Designing a Reliable Supply Chain Network Model under Disruption Risks

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Abstract: In this paper, we consider random disruption risks in designing a reliable distribution network model. We consider the disputations in the location and the capacity of the distribution centers. In our model, the probability of disruption in distribution centers is dependent to the amount of investment for opening and operating them.

We show that this problem can be formulated as a non-linear integer programming model, and then for obtaining optimal solution, we linearize the mentioned model. In the following to solve the model in large-sized instances, a tabu search algorithm is developed. The results indicate that the tabu search method is efficient for a wide variety of problem sizes.

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1. Introduction

Supply chain disruptions have gained considerable attention, especially in the last ten years. Although supply chain disruptions occur with very low probability, the consequences are typically catastrophic. In the literature, disruption risks are divided in two sections: random disruption risks and premeditated disruption risks. Random disruption risks may occur at any point in the supply chain networks, for example natural hazards (earthquake…) may strike at any point in the supply chain network. Premeditated disruption risks are more likely to target a supply chain to cause the maximum disruption. Terrorists and labor union are the examples of the premeditated disruption risks.

In this study, we focus on issues related to facility random disruption risks. For a thorough review of facility location problem and supply chain network design, see Hamacher and Drezner (2002), Barmel and Simchi-Levi (2000), Daskin (1995, 2003), Qin and tang (2010) and Klibi et al. (2010).

There are some papers in the literature for designing reliable network systems. Daskin (1983), ReVelle and Hogan (1989) and Batta et al. (1989) studied on the reliable network systems that their objective function was the maximizing the expected demand coverage while Hogan and ReVelle (1986) and Batta and Mannur (1990) focused on individual demand coverage with some degree of redundancy. Ostfeld and Shamir (1993) described the reliability methods for designing water distribution networks. Drezner (1987) proposed a reliable p-median problem and used a heuristic method for solving it. Recently, Tang et al. (2008) presented a facility location model based on reliability. They considered the level of customer service in their model. Gade and Pohl (2009) developed a capacitated facility location model with unreliable facilities. They used sample average approximation algorithm to solve their model. Wagner and Neshat (2009) developed an approach based on graph theory to quantify and mitigate supply chain disruption risks. Tancel and Alpan (2010) used a timed Petri nets framework for designing supply chain networks under risk.

The papers in the literature, consider the disruptions in the location of distribution centers. They assumed that when a disruption occurs at a distribution center, it fails. In this paper, we consider the disputations in the location and the capacity of the distribution centers. In this paper is assumed that when a disruption occurs at a distribution center, it dose not fail and the distribution center misses some of the capacity to service in disruption situation. The probability of disruption in distribution centers is dependent to the amount of investment for opening and operating them, i.e., we can reduce the probability of disruption in distribution centers with additional investments. In our model, distribution centers can ship goods together under disruption situation.

The remainder of this paper is organized as follows: In Section 2, mathematical formulation of the problem is presented. Section 3 discusses the solution approach for solving the problem. Our computational results are in Section 4. Conclusions are given in Section 5.

2. Problem description

Here, we present the reliable distribution network design model considering random disruption risk. We assume that there are two types of distribution centers in the model: reliable distribution centers and unreliable distribution centers. Disruptions occur in the unreliable distribution centers. Reliable distribution centers are safe against disruptions and also when a disruption occurs in an unreliable distribution center, it does not fail. In this case, the unreliable distribution center misses some of the capacity to service in disruption situation. In our model, the probability of disruption in unreliable distribution centers and the amount of the capacity which the unreliable distribution center misses in the disruption situation are dependent to the amount of investment for opening and operating unreliable distribution center, and finally, the reliable distribution centers can ship goods to the unreliable distribution centers in disruption situation.

Before presenting the model, let us introduce the notations that will be used throughout the paper:

Index sets

K : Set of customers.

JT : Set of potential distribution centers. $(JT = JU \bigcup JR)$

JU : Set of potential unreliable distribution centers.

JR : Set of potential reliable distribution centers.

N : Set of available investment levels for opening and operating unreliable distribution centers.

