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Designing a Reliable Distribution Network with Facility Fortification and Transshipment under Partial and Complete Disruptions

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ABSTRACT

This paper designs a reliability distribution network with limited capacity under partial and complete facility disruptions. To increase the reliability of the distribution network, a new mixed integer linear programing model is developed by considering multiple mitigation strategies including diversification, fortification, and transshipment. The distribution network constitutes of reliable distribution centers are more expensive, always available and not affected by disruption, and unreliable distribution centers. Thus, they might be fortified at any level of reliability. Several numerical examples with sensitivity analyses are conducted to illustrate the usefulness of the proposed model. Results demonstrate that the transshipment strategy is more effective than the other mitigation strategies on distribution network reliability and cost.

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1. INTRODUCTION

Distribution centers are critical part of any supply chains which support the distribution of goods and services from the suppliers to the consumers [1, 2]. In the recent decade, the trade-off between the total cost and the environment influence of supply chain have been studied comprehensively [3, 4]. Although most of the logistics network designs models in the literature typically assume that facilities never fail, and they are always available and absolutely reliable, but in the real world cases, every supply chain faces disruptions of various sorts and facilities are always subjected to partial or complete disruptions [5, 6]. Also, the new efficient initiatives exacerbated enterprises exposure to the risks such as lean manufacturing, just-in-time production, outsourcing, and slim inventories [1]. The recent events such as Hurricanes Katrina and Rita in 2005 on the U.S. Gulf Coast crippled the nation's oil refining capacity [7], a strike at two General Motors parts plants in 1998 led to production loss [8, 9], 2011 Thailand flood that disrupted the auto and hard disk supply chains of multinational companies including Apple, Ford Motor, Nissan Motor, Honda, Toshiba, Toyota Motor and Western Digital [6, 10]. All above proved that companies reputation, earnings consistency which show the necessity of considering disruptions risks while designing supply chain networks. In this study, we assume a set of customers which must be assigned to a set of Distribution Centers (DCs).

Distribution centers' failures were considered to happen independently with site specific probabilities, also they are not classified into two groups; totally reliable and unreliable like Lim et al. [11]. We consider several reliability levels for fortification strategy. According to the fortification strategy, distribution centers can be fortified to any reliability level up to becoming totally reliable. However, most network design models assumed that the unreliable facilities are fully failed when disruptions occur e.g., [11, 12], but they may be disrupted partially, and hence they may meet customers'

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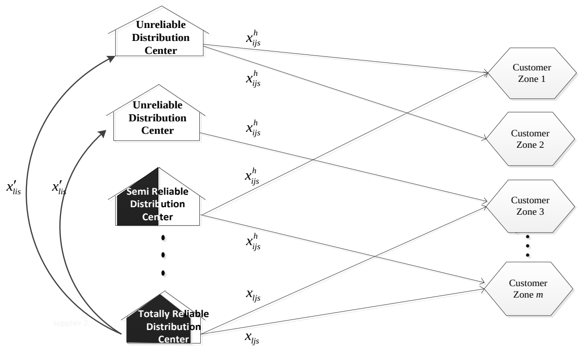

Figure 1. Overview of model

demand with a remaining of its initial capacity post disruptions. To address this issue, this paper which assumed unreliable DCs can be partially or completely disrupted and disrupted unreliable DC may serve customer demands with a remaining of its initial capacity. When there is an unreliable DC and imperfect performances of distribution centers, the quantity of products which is transformed from each DC to each customer may be less than what was originally planned, subsequently the system incurs penalty costs. In fact, it is not necessary that all demands have to be met. We assume the remaining capacity after disruption is depend on two factor; severity of disruption and fortification. As shown in Figure 1, set of customer must be assigned to set of DC. The reliability of distribution centers is also different from each other. By looking to Figure 1, the black side of DCs shows level of DCs reliability. The optimal level of reliability can also be determined.

Additionally, two types of transshipment can be available: (1) transshipment from totally reliable DCs to unreliable DCs and (2) transshipment among unreliable/semi-reliable DCs (i.e., unreliable DCs which fortified gradually) as shown in Figure 1.

According to comprehensive review of Snyder, Atan [13], another limitation is that the most models in literature of reliable supply chain design typically have not considered proactive and reactive strategies simultaneously. To the best of our knowledge, this is the first study which considers multiple mitigation strategies simultaneously: such as, diversification, fortification and transshipment, instead of single type of mitigation.

We aim to formulate problem as a mixed integer linear programming model, which objective minimizes expected total cost. The total cost includes fixed location costs, fortification costs of DCs, penalty costs of unreliable performances of DCs and lost sales costs. We consider scenario based approach (by defining disruption scenarios) to cope with the random nature of disruption risks. The fuzzy approach used in the paper is dealt with the capacity disruptions in each disruption scenario. In another words, in each disruption scenario, we uses the fuzzy concepts to define the partial and complete capacity disruptions occurred at unreliable facilities.

The problem lies in simultaneously determining:

1) Determining where DCs are located and which DCs are assigned to which customers? By considering failure probability of DC.

