Facility Location and Distribution Planning in a Disrupted Supply Chain

Himanshu Shrivastava, Pankaj Dutta, Mohan Krishnamoorthy and Pravin Suryawanshi

Abstract Most facility location models in the literature assume that facilities will never fail. In addition, models that focus on distribution planning assume that transportation routes are disruption-free. However, in reality, both the transportation routes and the facilities are subject to various sorts of disruptions. Further, not many supply chain models in the literature study perishable products. In this paper, we address issues of facility location and distribution planning in a supply chain network for perishable products under uncertain environments. We consider demand uncertainty along with random disruptions in the transportation routes and in the facilities. We formulate a mixed-integer optimisation model. Our model considers several capacitated manufacturers and several retailers with multiple transportation routes. We investigate optimal facility location and distribution strategies that minimise the total cost of the supply chain. We demonstrate the effectiveness of our model through an illustrative example and observe that a resilient supply chain needs to have a different design when compared to a disruption-free supply chain. The effects of various disruption uncertainties are also studied through statistical analysis.

Keywords Supply chain · Facility location · Distribution planning
Uncertainty · Perishable products

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1 Introduction

A supply chain (SC) must perform its planned operations effectively and efficiently and remain competitive in global markets. Thus, a SC has to consider multiple objectives such as (a) an increased level of responsiveness, (b) a reduction in the overall cost of the supply chain cost and (c) better distribution management [1]. Supply chain planning decisions are categorised on the basis of the time horizon into strategic, tactical and operational. According to Simchi et al. [2], strategic decisions will be long-term decisions and, typically, this includes the location of plants, the number and location of warehouses, the modes of transportation, the product that is to be manufactured or stored at various locations and the types of information systems that need to be employed. Tactical decisions reflect mid-term planning scenarios and deal with procurement contracts, production schedules and guidelines for meeting quality and safety standards. Operational decisions include planning that is related to machine/personnel/vehicle scheduling, sequencing, lot sizing, defining vehicle routes and so on.

The design of a supply chain network is an important aspect of supply chain management. This primarily involves the determining of facility location and distribution strategies in the supply chain. In the review paper, Melo et al. [3], the authors emphasise the role that facility location decisions play in the making of strategic supply chain decisions. Klibi et al. [4] describe a design of the supply chain network (SCN) by considering uncertain factors; they present a comprehensive review of the natural environmental factors that are responsible for SC disruptions. The paper covers aspects of SC modelling under uncertainty, robustness and resilience.

Qiang et al. [5] state, "supply chain disruption risk[s] are the most pressing issue[s] [that are] faced by firms in today's competitive global environment". Baghalian et al. [6] point out that disruptions are inevitable and are present in most business scenarios. One of the highlights of the World Economic Forum Report (2013) about global risk indicates that extreme weather events, major natural disaster and weapons of mass destruction can hinder the working of supply chains, which, in turn, results in financial losses to the industry. The report shows that there is, on an average, a 7% reduction in the share price of the affected companies [7]. This is alarming and indicates the pressing need for SC professionals to modify the existing working style and improve upon mitigation policies for the management of SC glitches. SC disruptions can be classified as "high-likelihood-low-impact, medium-likelihood-moderate-impact and low-likelihood-high-impact" [8, 9]. Further, Ray et al. [9] proposed an optimal ordering policy for sourcing decisions under disruption by maximising the expected profit and simultaneously minimising the buyers variance in a two-echelon SC structure. On the other hand, Ferrari [10] tries to ascertain the causes of major supply chain disruptions. The authors conclude by stating that "supply chain disruption remains a key executive level concern, and disruption takes on many dimensions, including lost business and industry competitive dimensions".

One of the early studies on facility location considering disruption was carried by Drezner et al. [11]. The authors used the reliability theory in order to capture the disruption effect. The authors had considered a predetermined probability of failure in facilities which were unreliable and could fail at any time. Ivanov et al. [12], in their recent study on SC disruption review, constructed a "risk-recovery" matrix that primarily includes the prominent risks that are responsible for the disruption in the SC and recovery strategies that are followed by various authors. The authors have also explained the various methodologies that are implemented to mitigate consequences due to SC disruptions.

