 3) = 1200X(3, 6, 4) = 1070X(3, 6, 6) = 1130 X(4, 6, 2) = 1440X(4, 6, 3) = 1250X(4, 6, 4) = 1000X(4, 6, 5) = 1290 X(5, 6, 1) = 1000X(5, 6, 4) = 1110X(5, 6, 5) = 1220X(5, 6, 6) = 1490 X(6, 6, 1) = 1020X(6, 6, 2) = 1030X(6, 6, 3) = 1490X(6, 6, 5) = 1330 E(1, 6, 1) = 268E(1, 6, 3) = 330E(1, 6, 5) = 360E(1, 6, 6) = 240 E(2, 6, 1) = 213E(2, 6, 3) = 298E(2, 6, 4) = 328E(2, 6, 5) = 328E(3, 6, 1) = 240E(3, 6, 2) = 225E(3, 6, 5) = 225 E(3, 6, 6) = 283E(4, 6, 2) = 360 E(4, 6, 3) = 313E(4, 6, 4) = 250E(4, 6, 5) = 323E(6, 6, 1) = 78$					
P7	5095	5722	5468	5804	4987	5139
Increased demand						
Regular order lot size	4900	5450	5170	5080	4660	4990
Emergency order lot size	501	673	315	0	476	0
Supplier selection	$X(1, 7, 2) = 1030 X(1, 7, 3) = 1360 X(1, 7, 4) = 1180 X(1, 7, 5) = 1330X(2, 7, 2) = 1370X(2, 7, 4) = 1350 X(2, 7, 5) = 1500 X(2, 7, 6) = 1230X(3, 7, 2) = 1100X(3, 7, 3) = 1400X(3, 7, 4) = 1260X(3, 7, 5) = 1410X(4, 7, 1) = 920X(4, 7, 2) = 1490X(4, 7, 3) = 1170X(4, 7, 5) = 1500 X(5, 7, 1) = 1130X(5, 7, 3) = 1360X(5, 7, 4) = 840X(5, 7, 6) = 1330 X(6, 7, 1) = 1080X(6, 7, 2) = 1220X(6, 7, 3) = 1400X(6, 7, 5) = 1290 E(1, 7, 3) = 206E(1, 7, 4) = 295E(2, 7, 3) = 298E(2, 7, 5) = 375 E(3, 7, 4) = 315 E(5, 7, 3) = 266E(5, 7, 4) = 210$					
P8	5927	4882	5115	5086	5788	5660
Increased demand						

Table 14 (continued)

	T1	T2	T3	T4	T5	T6
Regular order lot size	5350	5160	5240	4620	5450	4930
Emergency order lot size	577	620	355	156	0	0
Supplier selection	$X(1, 8, 1) = 1060 X(1, 8, 4) = 1500 X(1, 8, 5) = 1460 X(1, 8, 6) = 1330 X(2, 8, 1) = 1340 X(2, 8, 4) = 1310 X(2, 8, 5) = 1460 X(2, 8, 6) = 1050 X(3, 8, 1) = 1340 X(3, 8, 2) = 1110 X(3, 8, 3) = 1420 X(3, 8, 4) = 1370 X(4, 5, 1) = 1130 X(4, 5, 4) = 1190 X(4, 5, 5) = 1260 X(4, 5, 6) = 1120 X(4, 8, 2) = 1270 X(4, 8, 3) = 1050 X(4, 8, 4) = 1270 X(4, 8, 5) = 1030 X(5, 8, 1) = 1480 X(5, 8, 2) = 1420 X(5, 8, 5) = 1050 X(5, 8, 6) = 1500; X(6, 8, 2) = 1280(6, 8, 3) = 940 X(6, 8, 4) = 1340 X(6, 8, 6) = 1370 E(1, 8, 3) = 244E(1, 8, 6) = 333E(2, 8, 1) = 335E(2, 8, 2) = 285E(3, 8, 3) = 355E(4, 8, 6) = 156 E(5, 6, 1) = 250E(5, 6, 3) = 228E(5, 6, 4) = 278E(5, 6, 6) = 373$					

Table 15 Order allocation and supplier selection when COVID-19 leads to supplier capacity failures

