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A Collaborative Maximum Coverage Model Incorporating Reliability and Budget Constraints for Humanitarian Relief Chains

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ABSTRACT

Natural disasters impose significant casualties and financial losses every year. Effective and efficient planning before and during crises can help mitigate the impact. The prompt distribution of relief to affected populations is critical following a disaster. The effective location of distribution centers and the efficient allocation of affected individuals to relief centers are essential in this regard. Due to the possibility of disaster recurrence in an area, incorporating the reliability of the relief distribution centers and access roads to affected populations and maintaining backup centers to be deployed when the primary centers are unavailable play a vital role in ensuring uninterrupted relief delivery. This paper proposes a maximum coverage model to locate relief distribution centers under three key factors: (1) budget, (2) demand coverage, and (3) reliability. To analyze the impacts of changes in relief demand on the performance of the proposed model, three scenarios of low demand, medium demand, and high demand were evaluated. Two sub-scenarios were also assumed to study the impact of collaboration and non-collaboration between relief organizations. It was found that the demand coverage rate was maximized in the presence of collaboration, particularly under the high-demand scenario.

1. Introduction

In the past few decades, disasters have imposed increasing economic, social, and environmental impacts. According to the International Disaster Database [1], natural disasters and their

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consequences have significantly increased in number relative to the past decade (despite the reduced fatality rate). For instance, the 2011 Tōhoku earthquake and tsunami resulted in 19,846 casualties and a financial loss of 210 billion USD [2]. Given the growing number and impact of natural disasters and their widespread scale, greater attention has been directed towards effective disaster relief chain management. This ensures the prompt and effective delivery of resources and services to affected populations.

Humanitarian relief chains account for 80% of humanitarian logistics [3], engaging international relief organizations, governments, militaries, regional/local aid organizations, and private corporations.

Numerous factors can worsen coordination challenges in relief operations. For example, the lack of leadership, among various relief factors, may diminish the efficiency of relief chain management [4]. Moreover, the characteristics of humanitarian relief chains, such as unpredicted demand, strategic goals, prompt delivery risks, and shortage of resources, add to the complexity and challenges of relief chain management [5].

Some humanitarian relief practitioners are required to perform pre-disaster preparations and enhance their logistical capabilities to respond to emergencies and deliver sufficient aid within a relatively short timeframe. While budget constraints can impact the capability of relief actors to mobilize and deliver relief, effective planning can ensure the successful implementation of relief chain management systems [24].

This paper focuses on humanitarian relief chain management and develops a maximum coverage model incorporating various factors, including different types of relief items, collaboration coverage requirements, logistics budget constraints, reliability, and decisions related to distribution facilities. The concept of reliability is linked with the failure of some components of a system. A reliable system can accomplish its tasks even when some of its components are disrupted and/or fail. The incorporation of reliability substantially reduces unmet demand rates. Moreover, the deployment of backup facilities is a measure to raise reliability, ensuring that relief items can be delivered to the demand points when primary storage centers are unavailable. Since natural disasters can damage structural and block roads, incorporating the potential failure of storage centers and blocked roadways into the model enhances the reliability of the system [26].

The remainder of the study is organized as follows: Section 2 reviews the literature; Section 3 provides the problem statement; Section 4 formulates the mathematical model, Section 5 provides and discusses the numerical results; and, Section 6 concludes the work and provides future directions.

2. Literature Review

Quantitative instruments and optimization methods that analyze relief chain management are typically classified into (1) location models, (2) distribution models, (3) transportation network models, and (4) multi-commodity network models, seeking to optimize relief demand through distribution networks [7]. Researchers have widely used maximum coverage problems in various fields; however, collaborative coverage in humanitarian relief operations is yet to be comprehensively studied. Due to the intrinsic complexities of relief chain management, multiple factors impact demand in disaster-affected regions, which are to be managed by relief actors since it may sometimes be expensive or even financially infeasible to meet the entire demand. Furthermore, providing a large number of relief items for an unexpected disaster can be financially infeasible for relief organizations [24]. Thus, a maximum coverage model that incorporates collaborative coverage could be a more effective practice in relief chain management, which motivated the present work. Table 1 summarizes a number of studies in the literature.