2) Determining which one of DCs must be fortified and the optimal level of fortification/reliability? In our model, the reliability of fortified DCs is not limited to ‘‘totally reliable’’. Instead, a DC can be fortified to any reliability level up to becoming totally reliable. This option provide the opportunity to use limited fortification resources efficiently.

3) Determining which transshipment must be existed between unreliable DC and reliable DC? (Figure 1)

4) Considering multiple mitigation strategies simultaneously: such as, diversification, fortification and transshipment, instead of single type of mitigation strategy.

2. LITERATURE REVIEW

To our best knowledge, the first study on facility location with unreliable suppliers is conducted by Drezner [14]. Snyder [15] attempts minimize a weighted sum of the nominal cost (the cost when no disruptions occur) and the expected of random disruptions. For this, they presented two reliability models: reliable P-median and a reliable incapacitated fixed-charge location (RUFL) mode. Also, Berman, Krass [16] proposed a model for designing supply chain network design where the facility disruption probabilities are not identical. They applied several exact and heuristic solution approaches and analyzed the impact of the disruption probabilities on the centralization and co-location of the facilities.

Li and Savanchien [1] developed an extension of the reliable P-median facility location problem (RPMP) which was introduced by Snyder [15] and a reliable incapacitated fixed-charge location problem (RUFL). Lim et al. [11] applied mixed integer programming due to formulate facility reliability problem (FRP) against random facility disruptions. The authors extend the uncapacitated fixed charge location problem (UFLP) due to minimize the sum of the fixed facility and transportation costs and applied a Lagrangian relaxation algorithm as a solution method. The studies which is addressed earlier assumed that disruption occured independently.

However, Li [17] formulate reliable versions of the uncapacitated fixed-charge location problem (UFLP) by considering spatial correlation among facility disruptions. A Continuum Approximation (CA) approach is applied to estimate and design the complex system. Jabbarzadeh et al. [18] proposed a model for designing a reliable supply chain network under disruption which determine the number facilities, the assignment of customers to facilities, and the cycle-order quantities at facilities. They proposed two solution methods based on Lagrangian relaxation and genetic algorithm in order to obtain near-optimal. As looking to disruptions in a multi-echelon supply chain, Bunschuh [19] improved the robustness of the network by using redundancy strategy. It means that by adding supplier sourcing constraints customers are forced to be assigned to multiple suppliers. However, this approach does not explicitly consider the possibility of disruption for each supplier.

Several models for facility location and supply chain network design problems under disruptions presented by [20], including a network design model that an expected-cost objective rather than a robustness constraint. However, they did not suggest solution methods for model. Lim et al. [11] considered the first study on network design with fortification and analyzed the incapacitated fixed-charge facility location (UFLP) model with two types of facilities: unreliable and totally reliable or ‘‘hardened’’. Peng Peng [21] used scenario-based stochastic programming approach. They consider general, multi-echelon network design problems (of which facility location problems are special cases) and considered a robustness constraint rather than using an expected-cost objective. A hybrid metaheuristic algorithm was proposed. The integrated facility location design problem presented by Qi et al. [22]. They proposed the model due to determine the optimal locations of retailers, customer assignations and inventory policy. In their study, they considered the case in which supplier and retailers can be disrupted randomly. A resilient design problem for a coverage-type service system proposed by O’Hanley and Church [23]. The model seeks to locate optimally a set of facilities to maximize a combination of initial demand coverage and the minimum coverage level following the loss of one or more facilities.

Interdiction modeling also applied to identify the weakest elements of a system or the worst-case intentional disruption of a system [24]. Interdiction models have been studied comprehensively, in particular within the context of network flow problems. Interdiction models were first introduced by Wollmer [25]. Interdiction models also applied foridentification of critical components. The r-interdiction median problem with fortification (IMF) was first formulated as a mixed-integer program by Church [26] who examined the impact of facility fortification for reliability improvement.

A novel mathematical formulation and an effective solution technique for the optimal allocation of asset fortification in a service supply system given the possibility of interdiction provided by Scaparra and Church [24]. In other words, the aim of paper was to minimize disruptive effects of possible intentional attacks to the system. In summarized, Table 1 shows research gapin the literature and shows the main features of our proposed model in the literature.

TABLE 1. Summary of the main reliable facility location literature

Reference	Research Component									
	Fortification	**Type of Disruption**	**Failure events**	**Failure probability**	**Fortification Cost/budg**	**Modeling approach**	**Solution approach**	**Layer of back up**	**Lost sales Cost**	**Transshipment**
[11]	0-1	Random Disruption	Independent	homogenous	_	RPMP/ RFLP	LR	Multiple	_	_
[9]	0-1	Random Disruption	Independent	SS	_	RUFL	CA &LR	Multiple	_	_
[1]	Level of reliability	Random Disruption	independent	SS	Finite budget	RUFL-F	heuristic	One	_	_
[17]	0-1	Random Disruption	Correlated	SS	_	RUFL	CA	_	_	_
[18]	0-1	Intentional attacks	Independent	Non homogenous	Cost	IMF	heuristic	_	_	-
[14]	0-1	Intentional attacks	Independent	Non homogenous	Cost	S-RIMF	heuristic	_	_	-
Current	Level	Random Disruption	Independent	SS	Cost	MILP		_	√	√

0-1: 0 means unreliable, 1 means totally reliable; RPMP: reliable P-median problem; RFLP – reliable fixed charge location problem; RUFL – reliable uncapacitated facility location; RIM – r-interdiction median; RIMF – RIM with fortification; FRP – facility reliability problem; SS – site-specific; LR – Lagrangian relaxation; CA – continuum approximation; IE- implicit enumeration.