Parameters and notations

D_k : Demand of customer k, ($\forall k \in K$).

fU_{jn} : Fixed cost for opening and operating unreliable distribution center j with investment level n, $(\forall j \in JU, \forall n \in N)$.

fR_m : Fixed cost for opening and operating reliable distribution center m, $(\forall m \in JR)$.

d_{jk} : Transportation cost from unreliable distribution center j to customer k, $(\forall j \in JU, \forall k \in K)$.

l_{mk} : Transportation cost from reliable distribution center m to customer k, $(\forall m \in JR, \forall k \in K)$.

C_{mj} : Transportation cost from reliable distribution center m to unreliable distribution center j, $(\forall m \in JR, \forall j \in JU)$.

Cap_j : Capacity of unreliable distribution center j, $(\forall j \in JU)$.

a_{jn} : The percentage of total capacity of unreliable distribution center j that is affected by disruption when it is opened with investment level n, $(\forall j \in JU, \forall n \in N)$.

q_{jn} : Disruption probability in unreliable distribution center j when it is opened with investment level n, $(\forall j \in JU, \forall n \in N)$.

Decision variables

$$XU_{jn} = \begin{cases} 1 & \textit{if unreliable distribution center } j \textit{ is opened} \\ & \textit{with investment level } n. \\ 0 & \textit{otherwise} \end{cases}$$

$$XR_m = \begin{cases} 1 & \textit{if reliable distribution center } m \textit{ is opened}. \\ 0 & \textit{otherwise} \end{cases}$$

$$YU_{jk} = \begin{cases} 1 & \textit{if customer } k \textit{ is assigned to} \\ & \textit{unreliable distribution center } j. \\ 0 & \textit{otherwise} \end{cases}$$

$$YR_{mk} = \begin{cases} 1 & \textit{if customer } k \textit{ is assigned to} \\ & \textit{reliable distribution center } m. \\ 0 & \textit{otherwise} \end{cases}$$

T_{mj} : Amount of goods that is shipped from reliable distribution center m to unreliable distribution center j, $(\forall m \in JR, \forall j \in JU)$.

In terms of the above notations, the problem formulating is as follows:

$$\begin{aligned} Min: \ & \sum_{j\in JU}\sum_{n\in N} fU_{jn}\, XU_{jn} + \sum_{m\in JR} fR_m\, XR_m + \\ & \sum_{j\in JU}\sum_{k\in K} d_{jk}\, D_k\, YU_{jk} + \sum_{m\in JR}\sum_{k\in K} l_{mk}\, D_k\, YR_{mk} \\ & + \sum_{j\in JU}\sum_{n\in N} q_{jn}\, XU_{jn} \left(\sum_{m\in JR} T_{mj}\, C_{mj} \right) \end{aligned} \tag{1}$$

Subject to:

$$\sum_{j\in JU} YU_{jk} + \sum_{m\in JR} YR_{mk} = 1 \quad \forall k \in K \tag{2}$$

$$\sum_{m\in JR} XR_m \geq 1 \tag{3}$$

$$XR_h + \sum_{n\in N} XU_{hn} \leq 1 \quad \forall h \in JT \tag{4}$$

$$YR_{mk} \leq XR_m \quad \forall m \in JR, k \in K \tag{5}$$

$$\sum_{k\in K} D_k\, YU_{jk} \leq \sum_{n\in N} Cap_j\, XU_{jn} \quad \forall j \in JU \tag{6}$$

$$\sum_{m\in JR} T_{mj} + \left(1-\sum_{n\in N} a_{jn}\, XU_{jn}\right) Cap_j \geq \sum_{k\in K} D_k\, YU_{jk} \;\; \forall j \in JU \tag{7}$$