	T1	T2	T3	T4	T5	T6
P1						
Stochastic demand	2785	3324	3550	2262	3113	1792
Regular order lot size	3180	3770	2820	1170	1070	1090
Emergency order lot size	796	943	706	293	268	273
Supplier selection	$X(1, 1, 1) = 870 X(1, 1, 2) = 1170 X(1, 1, 6) = 1140 X(2, 1, 1) = 1060 X(2, 1, 2) = 1460 X(2, 1, 6) = 1250 X(3, 1, 1) = 1090 X(3, 1, 2) = 860 X(3, 1, 6) = 870 X(4, 1, 6) = 1170 X(5, 1, 6) = 1070 X(6, 1, 6) = 1090 E(1, 1, 1) = 218 E(1, 1, 2) = 293 E(1, 1, 6) = 285 E(2, 1, 1) = 265 E(2, 1, 2) = 365 E(2, 1, 6) = 313 E(3, 1, 1) = 273 E(3, 1, 2) = 215 E(3, 1, 6) = 218 E(4, 1, 6) = 293 E(5, 1, 6) = 268 E(6, 1, 6) = 273$					
P2						
Stochastic demand	1842	3057	3262	3617	1209	2719
Regular order lot size	3310	3460	2880	1260	1390	1220
Emergency order lot size	828	866	721	315	348	305
Supplier selection	$X(1, 2, 1) = 910 X(1, 2, 2) = 1240 X(1, 2, 6) = 1160 X(2, 2, 1) = 1260 X(2, 2, 2) = 910 X(2, 2, 6) = 1290 X(3, 2, 1) = 1090 X(3, 2, 2) = 860 X(3, 2, 6) = 930 X(4, 2, 6) = 1260 X(5, 2, 6) = 1390 X(6, 2, 6) = 1220 E(1, 2, 2) = 310 E(1, 2, 6) = 290 E(2, 2, 1) = 315 E(2, 2, 6) = 303 E(4, 2, 6) = 315 E(5, 2, 6) = 348 E(6, 2, 6) = 305$					
P3						
Stochastic demand	1764	3391	3893	3341	1864	3785
Regular order lot size	4070	4160	3790	910	1120	1260
Emergency order lot size	1019	1041	948	228	280	315
Supplier selection	$X(1, 3, 1) = 1310 X(1, 3, 2) = 1410 X(1, 3, 6) = 1350 X(2, 3, 1) = 1210 X(2, 3, 2) = 1480 X(2, 3, 6) = 1470 X(3, 3, 1) = 1340 X(3, 3, 2) = 1190 X(3, 3, 6) = 1260 X(4, 3, 6) = 910 X(5, 3, 6) = 1120 X(6, 3, 6) = 1260 E(1, 3, 2) = 353 E(1, 3, 6) = 338 E(2, 3, 1) = 303 E(2, 3, 6) = 278 E(3, 3, 1) = 335 E(3, 3, 2) = 298 E(3, 3, 6) = 315 E(4, 3, 6) = 228 E(5, 3, 6) = 280$					
P4						
Stochastic demand	2187	1231	1768	2269	2460	3449
Regular order lot size	3460	3720	3980	1330	1210	990
Emergency order lot size	865	931	995	333	303	248
Supplier selection	$X(1, 4, 1) = 984 X(1, 4, 2) = 1160 X(1, 4, 6) = 1220 X(2, 4, 1) = 1400 X(2, 4, 6) = 1090 X(3, 4, 1) = 1000 X(3, 4, 2) = 1500 X(3, 4, 6) = 1480 X(5, 4, 6) = 1210 X(6, 4, 6) = 990$					

Table 15 (continued)