3. PROBLEM DESCRIPTION

In this section, a mixed-integer programming model is proposed for facility location and protection problem by considering transshipment between DCs under disruption. Two types of DCs are considered; first totally reliable DCs, more expensive, always available and not affected by disruption as well, second, unreliable which can be fortified at any level of reliability, similar [1, 2]. We assume disruption occurs in unreliable DCs independently and when a disruption occurs at a distribution center, they may not fail completely and the distribution center misses some of the capacity to service in disruption situation. However, in contrast Li and Savachkin [1], we apply linear programming instead of non-linear programming. Totally reliable DCs and not affecteded unreliable supplier could transshipment goods to disrupted unreliable DCs in disruption situation as well as could ship goods to customer zone. The amounts of disruption in unreliable DCs and level of fortification can affect the remaining capacity of unreliable DCs. We apply the fuzzy concepts to incorporate the partial and complete capacity disruptions of unreliable facilities in each disruption scenario. To cope with epistemic uncertainty about distribution network design parameters (i.e: demand, disruption effect on unreliable DCs capacity and costs), we propose credibility-based fuzzy optimization model. In summery, proposed model is able to: (1) consider both partial and complete random disruption risk on unreliable DCs capacity when designing a logistics network, and (2) cope with epistemic uncertainty in the model parameters (i.e., costs, amount of disruption, etc.) resulting from unavailability and imprecise nature of input data in real cases.

Also, the problem lies in simultaneously determining:

a) Where DCs are located and which types of DCs are assigned to which customers?

b) Determine which one of unreliable DCs must be fortified and the optimal level of fortification?

c) Which transshipment must be existed between unreliable DC and reliable DC?

d) Determine the value and optimal deployment of such multi-pronged mitigation approaches (Diversification, Fortification, Transshipment).

As initial deterministic scenario-based formulation is as follows:

Indices	
I	Shows set of potential unreliable DCs (i=1,2,…,I)
L	Shows set of potential totally reliable DCs (l=1,2,…,L)
N	Shows potential DCs ($N = I \cup L$)
J	Shows number of customer zone (j=1,2,...,m)
H	Shows level of fortification for unreliable DCs (h=0,1,…,H)
S	Shows number of scenarios (s=1,2,…,S)
Parameters	
$\tilde{f}_i$	Fixed cost of opening unreliable DCs i
$\tilde{f}_l$	Fixed cost of opening unreliable DCs l
$\tilde{c}_{ijs}^h$	Shipment cost of unreliable DC i to customer zone j under scenario s at fortification level h
$\tilde{c}_{lj}$	Shipment cost of totally reliable DC l to customer zone j
$\tilde{c}_{li}$	Transshipment cost between totally reliable DC l and unreliable DC i
$\tilde{d}_j$	Demand of customer zone j
$\tilde{r}_{is}^h$	The percentage of total capacity of unreliable DC i which is affected by scenario s at fortification level h
$\tilde{A}_{is}^h$	Capacity disruption parameter: Total available capacity of unreliable DC i which is affected by scenario s at fortification level h ($\tilde{A}_{is}^h = \tilde{k}_i.\tilde{r}_{is}^h$)
$\tilde{\pi}_j$	Shortage cost of customer zone j
P_S	Probability of disruption scenario s
$\tilde{k}_i$	Capacity of unreliable DC i
$\tilde{k}_l$	Capacity of totally reliable DC l
$T\tilde{R}C_l$	Fixed cost of transshipment from total reliable DC l
Decision variables	
y_i	1, if unreliable DC i is opened; 0 otherwise
y_l	1, if totally reliable DC l is opened; 0 otherwise
b_j^s	Amount of shortage at customer zone j under scenario s
p_{li}	1, if totally reliable DC l transshipment good to unreliable DC i;0 otherwise
z_{ih}	1, if unreliable DC i protected up to level h; 0 otherwise
x_{ijs}^h	Amount of goods which is shipped from unreliable DC i at fortification level h to customer zone j under scenario s
x_{ljs}	Amount of goods which is shipped from totally reliable DC l to customer zone j under scenario s
x'_{lis}	Amount good which is shipped from totally reliable l to unreliable i under scenario s

Assumptions

1) All DCs have limited capacities.

2) A set of unreliable DC may be simultaneously disrupted partially and fully in a given scenario.

3) A totally reliable DC never fails.

4) The transshipment between totally reliable DCs and unreliable DCs could be existed.