Gupta et al. [13] proposed a stochastic programming-based approach in order to plan for manufacturing decisions that are termed as "here-and-now" decisions, which are made before the realisation of the demand. The logistics decisions, which are termed as "wait-and-see", are made when practitioners realise the uncertainty in the demand pattern. The authors have used the CPLEX optimisation solver, and the framework is illustrated using a real-life case study. Nasiri et al. [14] proposed two models for the designing of an optimal supply chain distribution network under demand uncertainty. Location and allocations decisions are made in the first model, while decisions that are related to production plan, such as production quantity, are made in the second model. The authors used a mixed-integer nonlinear model and solved it using the Lagrangian approach. Tang et al. [15] proposed robust strategies in order to handle disruption scenarios. Outlining the two properties for the strategies, the author stated, "(a) these strategies will manage the inherent fluctuations efficiently regardless of major disruptions, and (b) these strategies will make the SC more resilient in the face of major disruptions". Claypool et al. [16] designed a supply chain network for a new product in which the novelty lies in the combining of the effects of risk due to product development and due to SC. Sadghiani et al. [17] developed a retail SCN by considering operational and disruption risks. The authors validated the model by using illustrative examples and a real-life case study in retail SC. A review study by Snyder et al. [18] in the field of supply chain network design under disruptions describes various modelling approaches in the context of SC disruptions. The authors gathered 180 research articles under the four disruption-mitigating categories, namely "(a) mitigating disruption through inventories; (b) mitigating disruptions through sourcing and demand flexibility; (c) mitigating disruptions through facility location and (d) mitigating disruptions through interaction with external partners."

The impact of disruption in global SC is extravagant in its magnitude, because the impact in this case trickles between interlinked countries. Therefore, global enterprises should mitigate these disruptions and reduce vulnerabilities to disruption with resilient techniques. Mitigating disruptions has become an important research issue in the recent past [18–20].

The literature that has been discussed has been limited to "regular products", for which perishability is not a major concern. India stands second in the production of fruits and vegetables in the world, after China.[1] Moreover, the SC challenges of perishable goods are unexceptional when compared to the regular products, because the value of the product deteriorates significantly over time. In addition to quality-level challenges, the production and distribution of perishable goods are non-administrable. Furthermore, economic chocks, government implication, product varieties and management issues are unavoidable in the overall working of an SC. Shankar et al. [21] and Nasiri et al. [14] have developed a production–distribution problem under demand uncertainty for regular products. However, the diminishing value of the product is not taken into consideration. The review article on agri-food SC that was proposed by Ahumada and Villalobos [22] sheds light on the mathematical models that are developed in order to address SC-related challenges for both non-perishable and fresh products. Authors Pathumnakul et al. [23] addressed the inventory problem of cultivated shrimp and attempted to ascertain the optimal harvest that could maximise a farmer's bottom line by optimising the SC cost. Along similar lines, authors Lin et al. [24] discussed the optimal inventory levels, the price and the profit in the white shrimp SC industry in Taiwan. Negi et al. [25] studied the SC of the fruits and vegetables sector in India and addressed the following objectives: "(a) to identify the factors affecting [the] supply chain of fruits and vegetables sector in India and (b) to suggest mitigation strategies for the identified challenges in [the] supply chain of fruits and vegetables sector". In India, the food and grocery industries account for approximately 31% of India's consumption basket. This industry is currently valued at USD 39.71 billion and is expected to reach USD 65.4 billion with a Compounded Annual Growth Rate (CAGR) of 11% by 2018.[2]

The most cited examples (from the literature) of disruptions that severely affected the operations of SC in the past are Hurricane Katrina and Hurricane Rita in 2005 on the US Gulf Coast. These natural calamities had crippled the oil refineries and resulted in huge losses. The adverse effects were also palpable due to the destruction of large quantities of lumber and coffee produce, and the rerouting of bananas and other fresh produce [20]. The destruction highlighted the fact that, in the future, the designing of an SC network that is resilient to disruption is important. This research article is motivated by the need to quantify and mitigate the effects of disruptions in SC in the case of perishable products.

Shrivastava et al. [26] have studied the resilient supply chain network of the perishable product under random disruptions. The objective of their paper is "to address some practical issues of decision-making under uncertain environments; the focus is the designing of an optimal supply chain distribution network for perishable products under uncertain demand". They considered the disruption in the transportation links and formulated a mixed-integer optimisation model. However, they have assumed that the facilities are disruption-free. In reality, the facilities are also prone to disruption risks. In such a case, it could be challenging to determine the location of the

[1] http://mofpi.nic.in/documents/reports/annual-report.

