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Designing a Resilient Supply Chain Network for Perishable Products with Random Disruptions

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***Abstract*—In the literature, most mathematical models for supply chains assume that transportation links will not fail. However, in reality, transportation links are subject to various sorts of disruptions. Furthermore, in most supply chain models, there is little consideration given to the diminishing value of the product. In this paper, we have designed an integrated supply chain network for perishable products that takes into account random disruptions in transportation links. We also consider several capacitated manufacturing facilities and retail outlets and stochastic demands. This model considers both demand and process uncertainty (which is incorporated through random disruptions in the transportation link between the manufacturers and the retailers), simultaneously. The model also investigates the manufacturer's facility locations and shipment decisions in the supply chain and minimizes the total cost of the entire supply chain. The paper discusses the model output through a numerical example and we observe that the resilient model (the model considering transportation link disruptions) and the disruption free model yields different designs. Finally, the paper provides an extensive statistical analysis of disruption uncertainties in the supply chain.**

***Index Terms*—integrated supply chain, network design, disruptions, uncertainty analysis, perishable products.**

I. Introduction

THE effective and efficient management of its supply chain is a critical task for any firm. In order to remain competitive in the market, firms may need to plan decisions such as (a) an increase in the level of service, (b) a reduction in the cost of logistics, and (c) an improvement in the methods of distribution (see [1]). Three levels of planning have been identified for supply chains, depending on the time horizon, (see [2]): *strategic, tactical and operational*. Strategic decisions have a long-lasting impact on the organisation. Decisions regarding the number of warehouses, the location of plants and the capacities of manufacturing units are some examples of strategic decisions. Tactical decisions are relatively shorter-term and aim to optimise the use of the resources. Operational decisions are related to detailed machine/personnel/vehicle scheduling, sequencing, lot sizing, assigning of loads, defining vehicle routes, and so on [2].

The design of supply chain networks has been a well-studied area of research (see the review papers of Melo *et al.* [3] and Klibi *et al.* [4], for example). Supply chain network (SCN) design has a deep impact on supply chain management because it directly affects supply chain profitability and customer responsiveness [5]. These are long-term/strategic design decisions that must ideally consider disruptions too; disruptions are inevitable and are present in most business scenarios [6].

One of the highlights of the report that was presented in the World Economic Forum 2013 is the financial destruction that is caused by disruptions in a supply chain [7]. The report shows that there is, on average, a reduction of 7% in the share price of companies affected by disruptions. A global supply chain is exposed to a variety of disruptions, which include supply and transportation disruption, price fluctuations, supply delays, quality failure, information failure, capacity disruptions and such others [8]. Oke *et al.* [9] and Ray *et al.* [10] have classified such disruption events into three categories "high-likelihood-low-impact, low-likelihood-high-impact, and medium-likelihood-moderate-impact". Ray *et al.* [10] provides some example of the supply chain disruptions and adopted a novel mean-variance approach for managing disruption in a two-echelon supply chain. Qiang *et al.* [11] states, "supply chain disruption risk[s] are the most pressing issue[s] [that are] faced by firms in today's competitive global environment." On the other hand, Ferrari [12] tries to ascertain the causes of major supply chain disruptions. The conclusion states, "supply chain disruption remains a key executive level concern, and disruption takes on many dimensions, including lost business and industry competitive dimensions." Supply chain network designs that take disruption into account have recently emerged in the literature. One of the early studies in this field [13] considers a typical facility location problem that included disruption, for which two models were introduced. They captured the disruption effect with the help of reliability theory. In the first model, a basic p-median problem is considered with an assumption that the facility is unreliable and will fail with a predetermined probability. Their second model is the $(p; q)$-centre problem in which the objective is to locate p facilities such that the cost is minimised when, at most q facilities fail. Neighbourhood search-type heuristics were proposed for both problems. Gupta *et al.* [14] considered demand disruption and proposed a framework for manufacturing and logistics decisions. A two-stage stochastic programming was formulated: manufacturing decisions were modelled in the first stage, while logistics decisions were modelled in the second stage. CPLEX was used to solve the model, and the framework was illustrated through a case study. A review article by Snyder *et al.* [15] provides an overview of the study that was carried out in the field of supply chain network design under disruptions; it also discusses the various modelling approaches in the context of supply chain disruptions. Their paper also provides insights into 180 research articles under the four disruption mitigating

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categories: "(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."