5) If an unreliable DC fails, it doesn't becomes totally unavailable but it may serve manufactures demands with a remaining of its initial capacity.

6) Fortification doesn't reduce the probability of unreliable DCs failure, it reduces the loss of initial capacity.

7) The fortification of unreliable DCs to any level of reliability up to becoming totally reliable.

Objective 1

$$\min Z(s)=\sum_{i\in I}\tilde{f}_i y_i+\sum_{l\in L}\tilde{f}_l y_l+\sum_{i\in I}\sum_{h\in H} z_{ih}\tilde{g}_h+\sum_{i\in I}\sum_{l\in L} p_{li}\, T\tilde{R}C_l+\sum_{l\in L}\sum_{j\in J}\tilde{C}_{lj}x_{ljs}+\sum_{i\in I}\sum_{j\in J}\sum_{h\in H}\tilde{C}^h_{ijs}x^h_{ijs}+\sum_{i\in I}\sum_{l\in L}\tilde{C}'_{lis}x'_{lis}+\sum_{j\in J} b^s_j\tilde{\pi}_j \quad (1)$$

The aim of the objective is to minimize cost for each disruption scenario. The costs which is not related to scenarios includes fixed cost of opening potential unreliable and totally reliable DCs, fortification cost of unreliable DCs, fixed cost of transshipment and shipment of totally reliable DCs. The last part of Equation (1) minimize expected cost of system in which is related to costs in disruption situation; includes, shipment cost of unreliable DCs, transshipment cost between unreliable and totally reliable DCs and shortage cost under scenarios.

Constraints

$$\sum_{i\in I}\sum_{h\in H} x^h_{ij0}+\sum_{l\in L} x_{lj}\geq \tilde{d}_j \qquad \forall j\in J, \forall s=0 \quad (2)$$

$$\sum_{i\in I}\sum_{h\in H} x^h_{ijs}+\sum_{l\in L} x_{lj}+b^s_j\geq \tilde{d}_j \quad \forall j\in J \;\&\; s\in S-\{0\} \quad (3)$$

$$\sum_{j\in J} x^h_{ijs}-\sum_{l\in L} x'_{lis}\leq (\tilde{A}^h_{is}=\tilde{k}_i.\tilde{r}^h_{is}).y_i \quad \forall i\in I, \forall h\in H \quad (4)$$

$$\sum_{j\in J} x_{ljs}+\sum_{i\in I} x'_{lis}\leq \tilde{k}_l.y_l \qquad \forall l\in L, s\in S \quad (5)$$

$$\sum_{h\in H} z_{ih}=y_i \qquad \forall i\in I \quad (6)$$

$$x^h_{ijs}\leq M.z_{ih} \qquad \forall i\in I, \forall j\in J, \forall h\in H \quad (7)$$

$$x'_{lis}\leq \tilde{k}_l.p_{li} \qquad \forall l\in L, \forall i\in I \quad (8)$$

$$\sum_{l\in L} p_{li}\leq y_i \qquad \forall i\in I \quad (9)$$

$$\sum_{i\in I} p_{li}\leq y_l \qquad \forall l\in L \quad (10)$$

As mentioned earlier in normal situation, shortage is not allowed, constraint (2) ensures that all demands must be satisfied in normal situation (s=0 means there is no disruption). Constraint (3) determine total amount of shortage under each scenario except normal situation. Constraint (4) ensures total amounts of order which an unreliable DC could shipment, must not be greater than percentage available capacity of unreliable DC which is remained under disruption scenario plus transshipment from totally reliable DCs. Constraint (5) guarantees that total amount of order in which a totally reliable could shipment to customer or transshipment to unreliable DCs under each scenario must not be exceed than capacity of totally reliable DC. Constraint (6) ensures only selected DCs can be protected and just one level of fortification must be selected (h=0 means DC is not fortified). Constraint (7) shows only selected DCs could shipment order. Constraint (8) means totally reliable DC could shipment order to unreliable DC, if transshipment arc between them be available, in other word they must contracted with each other in advance. Constraints (9) and (10) ensure that only between selected reliable and unreliable DCs transshipment arc could be available.

Non-negativity and integrality conditions:

$$x^h_{ijs}\geq 0, x_{lj}\geq 0, x'_{lis}\geq 0, b^s_j\geq 0 \quad \forall i\in I, \forall l\in L, \forall j\in J, \forall s\in S, \forall h\in H \quad (11)$$

$$y_l\in\{0,1\} \qquad \forall l\in L \quad (12)$$

$$y_i\in\{0,1\} \qquad \forall i\in I \quad (13)$$

$$p_{li}\in\{0,1\} \qquad \forall l\in L, \forall i\in I \quad (14)$$

$$z_{ih}\in\{0,1\} \qquad \forall i\in I, \forall h\in H \quad (15)$$

In the next section, this measure will be discussed in details.

2. 1. P-Robust Formulation According to [13], although a few of the models in literature considered risk aversion; nearly all assume a risk-neutral decision maker who wishes to optimize the expected value of the objective function, its logical to minimize the maximum damage to a system for dealing with disruption risks and the supply chain network must be hedged against the worst-case scenario rather than expected cost, see [13, 27, 28]. In order to minimizing the worst case scenario, we incorporate p-robustness measure into our formulation, which is proposed by Snyder and Daskin [28], as follows.