Table 1: Summary of studies

Author(s)	Pub. Year	Description
Haghani & Oh	1996	A multi-commodity, multi-objective network flow model to minimize casualties and maximize the efficiency of disaster relief operations based on spatiotemporal networks. They proposed two heuristic methods by evaluating emergency logistics planning, including the delivery of commodities from distribution centers to the affected areas [8].
Ozdamar et al.	2004	A multi-period, multi-commodity network model to address vehicle routing problems in humanitarian logistics [9].
Barbarosoglu et al.	2002	Focus on utilizing helicopters in relief operations. They mainly developed mathematical models and addressed tactical and operational decisions regarding helicopter deployment and loading at two levels in a hierarchical manner [10].

Author(s)	Pub. Year	Description
Barbarosoglu & Arda	2004	A two-stage stochastic programming model for the transportation of relief commodities. They developed a multi-commodity, multi-modal network under uncertainty and vulnerability in crisis scenarios [11].
Balcik et al.	2008	A model based on the delivery time and resource allocation in relief operations to minimize transportation costs and maximize aid recipient advantages [12].
Tuzkaya et al.	2014	Focus on emergency networks and a methodology to minimize the supply-demand imbalance [13].
Current et al.	1994	Extension of coverage by formulating the maximal covering tour problem to minimize the total tour length/cost and demand coverage [14].
Berman et al.	2002	Formulation of coverage as a non-incremental function of distance from the nearest regions. They developed efficient formulations and heuristic approaches [15].
Karasakal et al.	2004	Formulation of the maximal coverage problem under partial coverage and extending the problem using Lagrangian relaxation [16].
Berman et al.	2010	Efficient formulations to demonstrate the advantages of collaborative coverage relative to non-collaborative coverage models. The results were compared to heuristic algorithms through computational tests [17].
Dabibi et al.	2016	A multi-objective model to optimize facility locations to minimize establishment costs and maximize demand coverage [18].
Zhang et al.	2016	A location model with reliability, risk, and relief chain disruptions to ensure that individuals assigned to facilities could be reallocated to other facilities in case of failure [19].

Author(s)	Pub. Year	Description
Klibi et al.	2013	A crisis supply chain network with backup facilities to enhance reliability [20].
Wang et al.	2014	A location and routing model in crisis scenarios with reliability enhancement as an independent objective [21].
Yuksori et al.	2008	A location and routing model considering the probability of route failures to improve reliability [22].
Asadi et al.	2018	Developed a facility location and allocation model with reliability under uncertainty and dynamic demand [26].
Mohammadi et al.	2014	A bi-objective mathematical model with backup facilities in relief logistics [27].

3. Problem Statement

This study develops a model to locate and allocate relief centers to the affected areas based on three factors: budget, demand coverage, and reliability. Essential relief required during the initial days following a disaster is mostly stored in pre-established storage centers and primary distribution centers to provide significant access to the affected areas. As a result, the number of relief resources that can maximize the advantage for populations in affected areas would be strongly dependent on the number and location of distribution centers. Due to resource limitations, the effective location of facilities highly contributes to balancing costs and risks in relief chain management [27-35]. Hence, it is advantageous to exploit the surplus capacity through collaboration with non-governmental organizations in different phases of relief operations. This study incorporated several primary distribution centers into the proposed model, each with different establishment costs, depending on the capacity and reliability. Moreover, a number of backup facilities are incorporated to replace the primary facilities in case of disruptions. Three scenarios are assumed: low, medium, and high demand. The performance of the model in each scenario is assessed based on the level of organizational collaboration. In the lack of collaboration, only the primary facilities of a relief organization can be deployed, depending on their reliability and budget. However, when relief organizations collaborate, pre-established backup facilities can also be used with minimal costs. This study also assumes a coverage constraint to maximize the met demand rate. It represents the radial distance covered by a distribution center. The primary and backup distribution centers have certain capacities; i.e., they can store up to a certain quantity of relief commodities.

4. Mathematical Formulation

This section provides the assumptions, symbols, and notations in the mathematical model. The mathematical model is developed in the absence of uncertainty. Then, uncertainty is incorporated into the proposed model.