Moreover, a global supply chain comprises sourcing raw materials from (and distributing goods to) other countries. This, inevitably gives rise to various disruptions. Enterprises must manage supply chain disruptions and reduce this vulnerability [5]. Therefore, managing and mitigating disruptions has become an important research issue in the recent past [16][5] [15].

Nasiri *et al.* [17] designed an optimal supply chain distribution network. The authors considered uncertainties in demand and proposed two models. In the first model, location and allocation decisions are made while the second model incorporates production plans and determines the production quantity. The first model is a mixed-integer nonlinear model which was solved using a Lagrangian approach. In this, the master problem is converted into four sub problems. The first and the second sub model were solved by a heuristic algorithm, and a genetic algorithm (GA) was used to solve the third and fourth sub models. The second model proposed by the author is a linear programming model, which was solved using CPLEX. Baghalian *et al.* [6] considered both supply and demand-side uncertainties and developed a stochastic programming formulation for the supply chain network design, considering multiple products. They investigated a location distribution problem and formulated a mixed-integer nonlinear model for the problem. In order to solve the model, they used a piecewise linearization method (solved using CPLEX). They illustrated the efficacy of their model through a real-life case study from the agri-food industry. Sadghiani *et al.* [18] developed a location-allocation problem by incorporating supply disruption and uncertainty in the transportation process. Khalifehzadeh *et al.* [1] study a production-distribution problem in a multi-echelon supply chain and have formulated a multi-objective mixed-integer linear model. The authors also used process uncertainty by considering reliability issues in the transportation systems. A heuristic based comparative particle swarm optimization was used to solve the model.

In the literature, however, most works only consider 'regular' products. For example, Nasiri *et al.* [17] only considers demand uncertainty in the production-distribution problem, while Shankar *et al.* [19] does not include any uncertainty in their model but have incorporated a fill rate (fraction of demand satisfied). However, both studies only model 'regular' products; the diminishing value of the product is not taken into consideration. In perishable goods, after a point of time (mostly denoted by the expiry date of the product), the value of goods goes down over time. In some cases, such as in seasonal and fashion products, there could be considerable salvage value. However, there is no salvage value in many other products; such products include fruits and vegetables, dairy products, meat, fish, cooked food and so on. Some authors have studied the supply chain models of such products. For example, Ahumada *et al.* [20] reviewed agri-food supply chain models. They first categorised the models as perishable and non-perishable agricultural products, and then studied the models according to their planning levels and optimisation approaches. Pathumnakul *et al.* [21] studied an inventory problem of cultivated shrimp and attempted to ascertain the optimal harvest that could maximise a farmers bottom line. They focused on the cost structure and not on the efficiency of the supply chain. Similarly, Lin *et al.* [22] studied the supply chain network of the shrimp industry in Taiwan and discussed the optimal inventory levels, the price and the profit in a shrimp supply chain for farmers, wholesalers and markets under varying conditions.

Negi *et al.* [23] studied three types of supply chains that are usually employed for fruits and vegetable products in India. They also highlighted the issues and challenges that persist in the supply chains of the fruit and vegetable sectors in India. Infact, in India, the perishable product sector is an emerging market. For example, it is estimated that the food and grocery market in India is likely to touch US $894.98 billion by 2020, with a stunning growth rate of 83% [24]. Also, the food wastage is one of the major problem in India. It ranges from Rs. 58,000 crores in 2004 to Rs. 30,000 crores in 2010. It is estimated that thirty percent of produce being wasted [25]. Disruptions could have adverse effects on the perishable products sectors too. For example, in 2005, hurricane Katrina and hurricane Rita destroyed large inventories of coffee and lumber on the U.S. Gulf Coast and forced the rerouting of bananas and other fresh produce [16]. And because of these, supply chain network design and optimisation under disruption is of paramount importance in the case of perishable goods. This paper is motivated by a desire to quantify the effects of disruptions in the supply chains of perishable products and to enable decision makers to develop better disruption management strategies.