Let (*X*, *Y*) be a feasible solution where *X* and *Y* indicate the vector of location and flow variables, respectively, and $F_s(X,Y)$ denotes the objective value of solution (*X*, *Y*) under scenario *s*. The relative regret for scenario *s* is defined as follows:

$$\frac{Z_s(X,Y)-Z^*_s}{Z^*_s}\leq p \quad , \forall s\in S \quad (16)$$

2. 2. Cridibility-based Chance Constraint Programming Although disruption risks which have a random nature in reality aren't fully considered by a fuzzy approach, we consider scenario based approach to deal with the random nature of disruption risks. In another words, in each disruption scenario, we uses the fuzzy concepts to define the partial and complete capacity disruptions occurred at unreliable facilities in order to determining the remained of initial capacity or capacity disruption parameters. To deal with this challenge we apply credibility-based fuzzy chance constrained programming model.

Advantages of this approach are as follows:

a) Do not increase the number of constraints;

b) Do not need additional information for objective function;

c) Apply the advantages of the chance constrained programming approach;

In this manner, we used possibility theory and credibility measure proposed by Liu [21]. According to their proposed methodology the final model will be as follows:

$$\begin{aligned}\min E[Z^{II}(s)] &= \sum_{i\in I}\Big(\frac{\tilde f_{i(1)}+\tilde f_{i(2)}+\tilde f_{i(3)}+\tilde f_{i(4)}}{4}\Big).y_i+\sum_{l\in L}\Big(\frac{\tilde f_{l(1)}+\tilde f_{l(2)}+\tilde f_{l(3)}+\tilde f_{l(4)}}{4}\Big).y_l\\ &+\sum_{i\in I}\sum_{h\in H}\Big(\frac{\tilde g_{h(1)}+\tilde g_{h(2)}+\tilde g_{h(3)}+\tilde g_{h(4)}}{4}\Big).z_{ih}+\sum_{i\in I}\sum_{l\in L}\Big(\frac{T\tilde RC_{l(1)}+T\tilde RC_{l(2)}+T\tilde RC_{l(3)}+T\tilde RC_{l(4)}}{4}\Big).p_{li}\\ &+\sum_{l\in L}\sum_{j\in J}\Big(\frac{\tilde C_{ij(1)}+\tilde C_{ij(2)}+\tilde C_{ij(3)}+\tilde C_{ij(4)}}{4}\Big).x_{lj}+\sum_{i\in I}\sum_{j\in J}\sum_{h\in H}\Big(\frac{\tilde C^h_{ij0(1)}+\tilde C^h_{ij0(2)}+\tilde C^h_{ij0(3)}+\tilde C^h_{ij0(4)}}{4}\Big).x^h_{ij0}\\ &+\sum_{i\in I}\sum_{l\in L}\Big(\frac{\tilde C'_{li0(1)}+\tilde C'_{li0(2)}+\tilde C'_{li0(3)}+\tilde C'_{li0(4)}}{4}\Big).x'_{li0}+\sum_{j\in J}\Big(\frac{\tilde\pi_{j(1)}+\tilde\pi_{j(2)}+\tilde\pi_{j(3)}+\tilde\pi_{j(4)}}{4}\Big).b^0_j\end{aligned} \quad (17)$$

s.t.

$$\begin{aligned}&\sum_{i\in I}\Big(\frac{\tilde f_{i(1)}+\tilde f_{i(2)}+\tilde f_{i(3)}+\tilde f_{i(4)}}{4}\Big).y_i+\sum_{l\in L}\Big(\frac{\tilde f_{l(1)}+\tilde f_{l(2)}+\tilde f_{l(3)}+\tilde f_{l(4)}}{4}\Big).y_l\\ &+\sum_{i\in I}\sum_{h\in H}\Big(\frac{\tilde g_{h(1)}+\tilde g_{h(2)}+\tilde g_{h(3)}+\tilde g_{h(4)}}{4}\Big).z_{ih}+\sum_{i\in I}\sum_{l\in L}\Big(\frac{T\tilde RC_{l(1)}+T\tilde RC_{l(2)}+T\tilde RC_{l(3)}+T\tilde RC_{l(4)}}{4}\Big).p_{li}\\ &+\sum_{l\in L}\sum_{j\in J}\Big(\frac{\tilde C_{ij(1)}+\tilde C_{ij(2)}+\tilde C_{ij(3)}+\tilde C_{ij(4)}}{4}\Big).x_{lj}+\Big(\sum_{i\in I}\sum_{j\in J}\sum_{h\in H}\Big(\frac{\tilde C^h_{ijs(1)}+\tilde C^h_{ijs(2)}+\tilde C^h_{ijs(3)}+\tilde C^h_{ijs(4)}}{4}\Big).x^h_{ijs}\\ &+\sum_{i\in I}\sum_{l\in L}\Big(\frac{\tilde C'_{lis(1)}+\tilde C'_{lis(2)}+\tilde C'_{lis(3)}+\tilde C'_{lis(4)}}{4}\Big).x'_{lis}+\sum_{j\in J}\Big(\frac{\tilde\pi_{j(1)}+\tilde\pi_{j(2)}+\tilde\pi_{j(3)}+\tilde\pi_{j(4)}}{4}\Big).b^s_j\le(1+P)*Z^*(s)\end{aligned} \quad (18)$$