A Collaborative Maximum Coverage Model Incorporating Reliability and Budget Constraints for Humanitarian Relief Chains is an optimization framework designed to support effective disaster-response planning by selecting and coordinating relief facilities in a resource-limited and uncertain environment. The model seeks to maximize the coverage of affected populations by strategically locating and sharing facilities among multiple humanitarian actors, while explicitly accounting for budget limitations and the unreliability of infrastructure caused by disasters. Facility reliability is modeled through probabilistic parameters, ensuring that solutions favor robust and dependable relief centers and allow for redundant coverage to reduce the risk of service failure. By integrating collaboration, financial constraints, and reliability into a single decision-making structure, the model enhances responsiveness, reduces duplication of efforts among organizations, and improves the overall effectiveness and resilience of humanitarian relief supply chains.

4.1. Assumptions

- Reliability is taken into account for the access roads from the distribution centers to the affected areas. The storage centers may also fail.
- Five damaged areas.
- Four primary distribution centers and four backup centers.
- Two types of relief commodities, both available in the distribution centers.
- Backup storage centers cannot fail as they are located in safe regions.

4.2. Symbols

Sets and Indices	**Description**
I	Damaged areas
J	Candidate distribution centers
R	Backup distribution centers
K	Relief commodities

T	Potential scenarios
O	Total facilities

Parameters	**Description**
d_{io}	Distance between distribution Center o and Area *i*
ϕ	Distance between a pair of points based on the coverage constraint
τ	Coverage constraint
P^t	Probability of Scenario t
ρ^k	Attractiveness factor of Commodity k
B	Budget
D_i^{tk}	Expected demand of Area i in Scenario t for Commodity k
h_o^k	Unit storage cost of Commodity k in Center o
c_{io}^k	Unit transportation cost of Commodity k from Center o to Area i
u^k	Unit volume of commodities of Type k
w_j^k	Availability of Commodity K in Center j
v_r	=1 if the distribution center r is available; otherwise, v_r=0.
c_o	Capacity of Center o
F_o	Cost of locating, establishing, and using Center o
p_j^t	Failure probability of primary center j under scenario t
re_i^j	Route reliability from Center j to Area i
re_i^r	Route reliability from Center r to Area i
M	A substantially large constant

Variable	**Description**
f_{io}^{tk}	Demand for commodity of type k in Area i under Scenario t met by Center o
Q_o^k	Quantity of commodity of type k in Center o
z_r	=1 if backup center r is available; otherwise, z_r=0.

x_j =1 if Center j is established; otherwise, x_j= 0

y_i =1 if Area i is covered under Scenario t

T_{ji}^{t} =1 if Area i is covered by Facility j under Scenario t

T_{ri}^{t} = 1 if area i is covered by Facility o under Scenario t

4.3 Mathematical Model

The mathematical model without reliability is formulated as:

$$\max Z = \sum_{t\in T}\sum_{k\in K}\sum_{i\in N}\sum_{o\in J\cup R} P^{t}\frac{f_{io}^{tk}\rho^{k}}{D_{i}^{tk}} \quad (1)$$

subject to

$$\sum_{i\in N} f_{ij}^{tk} \le Q_{j}^{k} x_{j} \qquad \forall j\in J, k\in K, t\in T \quad (2)$$

$$\sum_{i\in N} f_{ir}^{tk} \le Q_{r}^{k} z_{r} \qquad \forall r\in R, k\in K, t\in T \quad (3)$$

$$\sum_{j\in J} x_{j}F_{j} + \sum_{r\in R} z_{r}F_{r} + \sum_{o\in J\cup R}\sum_{k\in K} Q_{o}^{k}h_{o}^{k} + \sum_{i\in N}\sum_{k\in K}\sum_{o\in J\cup R} c_{io}^{k} f_{io}^{tk} \le B \qquad \forall t\in T \quad (4)$$

$$\sum_{j\in J}\phi(d_{ij})x_{j} + \sum_{r\in R}\phi(d_{ir})z_{r} \ge \tau y_{i} \quad \forall i\in I \quad (5)$$

$$\sum_{o\in J\cup R} f_{io}^{tk} \le D_{i}^{tk} y_{i} \qquad \forall i\in I, k\in K, t\in T \quad (6)$$

$$f_{io}^{tk} \ge 0 \qquad \forall i\in I, o\in J\cup R, k\in K, t\in T \quad (7)$$