	T1	T2	T3	T4	T5	T6
P5						
Stochastic demand	3800	2580	2742	1695	2585	3154
Regular order lot size	3240	3460	3800	1120	990	930
Emergency order lot size	810	866	951	280	248	233
Supplier selection	$X(1, 5, 1) = 940 X(1, 5, 2) = 960 X(1, 5, 6) = 1340X(2, 5, 1) = 1300 X(2, 5, 2) = 950 X(2, 5, 6) = 1210 X(3, 5, 1) = 1210X(3, 5, 2) = 1380X(3, 5, 6) = 1210X(4, 5, 6) = 1120X(5, 5, 6) = 990X(6, 5, 6) = 930 E(1, 5, 1) = 235 E(1, 5, 2) = 240 E(1, 5, 6) = 335E(2, 5, 1) = 325 E(2, 5, 2) = 238 E(2, 5, 6) = 303E(3, 5, 1) = 303E(3, 5, 6) = 276;E(4, 5, 6) = 280E(5, 5, 6) = 248E(6, 5, 6) = 233$					
P6						
Stochastic demand	3689	2703	1360	3288	2454	3726
Regular order lot size	2850	2750	2990	860	1490	880
Emergency order lot size	713	688	748	215	373	220
Supplier selection	$X(1, 6, 1) = 1070 X(1, 6, 2) = 820 X(1, 6, 6) = 960 X(2, 6, 1) = 850 X(2, 6, 2) = 1020 X(2, 6, 6) = 880;X(3, 6, 1) = 960X(3, 6, 2) = 900X(3, 6, 6) = 1130X(4, 4, 6) = 1330X(5, 6, 6) = 1490X(6, 7, 6) = 990;E(1, 6, 1) = 268 E(1, 6, 2) = 205 E(1, 6, 6) = 240E(2, 6, 1) = 213E(2, 6, 2) = 255E(2, 6, 6) = 220E(3, 6, 1) = 240E(3, 6, 2) = 225E(3, 6, 6) = 283E(4, 6, 6) = 215E(5, 6, 6) = 373E(6, 6, 6) = 220$					
P7						
Stochastic demand	3400	2559	1835	1512	3707	2481
Regular order lot size	3290	3560	3130	1400	1330	990
Emergency order lot size	824	891	783	350	333	248
Supplier selection	$X(1, 7, 1) = 1130 X(1, 7, 2) = 1030 X(1, 7, 6) = 1130X(2, 7, 1) = 960 X(2, 7, 2) = 1370 X(2, 7, 6) = 1230 X(3, 7, 1) = 1100X(3, 7, 2) = 1100X(3, 7, 6) = 930X(4, 7, 6) = 1400X(5, 7, 6) = 1330E(1, 7, 1) = 110E(2, 7, 1) = 240E(2, 7, 2) = 343E(2, 7, 6) = 308 E(3, 7, 1) = 275 E(5, 7, 6) = 333E(6, 7, 6) = 185$					



Table 15 (continued)

	T1	T2	T3	T4	T5	T6
P8						
Stochastic demand	1899	2179	2920	1563	3514	3374
Regular order lot size	3270	3530	3380	1050	1500	1370
Emergency order lot size	818	883	846	263	375	343
Supplier selection	$X(1, 8, 1) = 1060$ $X(1, 8, 2) = 880$ $X(1, 8, 6) = 1330$ $X(2, 8, 1) = 1340$ $X(2, 8, 2) = 1140$ $X(2, 8, 6) = 1050$ $X(3, 8, 1) = 1340$ $X(3, 8, 2) = 1110$ $X(3, 8, 6) = 930$ $X(4, 6, 6) = 860$ $X(4, 8, 6) = 1050$ $X(5, 8, 6) = 1500$ $X(6, 6, 6) = 880$ $X(6, 8, 6) = 1370$ $E(1, 8, 6) = 333$ $E(2, 8, 1) = 335$ $E(2, 8, 2) = 285$ $E(2, 8, 6) = 133$ $E(4, 8, 6) = 263$					

Table 16 Order allocation and supplier selection when COVID-19 leads to both demand disruptions and supplier failures simultaneously

	T1	T2	T3	T4	T5	T6
P1						
Increased demand	6236	6299	5120	5900	5349	6030
Regular order lot size	3180	3770	2820	3660	3400	1090
Emergency order lot size	796	943	706	916	851	273
Supplier selection	$X(1, 1, 1) = 870$ ; $X(1, 1, 2) = 1170$ ; $X(1, 1, 6) = 1140$ $X(2, 1, 1) = 1060X(2, 1, 2) = 1460X(2, 1, 6) = 1250$ $X(3, 1, 1) = 1090X(3, 1, 2) = 860X(3, 1, 6) = 870$ $X(4, 1, 1) = 1340X(4, 1, 2) = 1150X(4, 1, 6) = 1170X(5, 1, 1) = 1430X(5, 1, 2) = 900X(5, 1, 6) = 1070X(6, 1, 6) = 1090$ $E(1, 1, 1) = 218E(1, 1, 2) = 293E(1, 1, 6) = 285$ $E(2, 1, 1) = 265E(2, 1, 2) = 365$ $E(2, 1, 6) = 313E(3, 1, 1) = 273E(3, 1, 2) = 215E(3, 1, 6) = 218E(4, 1, 1) = 335E(4, 1, 2) = 288E(4, 1, 6) = 293E(5, 1, 1) = 358E(5, 1, 2) = 225E(5, 1, 6) = 268$					
P2						
Increased demand	5443	5720	6229	6590	5849	6436
Regular order lot size	3310	3460	2880	3870	3880	1220
Emergency order lot size	828	866	721	968	971	305
Supplier selection	$X(1, 2, 1) = 910$ $X(1, 2, 2) = 1240$ $X(1, 2, 6) = 1160$ $X(2, 2, 1) = 1260X(2, 2, 2) = 910X(2, 2, 6) = 1290$ $X(3, 2, 1) = 1090X(3, 2, 2) = 860X(3, 2, 6) = 930$ $X(4, 2, 1) = 1470X(4, 2, 2) = 1140X(4, 2, 6) = 1260X(5, 2, 1) = 1010$ $X(5, 2, 2) = 1480X(5, 2, 6) = 1390$ $X(6, 2, 6) = 1220$ $E(1, 2, 1) = 228E(1, 2, 2) = 310E(1, 2, 6) = 290$ $E(2, 2, 1) = 315E(2, 2, 2) = 228E(2, 2, 6) = 323E(3, 2, 1) = 273E(3, 2, 2) = 215E(3, 2, 6) = 233E(4, 2, 1) = 368E(4, 2, 2) = 285E(4, 2, 6) = 315E(5, 2, 1) = 253E(5, 2, 2) = 370E(5, 2, 6) = 348E(6, 2, 6) = 305$					
P3						
Increased demand	5635	5366	5251	6076	5499	5534
Regular order lot size	4070	4160	3790	3470	3450	1260
Emergency order lot size	1019	1041	948	868	863	315