$$\sum_{i\in I}\sum_{h\in H}x^h_{ij0}+\sum_{l\in L}x_{lj}\ge(2-2\alpha_j)d_{j(3)}+(2\alpha_j-1)d_{j(4)} \quad \forall j\in J \quad (19)$$

$$b^s_j+\sum_{i\in I}\sum_{h\in H}x^h_{ijs}+\sum_{l\in L}x_{lj}\ge(2-2\lambda_j)d_{j(3)}+(2\lambda_j-1)d_{j(4)} \quad \forall j\in J,\forall s\in S-\{0\} \quad (20)$$

$$\sum_{j\in J}x^h_{ijs}-\sum_{l\in L}x'_{lis}\le y_i[(2\beta_i-1)\mathrm{A}^h_{is(1)}+(2-2\beta_i)\mathrm{A}^h_{is(2)}] \ \forall i\in I,\forall s\in S,\forall h\in H \quad (21)$$

$$\sum_{j\in J}x_{lj}+\sum_{i\in I}x'_{lis}\le y_l.[(2\gamma_i-1)\mathrm{k}_{l(1)}+(2-2\gamma_i)\mathrm{k}_{l(2)}] \quad \forall l\in L,\forall s\in S \quad (22)$$

Constraints (6)-(16) $\forall s\in S$

TABLE 2. Details of numerical experiments

Problem No.	No. of unreliable DC (I)	No. of totally reliable DC(L)	No. of customer zone (J)	No. of fortification level (H)	No. of scenario (S)
1	4	4	7	4	11
2	8	8	14	4	15

TABEL 3. Demand of each customer zone

Customer zone (j)	Demands $(d_{j(1)},d_{j(2)},d_{j(3)},d_{j(4)})$	Shortage cost $(\pi_{j(1)},\pi_{j(2)},\pi_{j(3)},\pi_{j(4)})$
(1)	(120,130,150,180)	(5000,6500,8000,9500)
(2)	(135,140,150,190)	(4000,7000,8500,9000)
(3)	(160,175,190,210)	(6000,7500,8000,9500)
(4)	(125,130,150,170)	(6000,7000,8000,1000)
(5)	(110,140,150,160)	(8000,9500,10000,11500)
(6)	(150,175,190,200)	(7000,8500,10000,12500)
(7)	(140,150,175,185)	(5000,6500,8000,10500)
(8)	(130,140,150,180)	(3000,6500,7000,7500)
(9)	(100,130,150,160)	(5000,6000,7500,8000)
(10)	(120,130,150,180)	(6000,6500,8000,9500)
(11)	(100,130,150,200)	(7000,8500,95000,11500)
(12)	(140,150,160,180)	(5000,6000,8000, 10000)
(13)	(125,130,150,170)	(4500,8000,9000,9500)
(14)	(110,130,150,190)	(5000,6000,8000,9500)

3. NUMERICAL EXAMPLE

To illustrate the validity of the proposed model and the usefulness of the proposed solution methodology, several numerical experiments are solved and the related results are reported in this section. To this end, two test problems are designed and their sizes are shown in Table 2.

To estimate the possibility distribution of imprecise parameters, a focus group of field experts and firm's managers has been formed to determine the four prominent values of each trapezoidal fuzzy number according to the available data and their knowledge. Due to space limitation, only the value of some important imprecise parameters related to customer zones demand, distribution centers available capacity under each scenario and costs provided here through Tables 3 to 7, respectively.

4. RESULTS AND DISCUSSION

The optimal solution for test problems 1 and 2 are summarized in Table 8. As shown in Table 8, in this case, the worst-case cost is equal to 6648000, with an increase of 916966 or 16.03% in compare to its nominal cost. Similarly, for test problem 2, with an increase of 2908701 or 19.1%. As highlighted in disruption modeling literature, a little increase in costs can protect the network against the threat of disruptions. We also observe similar phenomena in our numerical results.

In this study, some sensitivity analyses are carried out. First of all is uncertainty level. As shown in Figure

2, the impact of uncertainty level on the objective function value is considered. It is anticipated as we increase the level of ($\alpha_j, \lambda_j, \beta_i$), the total cost is also raised. For sake of simplicity, we assume that ($\alpha_j = \lambda_j = \beta_i \quad \forall i, j$).

According to the Table 9, it can be affirmed the huge effectiveness of transshipment strategy.By eliminating transshipment strategy, we can see that the number of totally reliable DCs increases and the number of unreliable DCs decreases; however, the reliability level of unreliable DCs increases.