[2] http://www.ibef.org/industry/indian-food-industry.aspx.

facility when it is subjected to disruption risks. Another limitation of their study is that they have considered only single transportation routes between the supply chain entities. In reality, there could be multiple routes of transportation with the possibility of different risks of disruptions in each route.

The present paper extends the study of Shrivastava et al. [26] by considering multiple routes of transportation and disruption in facilities. The paper also examines the supply chain network for the perishable product under uncertain demand. The aim is to determine optimal facility locations and a distribution strategy in which the transportation routes and the facilities are subjected to disruption risks.

We have organised the rest of the sections of the study as follows: Sect. 2, which deals with the problem description and model formulation; Sect. 3, which presents an illustrative example of the developed model; Sect. 4, which presents the uncertainty analysis and Sect. 5, which concludes our study and suggests an area for future research.

2 Problem Description and Model Formulation

In this paper, we assume a two-echelon single-period supply chain system that consists of several manufacturers and retailers. The manufacturer produces a single product that is perishable. The demands are realised by the retailers, who anticipate their demand and order it from the manufacturer at the start of the period. The potential location and the capacities of the manufacturers are known in advance. There are multiple routes of transportation between each manufacturer and retailer. We assume that these transportation routes are subjected to disruptions, as a result of which some quantity of finished goods may be fully or partially lost in the transportation routes. Also, the manufacturing units are assumed to be prone to disruptions. If disruption occurs in the manufacturing units, the units may fully or partially lose their capacities. In order to ensure a full supply to the retailer, the manufacturers outsource the disrupted quantity from a third party manufacturer. It is assumed that the third party manufacturer has infinite capacity. We assume that demand and disruption are uncertain and follow a known probability distribution function. In this paper, we use the mixed-integer programming approach to formulate the mathematical model that determines the optimal supply chain structure under probabilistic disruptions. We also intend to determine a suitable distribution planning, while minimising the total supply chain's cost. We use the following notations to formulate mathematical model:

Indices:

$m \in M \longrightarrow$ The set of potential locations for manufacturers;
$r \in R \longrightarrow$ The set of retailers;
$f \in F \longrightarrow$ The set of transportation routes;

Decision variables:

$y_m \longrightarrow$ Binary variable equals 1 if manufacturer is open at candidate location m and 0 otherwise;
$x_{mrf} \longrightarrow$ Quantity of final product shipped from manufacturer m to retailer r through route f;
$x_{m\eta} \longrightarrow$ Quantity shipped from third party manufacturer to primary manufacturer m;

Parameters:

$F_m \longrightarrow$ Manufacturer's fixed opening cost at candidate location m;
$D_r \longrightarrow$ Demand at retailer r;
$E(D_r) \longrightarrow$ Expected demand at retailer r;
$F(D_r) \longrightarrow$ Cumulative distribution function of D_r;
$K_r \longrightarrow$ Handling cost per unit at retailer r which includes holding cost and processing/packaging cost;
$\phi_m \longrightarrow$ Capacity of manufacturer m;
$L_m \longrightarrow$ Sum of unit production and unit holding cost at manufacturer m;
$B \longrightarrow$ Budget limit of opening manufacturer's facilities;
$C_{mrf} \longrightarrow$ Unit cost of transportation from manufacturer m to retailer r through route f;
$C_{m\eta} \longrightarrow$ Unit cost of transportation from third party manufacturer to primary manufacturer m;
$\theta_m \longrightarrow$ Percentage of capacity disrupted at manufacturer m;
$\gamma_{mrf} \longrightarrow$ Fraction of supply disruption in the transportation route f between m and r;
$\upsilon \longrightarrow$ Unit penalty cost of disruption;
$\Omega \longrightarrow$ Desired level of fill rate;
$C_S \longrightarrow$ Unit shortage cost to retailer;
$C_E \longrightarrow$ Unit excess cost to retailer.

We assume that γ_{mrf} and θ_m follow a certain known distribution whose mean and standard deviation are known in advance. We deployed the same formulation style as used by Shrivastava et al. [26].