Based on the literature survey above and to the best of our knowledge, we have determined that there has been limited study in the area of supply chain network design for perishable products, which also takes random disruptions into account. This paper examines an integrated supply chain network design problem for perishable products under assumptions of disruptions too. The problem considers multiple manufacturers and retailers who are subject to different sorts of disruptions. The objective of this study is to address some practical issues of decision making under uncertain environments, in which our focus is to design an optimal supply chain distribution network for perishable products under uncertain demand. We aim to take random disruption into consideration and determine the optimal network structure that will minimise the supply chain's total cost.

The remaining section of the study is organised as follows: Section II deals with the problem description and model formulation. Results and discussions are carried out in section III in which subsection III-A presents a comparative analysis of disruption free and resilient design through an illustrative example, followed by the uncertainty analysis in subsection III-B. Finally, we conclude our study and suggest an area for future research in section IV.

II. Problem description and model formulation

In this paper, we have considered a two-echelon single period supply chain system that comprises several manufacturers and retailing outlets. These retailing outlets will serve as demand points in our model. The final products that are produced by the manufacturers are perishable and are delivered to retailers. The manufacturer's capacities and their potential locations are known in advance. The transportation link between manufacturer, m, and retailer, r, may face different amounts of disruptions. The retailers foresee their demand and orders it to the manufacturers at the beginning of the period. Demand is stochastic, with a known probability distribution function. The lead time for retailers is assumed to be constant. The model examines the supply chain network design under probabilistic disruptions. It involves the determining of facility locations and a suitable distribution strategy, while also minimising the total cost of the supply chain.

We have used the following notations to formulate mathematical model:

Indices:

- m $\in$ M : The set of potential locations for manufacturers (from a set of all candidate locations);
- r $\in$ R : The set of retailers that need to be serviced (these are demand points and are known in advance);

Decision variables:

- y_m : Binary variable, equals 1 if manufacturer is open at candidate location m and 0 otherwise;
- x_{mr} : Quantity of final product shipped from manufacturer m to retailer r;

Parameters:

- F_m : Manufacturer's fixed opening cost at candidate location m;
- D_r : Demand at retailer r;
- $E(D_r)$: Expected demand at retailer r;
- $F(D_r)$: Cumulative distribution function of D_r;
- O_r : Handling cost per unit at retailer r which includes holding cost and processing/packaging cost;
- K_m : Capacity of manufacturer m;
- P_m : Sum of unit production and unit holding cost at manufacturer m;
- B : Budget limit of opening manufacturer's facilities;
- C_{mr} : Unit cost of shipping final product from manufacturer m to retailer r;
- β_{mr} : Fraction of supply disruption in the link between m and r;
- σ_{mr} : Unit penalty cost of disruption;
- Z : Desired level of fill rate;
- C_S : Unit shortage cost to retailer;
- C_E : Unit excess cost to retailer;

We assume that β_{mr} follows a certain known distribution whose mean and standard deviation is known in advance.

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

$$F_m \cdot y_m + P_m \cdot x_{mr} + C_{mr} \cdot x_{mr} + \beta_{mr} \cdot x_{mr} \cdot \sigma_{mr} \quad (1)$$

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 last term in the above equation denotes the penalty cost of disruption as the transportation link is assumed to have an associated risk of disruption.

If disruption occurred $\beta_{mr}\%$ of supply is assumed to be disrupted. Hence the quantity arriving at the retailer r is $(1-\beta_{mr}) \cdot x_{mr}$.