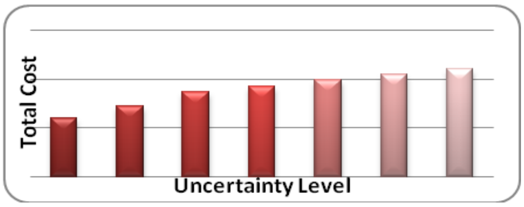

Figure 2. Sensetive analysis of the uncertainty level

TABLE 4. Fixed cost of opening facilities

Potential DC	Fixed cost of total reliable DC (l) $(f_{l(1)}, f_{l(2)}, f_{l(3)}, f_{l(4)})$	Fixed cost of DC (i) $(f_{i(1)}, f_{i(2)}, f_{i(3)}, f_{i(4)})$
(1)	(140000, 148000, 152000, 157000)	(66500, 74000, 76000, 82000)
(2)	(140000, 147000, 151000, 155000)	(57000, 78000, 126000, 130000)
(3)	(139000, 145000, 153000, 161000)	(66000, 90000, 100000, 131000)
(4)	(149000, 155000, 159000, 164000)	(77500, 99000, 125000, 15500)
(5)	(140000, 147000, 151000, 155000)	(53000, 60000, 62000, 65000)
(6)	(140000, 148000, 152000, 157000)	(66500, 74000, 76000, 82000)
(7)	(132000, 139000, 144000, 150000)	(60000, 78000, 112000, 131200)
(8)	(133000, 140000, 146000, 152000)	(50000, 72000, 112000, 131200)

TABLE 5. Fortification cost of unreliable DC

	Level of fortification H	Fortification cost $(g_{h(1)}, g_{h(2)}, g_{h(3)}, g_{h(4)})$	Available capacity of unreliable DC (i) $r_{is}^h = (r_{is(1)}^h, r_{is(1)}^h, r_{is(1)}^h, r_{is(1)}^h)$
(1)	h=0	0 (not fortified)	(0.1,0.15,0.2,0.25)
	h=1	(10000,12000,14000,15000)	(0.2,0.25,0.3,0.33)
	h=2	(13000,15000,17000,19000)	(0.2,0.3,0.35,0.4)
	h=3	(20000,25000,30000,35000)	(0.3,0.35,0.4,0.45)
(2)	h=0	0 (not fortified)	(0.12,0.18,0.2,0.25
	h=1	(12000,13000,17000,18000)	(0.2,0.22,0.3,0.4)
	h=2	(14000,15000,18000,20000)	(0.25,0.3,0.35,0.5)
	h=3	(22000,27000,30000,35000)	(0.3,0.35,0.4,0.5)
(3)	h=0	0 (not fortified)	(0.1,0.15,0.2,0.25)
	h=1	(11000,14000,17000,18000)	(0.2,0.22,0.3,0.4)
	h=2	(14000,15000,19000,27000)	(0.2,0.25,0.3,0.35)
	h=3	(22000,27000,33000,38000)	(0.3,0.35,0.4,0.45)
(4)	h=0	0 (not fortified)	(0.1,0.15,0.2,0.25)
	h=1	(9000,13000,15000,17000)	(0.2,0.22,0.3,0.4)
	h=2	(14000,15000,16000,27000)	(0.2,0.25,0.3,0.35)
	h=3	(19500,20000,30000,40000)	(0.3,0.35,0.4,0.5)
(5)	h=0	0 (not fortified)	(0.1,0.15,0.2,0.25)
	h=1	(13000,14000,16000,18000)	(0.2,0.25,0.3,0.4)
	h=2	(15500,18000,19000,25000)	(0.3,0.4,0.5,0.6)
	h=3	(22000,23000,28000,33000)	(0.4,0.45,0.6,0.7)
(6)	h=0	0 (not fortified)	(0.1,0.15,0.2,0.25)
	h=1	(10000,12000,16000,17500)	(0.2,0.25,0.3,0.35)
	h=2	(16000,18000,22000,25000)	(0.4,0.45,0.5,0.55)
	h=3	(21000,25000,28000,35000)	(0.3,0.4,0.6,0.7)
(7)	h=0	0 (not fortified)	(0.1,0.15,0.2,0.25)
	h=1	(9000,12000,14000,16000)	(0.2,0.25,0.3,0.4)
	h=2	(15000,18000,21000,25000)	(0.2,0.3,0.35,0.4)
	h=3	(23000,25000,27000,31000)	(0.4,0.45,0.6,0.7)
(8)	h=0	0 (not fortified)	(0.1,0.15,0.2,0.25)
	h=1	(13000,14000,15000,16000)	(0.2,0.22,0.3,0.4)
	h=2	(17000,19000,21000,26000)	(0.3,0.4,0.5,0.6)
	h=3	(28000,30000,35000,38000)	(0.4,0.45,0.5,0.55)