The total cost of the supply chain from manufacturer m to retailer r through route f:

$$F_m \cdot y_m + L_m \cdot x_{mrf} + C_{mrf} \cdot x_{mrf} + \gamma_{mrf} \cdot x_{mrf} \cdot \upsilon + y_m \cdot x_{m\eta} \cdot C_{m\eta} \tag{1}$$

The first term in Eq. (1) indicates the fixed opening cost of the manufacturer's facilities, and the second term denotes the production and holding costs at manufacturer m, while the third term indicates the transportation cost from manufacturer m to retailer r. The fourth term in the above equation denotes the penalty cost due to disruption in the transportation routes. If disruption occurred $\gamma_{mrf}\%$ of supply is assumed to be disrupted. Hence, the quantity arriving at the retailer r is $(1-\gamma_{mrf})\cdot x_{mrf}$. The last term in the above equation computes the transportation cost from third party manufacturer's location to primary manufacturer's locations when the disruption occurs at the primary manufacturing units.

The total cost at retailer r:

$$\sum_{m\in M}\sum_{f\in F}K_r\cdot(1-\gamma_{mrf})\cdot x_{mrf}+C_E\left(\sum_{m\in M}\sum_{f\in F}(1-\gamma_{mrf})\cdot x_{mrf}-D_r\right)^+ + C_S\left(D_r-\sum_{m\in M}\sum_{f\in F}(1-\gamma_{mrf})\cdot x_{mrf}\right)^+ \quad (2)$$

where, $A^+=\max\{\mathrm{A},0\}$.

In retailer's total cost expression, first term denotes the handling cost (which is a combination of holding cost and processing/packaging cost) while the second term is the excess cost and the last term is the shortage cost. To capture the product perishability, we are using news vendor concept [27–30] for managing inventory at the retailer. Equation (2) is simplified by using the following equations:

$$\left(\sum_{m\in M}\sum_{f\in F}(1-\gamma_{mrf})\cdot x_{mrf}-D_r\right)^+=\int_0^{\sum_{m\in M}\sum_{f\in F}(1-\gamma_{mrf})\cdot x_{mrf}}F\left(D_r\right)dD_r \quad (3)$$

$$\left(D_r-\sum_{m\in M}\sum_{f\in F}(1-\gamma_{mrf})\cdot x_{mrf}\right)^+=\left(\sum_{m\in M}\sum_{f\in F}(1-\gamma_{mrf})\cdot x_{mrf}-D_r\right)^+ - \sum_{m\in M}\sum_{f\in F}(1-\gamma_{mrf})\cdot x_{mrf}+E(D_r) \quad (4)$$

From Eqs. (3) and (4), the final expression of total cost at retailer r(T_r) is:

$$T_r=\sum_{m\in M}K_r\cdot(1-\gamma_{mrf})\cdot x_{mrf}+C_E\left(\int_0^{\sum_{m\in M}\sum_{f\in F}(1-\gamma_{mrf})\cdot x_{mrf}}F\left(D_r\right)dD_r\right) + C_S\left(\int_0^{\sum_{m\in M}\sum_{f\in F}(1-\gamma_{mrf})\cdot x_{mrf}}F\left(D_r\right)dD_r-\sum_{m\in M}\sum_{f\in F}(1-\gamma_{mrf})\cdot x_{mrf}+E(D_r)\right) \quad (5)$$

The total cost of the supply chain is the sum of Eqs. (1) and (5), and on rearranging the resulting equation, we get the following mathematical model:

Objective function:

$$
\begin{aligned}
Min\ \ U = & \sum_{m\in M} F_m \cdot y_m + \sum_{m\in M}\sum_{r\in R} P_m \cdot x_{mrf} + \sum_{r\in R}\sum_{m\in M} C_{mrf} \cdot x_{mrf} \\
& + \sum_{r\in R}\sum_{m\in M} \gamma_{mrf} \cdot x_{mrf} \cdot \upsilon_{mrf} + \sum_{m\in M} y_m \cdot x_{m\eta} \cdot C_{m\eta} \\
& + \sum_{r\in R}\sum_{m\in M} K_r \cdot (1-\gamma_{mrf}) \cdot x_{mrf} \\
& + \left(C_E + C_s\right)\left[\sum_{r\in R}\left(\int_0^{\sum_{m\in M}(1-\gamma_{mrf})\cdot x_{mrf}} F\left(D_r\right) dD_r\right)\right] \\
& - C_S\left[\sum_{r\in R}\left(\sum_{m\in M}(1-\gamma_{mrf})\cdot x_{mrf} - E(D_r)\right)\right]
\end{aligned}
\tag{6}
$$