$$XR_m \in \{0,1\} \;\; \forall m \in JR \tag{8}$$

$$XU_{jn} \in \{0,1\} \;\; \forall j \in JU, \forall n \in N \tag{9}$$

$$YR_{mk} \in \{0,1\} \;\; \forall m \in JR, \forall k \in K \tag{10}$$

$$YU_{jk} \in \{0,1\} \;\; \forall j \in JU, \forall k \in K \tag{11}$$

$$T_{mj} \geq 0 \;\; \forall m \in JR, \forall j \in JU \tag{12}$$

The model minimizes the total expected costs of the fixed cost for opening distribution centers, the transportation cost from distribution centers to the customers, and the expected cost of disruption situation. Constraints (2) make sure that each customer is assigned exactly one distribution center. Constraints (3) ensure that we locate at least one reliable distribution center. Constraints (4) state that we can not locate both reliable and unreliable distribution center at any potential node h. Constraints (5) link the location and allocation variables. Constraints (6) are the capacity constraints associated with the unreliable distribution centers. Constraints (7) state that for each unreliable distribution center j, the sum of the goods which is shipped from reliable distribution centers and the total capacity which is not affected by disruption, must be greater than the total demands of the customers that is assigned to it. Constraints (8)-(11) enforce the integrality restrictions on the binary variables and finally constraints (12) enforce the non-negativity restrictions on the corresponding decision variables.

2.1. Linearization of the model

Formulation (1)-(12) is nonlinear. However, the only nonlinear terms are $T_{mj} \times XU_{jn}$, each being a product of a continuous variable and a binary variable. We define a new variable as follows:

$$W_{mjn} = T_{mj} \times XU_{jn} \tag{13}$$

The formulation (1)-(12) can be written as follows:

$$\begin{aligned} Min:\;\; & \sum_{j\in JU}\sum_{n\in N} fU_{jn}\, XU_{jn} + \sum_{m\in JR} fR_m\, XR_m \\ & + \sum_{j\in JU}\sum_{k\in K} d_{jk}\, D_k\, YU_{jk} + \sum_{m\in JR}\sum_{k\in K} l_{mk}\, D_k\, YR_{mk} \\ & + \sum_{j\in JU}\sum_{n\in N}\sum_{m\in JR} q_{jn}\, W_{mjn}\, C_{mj} \end{aligned} \tag{14}$$

Subject to:

(2)-(12)

$$W_{mjn} \leq T_{mj} \quad \forall m \in JR, j \in JU, n \in N \tag{15}$$

$$W_{mjn} \leq M \times XU_{jn} \quad \forall m \in JR, j \in JU, n \in N, \quad M \text{ is a large number} \tag{16}$$

$$W_{mjn} \geq T_{mj} + M\left(XU_{jn} - 1\right) \quad \forall m \in JR, j \in JU, n \in N, \quad M \text{ is a large number} \tag{17}$$

$$W_{mjn} \geq 0 \quad \forall m \in JR, j \in JU, n \in N \tag{18}$$

3. Tabu search algorithm for solving the problem

In this section, for solving the large-sized instances, a tabu search algorithm is developed. Tabu search is a well known global search heuristic method to solve the combinatorial problems such as the proposed problem. The most important feature of tabu search algorithm is to avoid search cycling by systematically preventing moves taking the solution, in the next iteration, to points in the solution space previously visited. In the next sections, we describe the tabu search algorithm which we use for solving the problem.

3.1. Initial solution construction

For obtaining the initial solution, first we assign customers to the distribution centers, randomly. The procedure for obtaining the initial solution is as follows:

Step1: Put customers into a set K'.
Step2: 1- Select a customer from K' randomly. 2- Delete the customer from K'.
Step3: Select a distribution center randomly.
Step4: If the selected distribution center is reliable then assign the customer to the reliable distribution center and go to Step 7 otherwise (the selected distribution center is unreliable) go to Step 5.
Step5: If we select this unreliable distribution center for the first time then select an investment level for this distribution center randomly.
Step6: If remaining capacity of the unreliable distribution center is greater than the demand of the customer then assign the customer to the distribution center and go to Step 7 otherwise go to Step 3 for selecting another distribution center.
Step7: Is K' empty? If yes, go to Step 8, otherwise go to Step 2.
Step8: By using the heuristic algorithm (H1), determine amount of goods must be shipped form the

reliable distribution centers to the unreliable distribution centers in disruption situation.
Before presenting the improvement phase, let us describe the heuristic algorithm (H1). The steps of (H1) are as follows:
For each of the opened distribution center (a'_j), let L'_j be the sum of the demands of the customers that are assigned to a'_j.
Step1: 1-Put all of the unreliable opened distribution centers into a set K''.
2- Put all of the reliable opened distribution centers into a set E'.
Step2: Select an opened unreliable distribution center (a'_j) from K'', randomly.
Step3: For each reliable opened distribution center m in the set E', calculate
$H'_{mj} = \left(L'_j - (1 - a_{jn})Cap_j\right)C_{mj}$.
Step4: Select the supplier from E' that has the minimum value H'_{mj} (Supplier m), then
$T_{mj} = H'_{mj}$.
Step5: Delete the unreliable distribution center (a'_j) from K''.
Step6: Is K'' empty? If yes stop, otherwise go to Step 2.