TABLE 6. Capacity of total reliable and unreliable DC

Distribution centerNo.	Capacity of DC (i) $(k_{i(1)}, k_{i(2)}, k_{i(3)}, k_{i(4)})$	Capacity of total reliable DC (l) $(k_{l(1)}, k_{l(2)}, k_{l(3)}, k_{l(4)})$
(1)	(370,390,400,440)	(300,320,370,400)
(2)	(380,400,440,480)	(330,370,410,450)
(3)	(400,430,450,500)	(280,330,370,390)
(4)	**(430,450,500,530)**	(310,350,370,420)
(5)	(380,400,470,500)	(320,340,370,400)
(6)	(470,490,520,550)	(370,390,400,440)
(7)	(410,460,470,540)	(310,360,370,440)
(8)	(440,450,470,500)	(340,350,370,400)

TABLE 7. Fixed cost of the contract

Potential total reliable DC (l)	Fixed cost of transshipment $(TRC_{l(1)}, TRC_{l(2)}, TRC_{l(3)}, TRC_{l(4)})$
(1)	(4500,6000,7500,8000)
(2)	(5500,6000,8500,9000)
(3)	(5500,6500,7000,8500)
(4)	(5000,6000,7500,8000)
(5)	(6500,7000,7500,8000)
(6)	(7500,8000,8500,9000)
(7)	(7500,8000,9000,10000)
(8)	(6000,7000,7500,8000)

TABLE 8. Result of test problems 1 and 2

P-robustness=1, confidence level (α)=0.95		
Problem No	1	2
Total cost	6,648,000	18,217,650
Total Number of selected DCs	6	9
Totally Reliable DCs	2	1
Fortified DCs	2 (L_2,L_3)	5 (3L_4, 2L_2)
Transshipment	√	√
Nominal Cost	5,731,034	15,308,949
Percentage Increase in Nominal Cost	16.03%	19.1%

L:level of fortification, for example; L_2: means DC is fortified up to level 2

TABLE 9. Transshipment analysis (*P*-robustness=1, confidence level (*α*)=0.95)

Test problem 1	Transshipment	No Transshipment
Total cost	6,648,000	7,239,672 (26%)
Total number of selected DCs	6	7
Totally reliable DCs	2	3
Fortified DCs	2 (L_2,L_3)	1 (1L_3)
Test problem 2		
Total cost	18,217,650	24666727 (35%)
Total number of selected DCs	9	11
Totally reliable DCs	1	3
Fortified DCs	5 (3L_4, 2L_2)	4 (2L_3,2L_4)

L: level of fortification; for example, L_2: means DC is fortified up to level 2

5. CONCLUSION AND FUTURE RESEARCH

This paper has examined a reliable distribution network design with limited capacity under partial and complete disruption. Although disruption risks which have a random nature in reality aren't fully considered by a fuzzy approach, we apply scenario based approach to deal with the random nature of disruption risks. We applied credibility-based fuzzy chance constrained programming modelto deal with epistemic uncertainty in each disruption scenario; such as, all types of cost, demand, capacity disruption parameter and so on. In contrast most models which assume a single type of mitigation strategy, this paper includes multiple strategies; fortification, transshipment, facility location or diversification overcome disruption. We studied on these mitigation strategies due to examining their effectiveness and their effect on network reliability to determine the optimal deployment of multi-pronged mitigation approaches.

These results demonstrate the transshipment strategy is more useful and effective than fortification strategy especially when the shortage cost is high. We proved that it is necessary to take disruption into account, when we are in design phase as well as the uncertainty parameter, and neglecting them might impose high risk and cost to the network. Also, in real-world cases, a facility may be partially disrupted and could serve customers' demands with a remaining of its initial capacity. Our solution also reveals the necessity of considering partially disruptions. For the limited number of scenarios considered, the proven optimal can be found, using the CPLEX solver for mixed integer programming, but it does not help much and heuristic approaches for solving large size problems should be considered in the future research. Furthermore, scholars can improve the proposed mathematical programming model based on the different case studies in real-world problems.

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Designing a Reliable Distribution Network with Facility Fortification and Transshipment under Partial and Complete Disruptions

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چکیده

این مقاله سعی دارد تا مدلی به منظور طراحی یک شبکه توزیع پایا با در نظرگرفتن ریسک اختلال توسعه دهد. در مدل توسعه یافته ظرفیت تجهیزات محدود بوده و در اثر اختلال تمامی یا بخشی از ظرفیت آنها دست خواهد رفت. به منظور تقویت پایایی شبکه توزیع، یک مدل برنامه ریزی عدد صحیح مبتنی بر استراتژی‌های متنوع ارایه شده است. استراتژی‌ها شامل استراتژی مقاوم‌سازی، تنوع و پخش و همچنین اشتراک‌گذاری و انتقال محصولات بین مراکز توزیع می‌باشد. استراتژی مقاوم‌سازی در این مدل به صورت سطحی در نظر گرفته شده است. در واقع با صرف هزینه می‌توان مرکز توزیعی ایجاد نمود که هیچگاه در اثر اختلالات مختل نگردد. جهت ارزیابی مدل و رویکرد حل آن، به حل چند مثال عددی پرداخته شده است. نتایج قابلیت مدل و توانمندی رویکرد حل را برای مواجهه با چنین مسئله‌ای را نشان می‌دهد.

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