Subject to:

$$\sum_{r\in R}\sum_{f\in F} x_{mrf} \le x_{m\eta} + \left((1-\theta_m)y_m\right)\phi_m \ \ ; \quad \forall \quad m \in M \ \ ; \quad \forall \ \ f \in F \tag{7}$$

$$\sum_{m\in M} F_m \cdot y_m \le B \tag{8}$$

$$\Omega \le \frac{\sum_{f\in F}\sum_{m\in M}(1-\gamma_{mrf})\cdot x_{mrf}}{E(D_r)} \ \ ; \qquad \forall \quad r \in R \tag{9}$$

$$x_{mrf} \ge 0 \ \ ; \qquad \forall \quad m \in M, \quad \forall \quad r \in R, \quad \forall \quad f \in F \tag{10}$$

$$y_m \in \{0, 1\} \qquad \forall \quad m \in M \tag{11}$$

The objective function minimises the total cost of the supply chain network. Constraint Eq. (7) imposes disruption capacity constraint which ensures that the supply to the retailer should not be affected by the disruption at the manufacturing facilities. Equation (8) represents the budget limit. Constraint Eq. (9) ensures that service level should be greater or equal to Ω%. Constraint Eq. (10) and Eq. (11), respectively, impose the non-negativity and binary restrictions.

The decision variables address the optimal network structure. The decision variable in our model includes binary variables that represents the existence of manufacturers and the continuous variable that represent the material flow from manufacturers to retailers.

The mathematical model explained above is nonlinear due to its nonlinear objective function described in Eq. (6). The term responsible for nonlinearity is $y_m \cdot x_{m\eta}$.

To handle this nonlinearity, we define new variable, Ξ_m, such that $\Xi_m = y_m \cdot x_{m\eta}$, and add the following additional constraints to the model:

$$\Xi_m \leq x_{m\eta} \quad ; \quad \forall \quad m \in M \tag{12}$$

$$\Xi_m \leq N \cdot y_m \quad ; \quad \forall \quad m \in M \quad (\textit{where } N \textit{ is a large number}) \tag{13}$$

$$\Xi_{ms} \geq x_{m\eta} + N \cdot (y_m - 1) \quad ; \quad \forall \quad m \in M \tag{14}$$

We assume demand to be uniformly distributed. However, the model can be used for other distributions too. The uniform demand distribution, $F(D)$, in the interval $[a, b]$ is given as:

$$F(D) = \frac{D - a}{b - a} \qquad a \leq D \leq b \tag{15}$$

Substituting $F(D)$ in the objective function, the resulting expression is:

$$\begin{aligned} Min \;\; U = & \sum_{m \in M} F_m \cdot y_m + \sum_{m \in M} \sum_{r \in R} \sum_{f \in F} L_m \cdot x_{mrf} + \sum_{r \in R} \sum_{m \in M} \sum_{f \in F} C_{mrf} \cdot x_{mrf} \\ & + \sum_{r \in R} \sum_{m \in M} \sum_{f \in F} \gamma_{mrf} \cdot x_{mrf} \cdot \upsilon + \sum_{m \in M} y_m \cdot x_{m\eta} \cdot C_{m\eta} \\ & + \sum_{r \in R} \sum_{m \in M} \sum_{f \in F} K_r \cdot (1 - \gamma_{mrf}) \cdot x_{mrf} \\ & + \left(C_E + C_s\right) \left[\sum_{r \in R} \left(\frac{\left(\sum_{m \in M} \sum_{f \in F} (1 - \gamma_{mrf}) \cdot x_{mrf} \right)^2}{2 \cdot (b_r - a_r)} \right. \right. \\ & \qquad \left. \left. - a_r \cdot \frac{\left(\sum_{m \in M} \sum_{f \in F} (1 - \gamma_{mrf}) \cdot x_{mrf} \right)}{b_r - a_r} \right) \right] \\ & - C_S \left[\sum_{r \in R} \left(\sum_{m \in M} \sum_{f \in F} (1 - \gamma_{mrf}) \cdot x_{mrf} - E(D_r) \right) \right] \end{aligned} \tag{16}$$

subject to: Eqs. (7)–(11) and Eqs. (12)–(14).