The total cost at retailer r:

$$\begin{aligned} T_r \;=\; & \sum_{m\in M} O_r \cdot (1-\beta_{mr}) \cdot x_{mr} \\ & + C_E\Big(\sum_{m\in M}(1-\beta_{mr})\cdot x_{mr} - D_r\Big)^+ \\ & + C_S\Big(D_r - \sum_{m\in M}(1-\beta_{mr})\cdot x_{mr}\Big)^+, \end{aligned} \quad (2)$$

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

In other words, the total cost of the retailer is comprised of handling cost (which is a combination of holding cost and processing/packaging cost) plus excess cost (of overstocking) plus shortage cost (of unfulfilled demand). Due to the perishable nature of the product and single period supply chain distribution planning, we are deploying a *newsvendor style* model [26] for managing and calculating the inventory of the retailer. Eq. (2) is simplified to following equation:

$$\begin{aligned} T_r \;=\; & \sum_{m\in M} O_r \cdot (1-\beta_{mr}) \cdot x_{mr} \\ & + C_E\Big(\int_0^{\sum_{m\in M}(1-\beta_{mr})\cdot x_{mr}} F\left(D_r\right) dD_r\Big) \\ & + C_S\Big(\int_0^{\sum_{m\in M}(1-\beta_{mr})\cdot x_{mr}} F\left(D_r\right) dD_r \\ & - \sum_{m\in M}(1-\beta_{mr})\cdot x_{mr} + E(D_r)\Big) \end{aligned} \quad (3)$$

The total cost of the supply chain is the sum of eq. (1) and eq. (3) and on rearranging the resulting equation, we get the mathematical model of our problem.

Objective function:

$$\begin{aligned} U \;=\; & \sum_{m\in M} F_m \cdot y_m + \sum_{m\in M}\sum_{r\in R} P_m \cdot x_{mr} \\ & + \sum_{r\in R}\sum_{m\in M} C_{mr}\cdot x_{mr} + \sum_{r\in R}\sum_{m\in M} \beta_{mr}\cdot x_{mr}\cdot\sigma_{mr} \\ & + \sum_{r\in R}\sum_{m\in M} O_r\cdot(1-\beta_{mr})\cdot x_{mr} + (C_E + C_s) \\ & \left[\sum_{r\in R}\left(\int_0^{\sum_{m\in M}(1-\beta_{mr})\cdot x_{mr}} F\left(D_r\right) dD_r\right)\right] \\ & - C_S\left[\sum_{r\in R}\left(\sum_{m\in M}(1-\beta_{mr})\cdot x_{mr} - E(D_r)\right)\right] \end{aligned} \quad (4)$$

Subject to:

$$\sum_{r\in R} x_{mr} \le K_m \cdot y_m \qquad \forall \quad m\in M \quad (5)$$

$$\sum_{m\in M} F_m \cdot y_m \le B \quad (6)$$

$$Z \le \frac{\sum_{r\in R}\sum_{m\in M}(1-\beta_{mr})\cdot x_{mr}}{\sum_{r\in R} E(D_r)} \quad (7)$$

$$x_{mr} \ge 0 \qquad \forall \quad m\in M, \quad \forall \quad r\in R \quad (8)$$

$$y_m \in \{0,1\} \qquad \forall \quad m\in M \quad (9)$$

The objective function minimises the total cost of the supply chain network. Constraint eq. (5) and eq. (6) imposes

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capacity constraints and budget constraints respectively on manufacturers. Constraint eq. (7) ensures that service level should be greater or equal to Z%. Constraint eq. (8) and eq. (9) respectively impose the non-negativity and binary restrictions.

The decision variables addresses 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.

We have considered 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:

$$F(D) = \frac{D-a}{b-a} \qquad a \leq D \leq b \tag{10}$$

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

$$\begin{aligned}
U \quad = \quad & \sum_{m \in M} F_m \cdot y_m + \sum_{m \in M} \sum_{r \in R} P_m \cdot x_{mr} \\
& + \sum_{r \in R} \sum_{m \in M} C_{mr} \cdot x_{mr} + \sum_{r \in R} \sum_{m \in M} \beta_{mr} \cdot x_{mr} \cdot \sigma_{mr} \\
& + \sum_{r \in R} \sum_{m \in M} O_r \cdot (1-\beta_{mr}) \cdot x_{mr} + (C_E + C_s) \\
& \left(\sum_{r \in R} \frac{\left(\sum_{m \in M} (1-\beta_{mr}) \cdot x_{mr}\right)^2}{2 \cdot (b_r - a_r)} \right) - (C_E + C_S) \\
& \left(\sum_{r \in R} a_r \cdot \frac{\left(\sum_{m \in M} (1-\beta_{mr}) \cdot x_{mr}\right)}{b_r - a_r} \right) \\
& - C_S \left[\sum_{r \in R} \left(\sum_{m \in M} (1-\beta_{mr}) \cdot x_{mr} - E(D_r) \right) \right]
\end{aligned}$$

subject to: eq. (5)-eq. (9). The above is a quadratic expression and hence we have mixed integer quadratic model.