Table 16 (continued)

	T1	T2	T3	T4	T5	T6
Supplier selection	$X(1, 3, 1) = 1310 X(1, 3, 2) = 1410 X(1, 3, 6) = 1350 X(2, 3, 1) = 1210X(2, 3, 2) = 1480X(2, 3, 6) = 1470 X(3, 3, 1) = 1340X(3, 3, 2) = 1190X(3, 3, 6) = 1260 X(4, 3, 1) = 1140X(4, 3, 2) = 1420X(4, 3, 6) = 910X(5, 3, 1) = 1000 X(5, 3, 2) = 1330X(5, 3, 6) = 1120:X(6, 3, 6) = 1260 E(1, 3, 1) = 328E(1, 3, 2) = 353E(1, 3, 6) = 338 E(2, 3, 1) = 303E(2, 3, 2) = 370E(2, 3, 6) = 368E(3, 3, 1) = 335E(3, 3, 2) = 298E(3, 3, 6) = 315E(4, 3, 1) = 285E(4, 3, 2) = 355E(4, 3, 6) = 228E(5, 3, 1) = 250E(5, 3, 2) = 333E(5, 3, 6) = 280E(6, 3, 6) = 315$					
P4						
Increased demand	6600	6220	5596	5607	5198	5720
Regular order lot size	3460	3720	3980	3440	3990	990
Emergency order lot size	865	931	995	861	998	248
Supplier selection	$X(1, 4, 1) = 1080 X(1, 4, 2) = 1160 X(1, 4, 6) = 1220 X(2, 4, 1) = 1400X(2, 4, 2) = 1230X(2, 4, 6) = 1090 X(3, 4, 1) = 1000X(3, 4, 2) = 1500X(3, 4, 6) = 1480 X(4, 4, 1) = 1060X(4, 4, 2) = 1050X(4, 4, 6) = 1330X(5, 4, 1) = 1280 X(5, 4, 2) = 1500X(5, 4, 6) = 1210:X(6, 4, 6) = 990 E(1, 4, 1) = 270E(1, 4, 2) = 290E(1, 4, 6) = 305 E(2, 4, 1) = 350E(2, 4, 2) = 308E(2, 4, 6) = 273E(3, 4, 1) = 250E(3, 4, 2) = 375E(3, 4, 6) = 370E(4, 4, 1) = 265E(4, 4, 2) = 263E(4, 4, 6) = 333E(5, 5, 1) = 328E(5, 5, 2) = 253E(5, 5, 6) = 248E(6, 4, 6) = 248$					
P5						
Increased demand	3800	5950	5644	6073	5575	5101
Regular order lot size	3240	3460	3800	3470	3310	930
Emergency order lot size	810	866	951	868	829	233
Supplier selection	$X(1, 5, 1) = 940 X(1, 5, 2) = 960 X(1, 5, 6) = 1340 X(2, 5, 1) = 1300X(2, 5, 2) = 950X(2, 5, 6) = 1210 X(3, 5, 1) = 1210X(3, 5, 2) = 1380X(3, 5, 6) = 1210 X(4, 5, 1) = 1130X(4, 5, 2) = 1220X(4, 5, 6) = 1120: X(5, 5, 1) = 1310X(5, 5, 2) = 1010X(5, 5, 6) = 990:X(6, 5, 6) = 930 E(1, 5, 1) = 235E(1, 5, 2) = 240E(1, 5, 6) = 335 E(2, 5, 1) = 325E(2, 5, 2) = 238E(2, 5, 6) = 303E(3, 5, 1) = 303E(3, 5, 2) = 345E(3, 5, 6) = 303E(4, 5, 1) = 283E(4, 5, 2) = 305E(4, 5, 6) = 280E(5, 4, 1) = 320E(5, 4, 2) = 375E(5, 4, 6) = 303E(6, 5, 6) = 233$					