The above expression is quadratic expression, and hence we have mixed-integer quadratic model.

3 Illustrative Example

In this section, we validate our model through a two-echelon supply chain design, which is subjected to disruption risks at facilities and transportation routes. We consider four manufacturing units and five retail zones and assume that there are two routes from each manufacturing unit to each retail zone. We solved our model by using the default settings of the CPLEX optimisation solver. The input parameters of the problem are shown in Tables 1 and 3. The unit excess cost and unit shortage cost are assumed to be 1 and 2, respectively. The disruption in the transportation routes and facilities are characterised by γ and θ, respectively. The disruption probability matrix (γ) for both the routes is shown in Table 2. θ for $m1$ is assumed to be 0.35, while it is 0.20, 0.05 and 0.15 for $m2$, $m3$ and $m4$, respectively.

The total cost of the supply chain is 44,980. It is observed that this design (which is the resilient design) selects all the four manufacturers. The quantity shipment decisions from the manufacturing units to the retailers are shown in Table 4. The quantity that needs to be outsourced from the third party manufacturer are 35, 30, 0 and 0 for manufacturer $m1$, $m2$, $m3$ and $m4$, respectively. We have also analysed the disruption-free design. In the disruption-free design, γ and θ are considered to be zero. The total cost of the supply chain for the disruption-free design is 41,330. This disruption-free design selects only three manufacturers, $m2$, $m3$ and $m4$. The quantity shipment decisions from the manufacturing units to the retailers are shown in Table 5. Here it should be noted that the supply chain network structure that is obtained for the

Table 1 Manufacturers and retailers input parameters

Manufacturers				Retailers	
Manufactuer	Capacity	Fixed opening cost	Per unit production cost	Retailer	Handling cost
m1	100	2000	30	r1	9
m2	250	3500	35	r2	12
m3	180	2000	40	r3	9.5
m4	200	2500	37	r4	10
				r5	11

Table 2 Disruption probabilities

Supply disruption probability in route f1						Supply disruption probability in route f2					
	r1	r2	r3	r4	r5		r1	r2	r3	r4	r5
m1	0.02	0.04	0.03	0.04	0.01	m1	0.3	0.25	0.1	0.17	0.15
m2	0.04	0.02	0.04	0.05	0.03	m2	0.22	0.16	0.12	0.26	0.27
m3	0.05	0.02	0.04	0.05	0.03	m3	0.15	0.1	0.8	0.05	0.07
m4	0.07	0.03	0.3	0.2	0.02	m4	0.07	0.03	0.3	0.2	0.02

Table 3 Transportation cost parameters

Unit transportation cost in route f1: manufacturers to retailers						Unit transportation cost in route f2: manufacturers to retailers					
	r1	r2	r3	r4	r5		r1	r2	r3	r4	r5
m1	8	15	7.5	8.5	9	m1	10	12	9	8	11
m2	12	11	7	8	10	m2	9	13	8	7	10.5
m3	8	9	7	8	9	m3	9	8	8.5	7.5	8.5
m4	9	10	9.5	12	8	m4	11	9	12	10	7

Table 4 Distribution decisions in resilient model

Quantity shipment through route f1:						Quantity shipment through route f2:					
	r1	r2	r3	r4	r5		r1	r2	r3	r4	r5
m1	100	0	0	0	0	m1	0	0	0	0	0
m2	0	0	103.1	25.7	0	m2	21.2	0	0	0	0
m3	0	113.5	0	0	0	m3	0	0	0	57.7	0
m4	0	0	0	0	0	m4	0	69	0	0	100

Table 5 Distribution decisions in disruption-free model

Quantity shipment through route f1:						Quantity shipment through route f2:					
	r1	r2	r3	r4	r5		r1	r2	r3	r4	r5
m1	0	0	0	0	0	m1	0	0	0	0	0
m2	0	0	70.8	0	0	m2	100	0	0	79.2	0
m3	0	0	28.2	0	0	m3	0	96	0	0	0
m4	21	0	0	0	0	m4	0	82.2	0	0	100

resilient supply chain is different from the disruption-free supply chain. The resilient supply chain selects all four manufacturers, while the disruption-free supply has only three manufacturers. Also, the total cost of the resilient supply chain is 8% higher than that of the disruption-free supply chain.