III. Results and discussions

A. Comparative analysis

We have implemented our formulation in order to design a small supply chain that has the risk of being disrupted at transportation links. The disruption free design (with no disruptions) is also analysed. In our example, we have considered four manufacturers and five retailers. We have solved our model using the default settings of the CPLEX optimisation software (version 12.6) on an Intel(R) 2.4 gigahertz computer with 4 gigabyte RAM.

The decisions obtained from both the design are shown in Table II and Table III. The disruption free model and the resilient model yield different designs; the first model selects the locations of only three manufacturers, while the later selects all four manufacturers. It should be noted that, in the resilient model, there is an extra parameter for the supply disruption probability (β), and this probability matrix is shown in Table I; the disruption free model does not require any such parameter.

A detailed comparison of the disruption free model and the resilient model is presented in Table IV. It can be observed that the total cost of the supply chain is higher in the resilient model. Fixed, transportation and production costs are also higher in the resilient model. Further, the experiment shows that if the disruption free model is used in the disruption situation, the supply chain's cost is much higher than in the resilient model.

TABLE I
Disruption probabilities

Supply disruption probability (β)					
	r1	r2	r3	r4	r5
m1	0.3	0.25	0.1	0.17	0.15
m2	0.22	0.16	0.12	0.26	0.27
m3	0.15	0.1	0.8	0.05	0.07
m4	0.07	0.03	0.3	0.2	0.02

TABLE II
Design decisions for resilient model

Quantity shipment decisions						Location decisions	
	r1	r2	r3	r4	r5	m1	1
m1	0	0	10	0	0	m2	1
m2	15	0	0	0	0	m3	1
m3	0	8.87	0	4.12	0	m4	1
m4	0	0	0	0	19.99	Decisions :1 - open 0 - closed	

TABLE III
Design decisions for disruption free model

Quantity shipment decisions						Location decisions	
	r1	r2	r3	r4	r5	m1	0
m1	0	0	0	0	0	m2	1
m2	15	0	1.225	0	0	m3	1
m3	0	17.2	0	0.036	0	m4	1
m4	0	0	0	0	20.00	Decisions :1 - open 0 - closed	

TABLE IV
Comparative results

Expected Costs	Disruption free model	Resilient model
Fixed cost	8000	10000
Transportation cost	69035.59	77808.44
Production cost	41919.92	43394.48
Handling cost	5627.92	5270.78
Penalty cost	0	422.13
Total supply chain's cost	125144.43	136293.22

TABLE V
Supply chain's total cost statistics

Statistics		Percentile	
Minimum	136263.17	5%	136277.23
Maximum	136324.94	10%	136280.41
Mean	136293.35	15%	136283.07
Std Dev	10.13	20%	136284.93
Variance	102.61	25%	136286.35
Skewness	0.14	30%	136287.77
Kurtosis	3.01	35%	136288.94
Median	136293.14	40%	136290.34
Mode	136294.55	45%	136291.78
Left X	136277.23	50%	136293.14
Left P	5%	55%	136294.29
Right X	136310.34	60%	136295.42
Right P	95%	65%	136296.97
Diff X	33.11	70%	136298.51
Diff P	90%	75%	136300.12
Errors	0	80%	136302.04
Filter Min	Off	85%	136303.59
Filter Max	Off	90%	136306.61
Filtered	0	95%	136310.34

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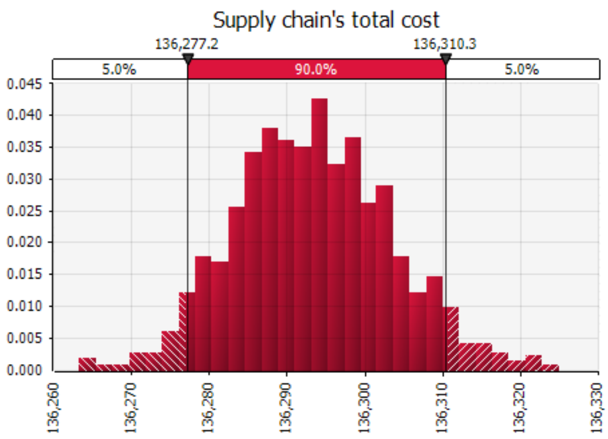