3.2. Improving the initial solution

In this phase, the main objective is to improve the initial solution. We apply five different types of move for generating a candidate move: mov1, mov2, mov3, mov4, mov5. We generate a candidate move (from X_0 to the candidate solution X_n) using one of the five moves randomly.

Mov1: Randomly, one of the opened distribution centers (a'_j) is closed and all of the customers are reallocated among the remaining opened distribution centers. Finally, we apply heuristic algorithm (H1) to determine amount of good that must be shipped from the reliable distribution centers to the unreliable distribution centers in disruption situation. In this move, we must check that at least one reliable distribution center is located.
Mov2: In this move we select two opened distribution centers randomly, (a'_i, a'_j), and exchange a'_i and a'_j. Finally, we use the heuristic algorithm (H1) to determine amount of good that must be shipped form the reliable distribution centers to the unreliable distribution centers in disruption situation. In this move capacities of a'_i and a'_j are checked for serving the customers. Also, we must check that at least on reliable distribution center is located.
Mov3: One of the opened distribution centers (a'_i) is closed randomly, and a closed distribution center (a'_j) is opened randomly. If the opened distribution center is unreliable, we select an investment level for this distribution center randomly. Then we assign all of the customers corresponding to the eliminated distribution center (a'_i) to the new opened distribution center (a'_j). Finally, we use the heuristic algorithm (H1) to determine amount of good that must be shipped form the reliable distribution centers to the unreliable distribution centers in disruption situation. In this move the capacity of a'_j is checked for serving the customers.
Mov4: Select two opened distribution centers, randomly, (a'_i, a'_j). Then randomly select a customer (c'_i) in a'_i and a customer (c'_j) in a'_j and exchange c'_i and c'_j. Finally, we use the heuristic algorithm (H1). In this move we must check the capacities of distribution centers.
Mov5: Select one opened unreliable distribution center, randomly. Then randomly change the investment level for this distribution center.

4. Computational results

To evaluate the performance of our overall solution procedure, extensive computational experiments are designed with respect to series of test problems. The program is coded in Visual Basic 6.

4.1. Comparison of tabu search solution with optimal solution

For evaluating the tabu search method, nineteen instances are solved by LINGO.8 software (Table 1). For each instance, the tuning of the parameters is done by carrying out random experiments. For each instance, we run the tabu search method 20 times, and the average objective value is reported in Tables 1 to 2. Also, in Tables 1, 2 the coefficient of variation for each instance is reported (Coefficient of variation for the random variable X is defined as: Standard Deviation (X)/Average (X)). In the following tables DC and CV are the abbreviations of Distribution Center and Coefficient of variation, respectively.

It can be seen that the proposed tabu search solution are optimal (or near optimal) in different problem instances (Table 1). For instances 1 to 19, the average CPU time are less than or equal to 268 seconds for the proposed tabu search method; however, the maximal average CPU time for obtaining the optimal solutions is equal to 6783 seconds, and for problem instances 15 to 19 by a reasonable amount of time limit, LINGO cannot find the optimal solution, and the tabu search solutions in these problem instances are better than the best solutions that are obtained by LINGO software.

4.2. Comparison of tabu search solution with simulated annealing (SA) solution

For evaluating the proposed tabu search algorithm, we compare the proposed tabu search with the case that we use the simulated annealing (SA) algorithm instead of tabu search algorithm. The procedure of obtaining candidate moves used in the SA algorithm is the same as that in the tabu search algorithm.

From Table 2, it can be seen that the Average costs and CV values obtained by the tabu search algorithm are better than those obtained by the SA algorithm. This shows that selection of tabu search method is a good strategy in our solution method.