We further analyse the effect of fill-rate measures on the total cost of the supply chain. We observed that as the fill rate increases the total cost of the supply chain also increases. The variation of the total SC with the fill-rate measures is observed through the graph shown in Fig. 1.

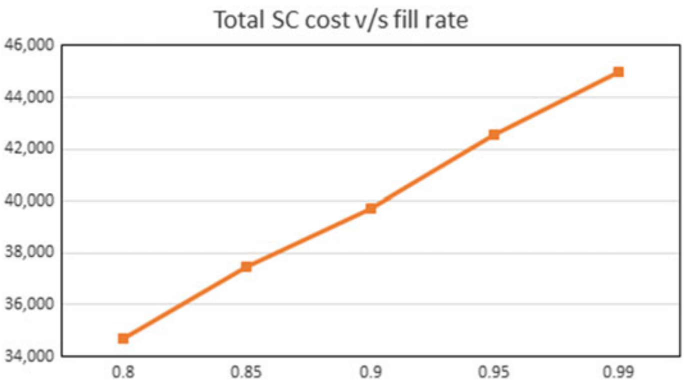

Fig. 1 Variation of the total SC cost with fill rate

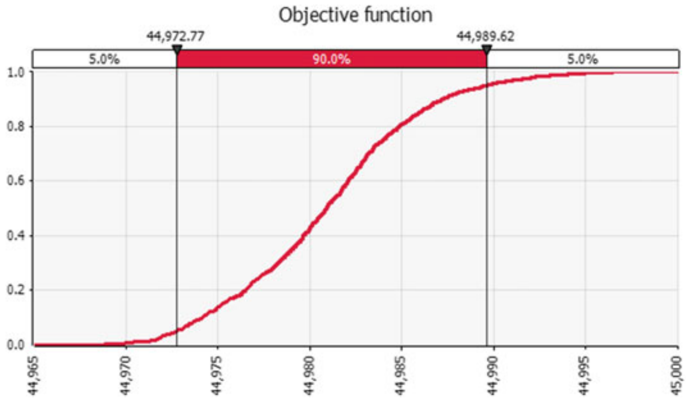

Fig. 2 Percentile analysis of the total SC's cost

4 Uncertainty Analysis

This section analyses the disruption effects that are present in the facilities and the transportation routes. We have assumed that these disruptions are uncertain and that they follow a normal distribution with known mean and variance. On executing a simulation of 1000 iterations by using @Risk,[3] the uncertainty effect (due to disruptions in the manufacturing facilities and in the transportation routes) is analysed through various graphs (Figs. 2 and 3).

The graph shown in Fig. 4 represents the overall nature of the objective function (the total cost of the supply chain). The Kolmogorov–Smirnov normality test is performed on the 1000 observed data of the total cost of the supply chain, and it is found that the outcome is also normal. Through simulation and t-test analysis by using @Risk, it is observed that the overall cost of the supply chain would lie between 44,972.7 and 44,989.6 with 90% confidence. The chance that the total cost exceeds 44,989.6 is only 5%. Figure 2 statistically summarises the objective function.

We now analyse the effect of the uncertain parameters, γ and θ on the supply chain by using the tornado graph. Figure 3 shows the tornado graph of top five most dominated uncertain parameters. In this figure, we calculated the variability on the total cost due to uncertainty in the parameters using the simulation output of the Pearson coefficient value. The γ in the transportation route, $f2$, which is between $m4$ and $r3$, is highly effective and causes a huge variation in the total cost of the supply chain. In other words, this is the most risky route. The route $f1$, between $m4$ and $r3$, causes approximately 63.5% variability in the total cost of the supply chain. However, route f1, between $m4$ and $r3$, is less risky than route f2, because the variation in the cost of its supply chain is lesser. This route is responsible for 11% variation in the total cost. This route is best for the risk-averse decision maker, while the risk-seeking decision maker could choose route $f2$. Similarly, the least variation

[3] http://www.palisade.com/risk/.