Table 16 (continued)

	T1	T2	T3	T4	T5	T6
P6						
Increased demand	5335	6370	5448	6209	6733	4948
Regular order lot size	2850	2750	2990	3220	3390	880
Emergency order lot size	713	688	748	805	848	220
Supplier selection	$X(1, 6, 1) = 1070 X(1, 6, 2) = 820 X(1, 6, 6) = 960 X(2, 6, 1) = 850 X(2, 6, 2) = 1020 X(2, 6, 6) = 880 X(3, 6, 1) = 960 X(3, 6, 2) = 900 X(3, 6, 6) = 1130 X(4, 6, 1) = 920 X(4, 6, 2) = 1440 X(4, 6, 6) = 860 X(5, 6, 1) = 1000 X(5, 6, 2) = 900 X(5, 6, 6) = 1490 X(6, 6, 6) = 880$ $E(1, 6, 1) = 268 E(1, 6, 2) = 205 E(1, 6, 6) = 240 E(2, 6, 1) = 213 E(2, 6, 2) = 255 E(2, 6, 6) = 220 E(3, 6, 1) = 240 E(3, 6, 2) = 225 E(3, 6, 6) = 283 E(4, 6, 1) = 230 E(4, 6, 2) = 360 E(4, 6, 6) = 215 E(5, 6, 1) = 250 E(5, 6, 2) = 225 E(5, 6, 6) = 373 E(6, 6, 6) = 220$					
P7						
Increased demand	5095	5722	5468	5804	4987	5139
Regular order lot size	3290	3560	3130	3810	3280	990
Emergency order lot size	824	891	783	953	821	248
Supplier selection	$X(1, 7, 1) = 1130 X(1, 7, 2) = 1030 X(1, 7, 6) = 1130 X(2, 7, 1) = 960 X(2, 7, 2) = 1370 X(2, 7, 6) = 1230 X(3, 7, 1) = 1100 X(3, 7, 2) = 1100 X(3, 7, 6) = 930 X(4, 7, 1) = 920 X(4, 7, 2) = 1490 X(4, 7, 6) = 1400 X(5, 7, 1) = 1130 X(5, 7, 2) = 820 X(5, 7, 6) = 1330 X(6, 7, 6) = 990$ $E(1, 7, 1) = 283 E(1, 7, 2) = 258 E(1, 7, 6) = 283 E(2, 7, 1) = 240 E(2, 7, 2) = 343 E(2, 7, 6) = 308 E(3, 7, 1) = 275 E(3, 7, 2) = 275 E(3, 7, 6) = 233 E(4, 7, 1) = 230 E(4, 7, 2) = 373 E(4, 7, 6) = 350 E(5, 7, 1) = 283 E(5, 7, 2) = 205 E(5, 7, 6) = 333 E(6, 7, 6) = 248$					
P8						
Increased demand	5927	4882	5115	5086	5788	5660
Regular order lot size	3270	3530	3380	3280	4400	1370
Emergency order lot size	818	883	846	821	1100	343
Supplier selection	$X(1, 8, 1) = 1060 X(1, 8, 2) = 880 X(1, 8, 6) = 1330 X(2, 8, 1) = 1340 X(2, 8, 2) = 1140 X(2, 8, 6) = 1050 X(3, 8, 1) = 1340 X(3, 8, 2) = 1110 X(3, 8, 6) = 930 X(4, 8, 1) = 960 X(4, 8, 2) = 1270 X(4, 8, 6) = 1050 X(5, 8, 1) = 1480 X(5, 8, 2) = 1420 X(5, 8, 6) = 1500 X(6, 8, 6) = 1370$ $E(1, 8, 1) = 265 E(1, 8, 2) = 220 E(1, 8, 6) = 333 E(2, 8, 1) = 335 E(2, 8, 2) = 285 E(2, 8, 6) = 263 E(3, 8, 1) = 335 E(3, 8, 2) = 278 E(3, 8, 6) = 233 E(4, 8, 1) = 240 E(4, 8, 2) = 318 E(4, 8, 6) = 263 E(5, 8, 1) = 370 E(5, 8, 2) = 355 E(5, 8, 6) = 375 E(6, 1, 6) = 273 E(6, 8, 6) = 343$					

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