Fig. 1. Variation in supply chain's total cost due to uncertain disruptions

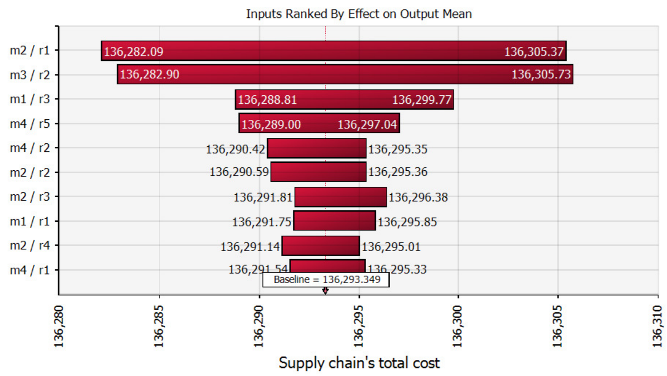

Fig. 2. Effect of β on the supply chain's total cost

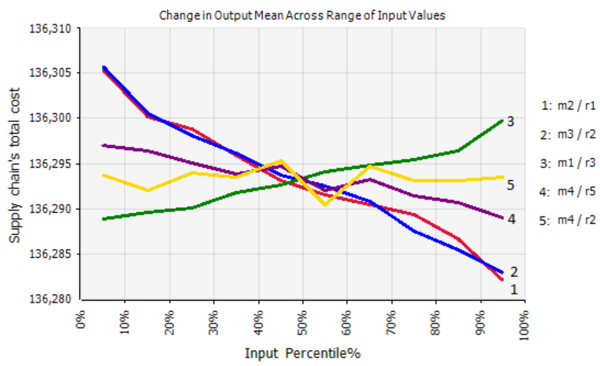

Fig. 3. Percentile effect of β on the supply chain's cost

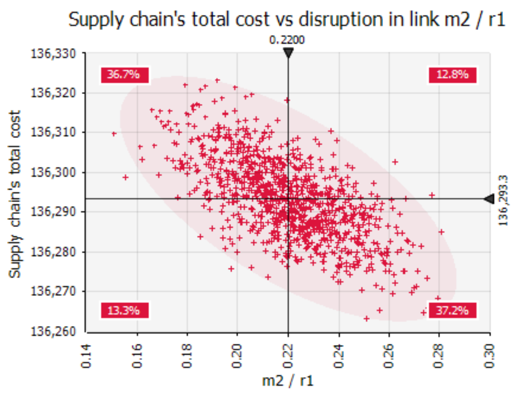

Fig. 4. Effect of disruption in link m2-r1

B. *Uncertainty analysis and discussions*

In this subsection we analyse the effect of the disruptions that is present in the transportation link between the manufacturers and the retailers. This disruption is considered to be uncertain and follows a normal distribution of known mean and variance. A simulation of 1000 iterations is executed using @Risk [27]. The effect of uncertainty (due to disruptions in the transportation link) is observed through various graphs and Table V.

The graph shown in Figure 1 represents the overall nature of the objective function (the supply chain's total cost). Through simulation, it is observed that the overall cost of the supply chain would lie between 136263.165 and 136324.94 with 90% confidence. The chance of exceeding 136310.3 is only 5%. Table V statistically summarise the objective function.