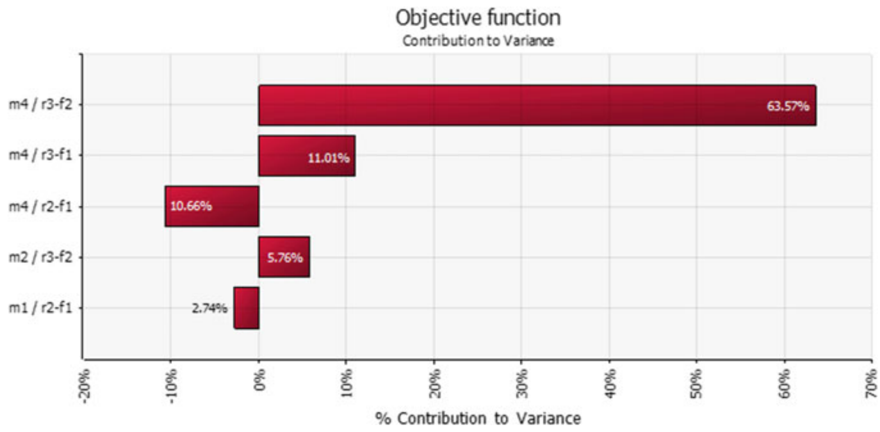

Fig. 3 Effect of uncertainty on supply chain's total cost

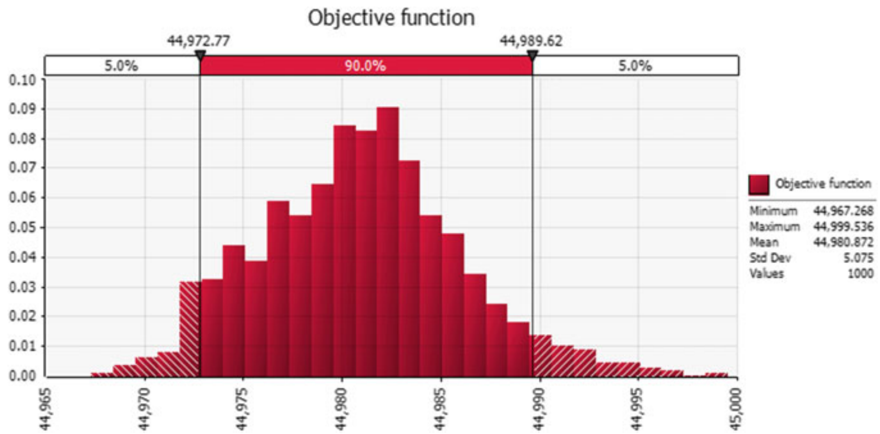

Fig. 4 Variation in supply chain's total cost due to uncertain disruptions

in the total cost of the supply chain is observed in route $f1$, between $m1$ and $r2$. The Pearson coefficient in this route is negative, and the variability due to this route is 2.7%. It should be noted that the disruption in facilities causes very less variation in the total cost, and hence, the uncertainty effect of θ is not dominant.

5 Conclusions and Future Work

In this paper, we have extended the model of Shrivastava et al. [26] and formulated the problem of facility location and the allocation of a two-echelon supply chain system under uncertainty as a mixed-integer quadratic model. The model addresses the decision variable, which corresponds to the location of the manufacturer and the quantity flow from the manufacturer to the retailer. We have considered disruption in the transportation routes and in the facilities, simultaneously. During disruptions, the manufacturing facilities may fully or partially lose their capacity. In order to ensure full supply to the retailer, we assumed that the manufacturer outsources its disrupted capacity from the third party manufacturer. We observed that the supply chain decisions in the resilient model and the disruption-free model are not same. We have also carried out an extensive analysis of the uncertain disruptions that are present in the transportation link between the manufacturers and the retailers, and in the manufacturing facilities. We have statistically studied the overall nature of the cost function. In the current parameter setting, we have found that the disruption parameter, γ, is highly effective in the link, $f2$, which is between $m4$ and $r3$; this parameter also causes a large amount of variation in the cost function.

Realising a more realistic supply chain that has a greater number of echelons could be a possible extension of this study. We have assumed a single-product and single-period model, which can be extended for multi-products and multi-periods. Along with demand and disruption uncertainties, cost parameter uncertainties can be considered as well.

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