5. Conclusions

In this paper, we have considered random disruption risks in designing reliable distribution network model. We considered the disputations in the location and the capacity of the distribution centers. In our model, we assumed that the distribution centers can ship goods together under disruption situation.

We showed that our model can be formulated as a linear model. Also, we presented an effective tabu search algorithm to solve the large-sized instances. We comprised the tabu search algorithm with optimal solution and simulated annealing algorithm. The computational results indicated that the tabu search method is effective for solving the problem. For future works, it is interesting to consider disruptions in the transportation costs.

Table 1. Comparison of tabu search solution and optimal solution

				Optimal Solution		Tabu Search Algorithm			
NO.	# Customers	# Potential reliable DCs	# Potential unreliableDCs	Average Cost	CPU time	Average Cost	CPU time	CV	Gap(%)
1	4	2	2	16989.7	3	16989.7	1	0	0.00
2	6	3	3	23601.6	6	23601.6	3	0	0.00
3	7	3	3	27341.7	9	27341.7	4	0	0.00
4	8	4	4	30282.0	12	30282	8	0	0.00
5	9	4	4	32877.9	18	32877.9	10	0	0.00
6	20	5	5	74805.8	96	74805.8	25	0	0.00
7	30	6	6	102040.3	135	102040.3	35	0	0.00
8	40	8	8	135337.3	241	135434.1	45	0	0.07
9	50	10	10	169934.1	368	170131.2	60	0	0.12
10	60	12	12	195877.4	731	196290.7	71	0.0001	0.21
11	70	14	14	233535.2	1324	234178	85	0.0001	0.28
12	80	16	16	278781.6	2011	279676.9	102	0.0001	0.32
13	90	18	18	320957.4	3312	321971.4	119	0.0001	0.32
14	100	20	20	350218	6783	351415.9	134	0.0001	0.34
15	120	23	23	433318.1	2 hours limit	416206.4	170	0.0001	
16	140	26	26	509494.1	3 hours limit	482168.5	201	0.0001	
17	150	27	27	539791.7	3 hours limit	507161.8	220	0.0001	
18	160	28	28	583263.6	3 hours limit	542286.4	234	0.0001	
19	180	30	30	668868.9	4 hours limit	605107.3	268	0.0001	

Gap(%)= 100*(tabu search solution value – LINGO best solution value) / LINGO best solution value.
CV= Coefficient of variation

Table 2. Comparison the results of tabu search algorithm with SA algorithm

NO.	# Customers	# Potential reliable DCs	# Potential unreliableDCs	Based on tabu algorithm			Based on SA algorithm			Percent of improved cost
				Average cost	CPU time	CV	Average cost	CPU time	CV	
1	30	8	8	102040.3	35	0	106426.9	35	0.0002	4.30
2	40	10	10	135434.1	45	0	140368.6	45	0.0002	3.64
3	50	12	12	170131.2	60	0	178109.6	59	0.0002	4.69
4	60	14	14	196290.7	71	0.0001	206081.6	71	0.0002	4.99
5	70	16	16	234178	85	0.0001	245055.6	86	0.0002	4.65
6	80	18	18	279676.9	102	0.0001	295041.5	102	0.0002	5.49
7	90	20	20	321971.4	119	0.0001	338922.3	116	0.0003	5.26
8	100	23	23	351415.9	134	0.0001	374588.4	132	0.0003	6.59
9	120	26	26	415600.8	170	0.0001	441435.8	168	0.0003	6.22
10	140	27	27	481463.5	201	0.0001	515848.3	198	0.0003	7.14
11	150	28	28	506181.8	220	0.0001	543736.9	219	0.0003	7.42
12	160	30	30	540939.4	234	0.0001	582330.2	234	0.0004	7.65
13	180	32	32	603000.8	268	0.0001	653191	265	0.0004	8.32
14	200	34	34	686791	304	0.0001	746256	302	0.0004	8.66
15	230	36	36	801394.1	360	0.0001	880129.4	357	0.0005	9.82
16	250	38	38	886215.8	396	0.0001	978251.6	392	0.0005	10.39
17	280	40	40	1010105.9	452	0.0001	1121535.8	448	0.0005	11.03
18	300	42	42	1094798.4	491	0.0001	1224386.4	488	0.0005	11.84

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