The disruption in the transportation link between manufacturer, m and retailer, r is characterized by β and we analyse the effect of the uncertainty parameter β on the supply chain. The tornado graph in Figure 2 shows the effect. We have taken top ten links for the analysis in which the effect of uncertainty in disruptions is most dominant. From this graph, we can infer that the β in the transportation link between $m2$ and $r1$ 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. This route offers the minimum cost of 136,282.09 which is lowest among all the other routes but at the same time there is a chance that total cost goes maximum to 136,305.73 which is the highest cost among all the other routes. This is followed by the uncertainty in the link between $m3$ and $r2$ which causes next higher variation in the supply chains total cost. Similarly the lowest variation occurs in the link between $m4$ and $r1$. This route is best for the risk averse decision maker while risk seeking decision maker could go for the route between $m2-r1$. The percentile effect of top five influencing β on the objective function is shown in Figure 3.

The scatter plots shown in the Figure 4 - Figure 6 show the effect of the individual link disruption on the total cost. The top three influencing link disruptions are shown. The disruption in the link $m2 - r1$ is most dominant. The mean value of the supply disruption in the link $m2 - r1$ is 0.22 and the corresponding mean value of the cost function is 136,293.35. Also, it is negatively correlated (Pearson correlation coefficient is -0.657) to the cost function. The Pearson coefficient also signifies the measure of variability through R^2 value (i.e. coefficient of determination). The R^2 value in this link is $|0.657|^2$ i.e. 0.432. That means 43.2% variability in the total cost is due to the disruptions while the rest 56.8 % variability can be explained by the other cost (such as transportation cost, production cost, fixed cost and the like) that incurred in the supply chain.

The figure 4 also shows that there is 36.7% chance of the disruption probability being lower than the mean value of 0.22 and incurring total expense more than mean of 136,293.35. Similarly, disruption in the link $m3 - r2$ is also negatively correlated to the total supply chain's cost while the disruption in the link $m1 - r3$ is positively correlated to the total supply chain's cost.

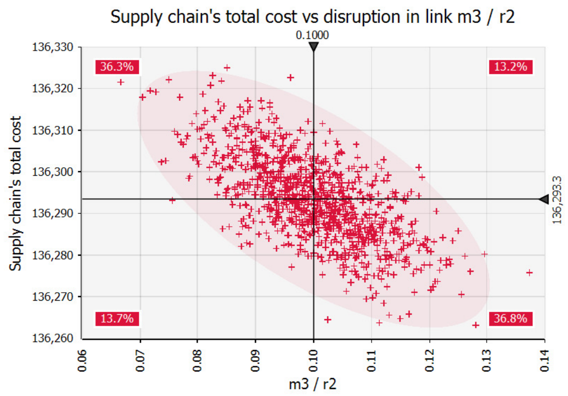

Fig. 5. Effect of disruption in link m3-r2

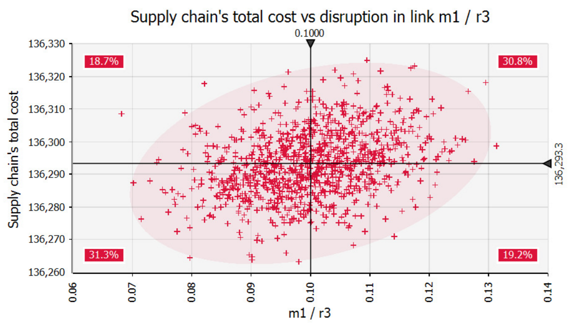

Fig. 6. Effect of disruption in link m1-r3

IV. Conclusions and Future Work

In our study, we have formulated the problem of locating and allocating facilities of a two echelon supply chain network under disruption as a mixed integer quadratic model. The decision variable in our model includes binary variables that represent the location of manufacturers in the supply chain, and the continuous variables represent the various shipment decisions. To capture the stochastic nature of demand we have used uniform distribution (other suitable distributions can also be used). We observed that the disruption free model and the resilient model yield different designs. We have statistically studied the overall nature of the cost function. In the current parameter setting we found that the disruption parameter β is highly effective in the link between $m2$ and $r1$ and causes huge variation in the cost function. We also observed the effect of disruptions in individual links in the total cost function. This model can be extended by realising a more realistic supply chain and can be studied for a greater number of echelons. In the present model, we have assumed that the manufacturers facilities will never fail. However, in reality, the manufacturers facilities may be prone to disruptions. Additionally, we have considered a single product, single period and a single route between the manufacturers and the retailers, which can be extended for multi-products, multi-periods and multiple routes.

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