$$\sum_{k\in K} u^{k}Q_{j}^{k} \le c_{j}x_{j} \qquad \forall j\in J \quad (8)$$

$$\sum_{k\in K} u^{k}Q_{r}^{k} \le c_{r}z_{r} \qquad \forall r\in R \quad (9)$$

$$u^{k}Q_{j}^{k} \le c_{j}w_{j}^{k} \qquad \forall j\in J, k\in K \quad (10)$$

$$z_{r} \le v_{r} \qquad \forall r\in R \quad (11)$$

$$x_{j} \in \{0,1\} \qquad \forall j\in J \quad (12)$$

$$y_{i}, z_{r} \in \{0,1\} \qquad \forall i\in I, \quad r\in R \quad (13)$$

The mathematical model with reliability is rewritten as:

$$\max Z = \sum_{t\in T}\sum_{k\in K}\sum_{i\in N}\sum_{o\in J\cup R} P^{t}\frac{f_{io}^{tk}\rho^{k}(1-p_{j}^{t})re_{i}^{j}T_{ji}^{t}}{D_{i}^{tk}}+$$

$$\sum_{t\in T}\sum_{k\in K}\sum_{i\in N}\sum_{o\in J\cup R} P^{t}\frac{f_{io}^{tk}\rho^{k}p_{j}^{t}re_{i}^{j}re_{i}^{r}T_{ji}^{t}T_{ri}^{t}}{D_{i}^{tk}}+$$

$$\sum_{t\in T}\sum_{k\in K}\sum_{i\in N}\sum_{o\in J\cup R} P^{t}\frac{f_{io}^{tk}\rho^{k}(1-re_{i}^{j})re_{i}^{r}T_{ji}^{t}T_{ri}^{t}}{D_{i}^{tk}} \tag{1}$$

subject to

$$\sum_{r\in R} T_{ir}^{t}=1 \qquad \forall i\in I, r\in R, t\in T \tag{2}$$

$$\sum_{j\in J} T_{ij}^{t}=1 \qquad \forall i\in I, j\in J, t\in T \tag{3}$$

$$T_{ir}^{t}\le z_{r} \qquad \forall i\in I, r\in R, t\in T \tag{4}$$

$$T_{ij}^{t}\le x_{j} \qquad \forall i\in I, j\in J, t\in T \tag{5}$$

$$\sum_{i\in N} f_{ij}^{tk}\le Q_{j}^{k}x_{j} \qquad \forall j\in J, k\in K, t\in T \tag{6}$$

$$\sum_{i\in N} f_{ir}^{tk}\le Q_{r}^{k}z_{r} \qquad \forall r\in R, k\in K, t\in T \tag{7}$$

$$\sum_{j\in J} x_{j}F_{j}+\sum_{r\in R} z_{r}F_{r}+\sum_{o\in J\cup R}\sum_{k\in K} Q_{o}^{k}h_{o}^{k}+\sum_{i\in N}\sum_{k\in K}\sum_{o\in J\cup R} c_{io}^{k}f_{io}^{tk}\le$$
$$B \qquad \forall t\in T \tag{8}$$

$$\sum_{j\in J}\phi(d_{ij})x_{j}+\sum_{r\in R}\phi(d_{ir})z_{r}\ge \tau y_{i} \quad \forall i\in I \tag{9}$$

$$\sum_{o\in J\cup R} f_{io}^{tk}\le D_{i}^{tk}y_{i} \qquad \forall i\in I, k\in K, t\in T \tag{10}$$

$$f_{io}^{tk}\ge 0 \qquad \forall i\in I, o\in J\cup R, k\in K, t\in T \tag{11}$$

$$\sum_{k\in K} u^{k}Q_{j}^{k}\le c_{j}x_{j} \qquad \forall j\in J \tag{12}$$

$$\sum_{k\in K} u^{k}Q_{r}^{k}\le c_{r}z_{r} \qquad \forall r\in R \tag{13}$$

$$u^{k}Q_{j}^{k}\le c_{j}w_{j}^{k} \qquad \forall j\in J, k\in K \tag{14}$$

$$z_{r}\le v_{r} \qquad \forall r\in R \tag{15}$$

$$x_{j}\in\{0,1\} \qquad \forall j\in J \tag{16}$$

$$y_{i}, z_{r}\in\{0,1\} \qquad \forall i\in I, \quad r\in R \tag{17}$$

$$T_{ir}^{t}, T_{ij}^{t}\in\{0,1\} \qquad \forall i\in I, j\in J, t\in T \tag{18}$$

4.4 Linearization of the model

Linearization of the product of a binary variable and a continuous variable:

Let z be the product of binary variable x1 and continuous variable x2. When the binary variable takes a value of 1, variable z is a continuous variable; otherwise, it is 0. To linearize this product, three constraints are used [24]:

$$z \le x_2$$
$$z \le Mx_1$$
$$z \ge x_2 - M(1-x_1)$$

Linearization of the product of two binary variables:

Let z be the product of binary variables x1 and x2. When both binary variables are 1, z =1; otherwise, z=0. This product is linearized using three constraints [25]:

$$z \le x_2$$
$$z \le x_1$$
$$z \ge x_2 + x_1 - 1$$

The objective function of the proposed model contains the product of two binary variables, and constraints (6) and (7) contain the product of a continuous variable and a binary one. These products were linearized, rewriting the mathematical model as:

$$\max Z = \sum_{t\in T}\sum_{k\in K}\sum_{i\in N}\sum_{o\in J\cup R} P^t \frac{ft_{io}^{tk}\rho^k(1-p_j^t)re_i^j}{D_i^{tk}} +$$
$$\sum_{t\in T}\sum_{k\in K}\sum_{i\in N}\sum_{o\in J\cup R} P^t \frac{fti_{io}^{tk}\rho^k p_j^t re_i^j re_i^r}{D_i^{tk}} +$$
$$\sum_{t\in T}\sum_{k\in K}\sum_{i\in N}\sum_{o\in J\cup R} P^t \frac{fti_{io}^{tk}\rho^k(1-re_i^j)re_i^r}{D_i^{tk}} \qquad (1)$$

subject to

$$\sum_{r\in R} T_{ir}^t = 1 \qquad \forall i\in I, r\in R, t\in T \qquad (2)$$
$$\sum_{j\in J} T_{ij}^t = 1 \qquad \forall i\in I, j\in J, t\in T \qquad (3)$$
$$T_{ir}^t \le z_r \qquad \forall i\in I, r\in R, t\in T \qquad (4)$$
$$T_{ij}^t \le x_j \qquad \forall i\in I, j\in J, t\in T \qquad (5)$$
$$\sum_{i\in N} f_{ij}^{tk} \le Qx_j^k \qquad \forall j\in J, k\in K, t\in T \qquad (6)$$
$$\sum_{i\in N} f_{ir}^{tk} \le Qz_r^k \qquad \forall r\in R, k\in K, t\in T \qquad (7)$$
$$\sum_{j\in J} x_j F_j + \sum_{r\in R} z_r F_r + \sum_{o\in J\cup R}\sum_{k\in K} Q_o^k h_o^k + \sum_{i\in N}\sum_{k\in K}\sum_{o\in J\cup R} c_{io}^k f_{io}^{tk} \le$$
$$B \qquad \forall t\in T \qquad (8)$$
$$\sum_{j\in J}\phi(d_{ij})x_j + \sum_{r\in R}\phi(d_{ir})z_r \ge \tau y_i \quad \forall i\in I \qquad (9)$$
$$\sum_{o\in J\cup R} f_{io}^{tk} \le D_i^{tk} y_i \qquad \forall i\in I, k\in K, t\in T \qquad (10)$$

$$f_{io}^{tk} \geq 0 \qquad \forall i \in I, o \in J \cup R, k \in K, t \in T \tag{11}$$

$$\sum_{k \in K} u^k Q_j^k \leq c_j x_j \qquad \forall j \in J \tag{12}$$

$$\sum_{k \in K} u^k Q_r^k \leq c_r z_r \qquad \forall r \in R \tag{13}$$

$$u^k Q_j^k \leq c_j w_j^k \qquad \forall j \in J, k \in K \tag{14}$$

$$z_r \leq v_r \qquad \forall r \in R \tag{15}$$

$$ft_{io}^{kt} \leq f_{io}^{kt} \qquad \forall r \in R, k \in K, t \in T, o \in O \tag{16}$$

$$ft_{io}^{kt} \leq T_{ij}^{t} \qquad \forall i \in I, j \in J, r \in R, k \in K, t \in T, o \in O \tag{17}$$

$$ft_{io}^{kt} \geq f_{io}^{kt} + T_{ij}^{t} - 1 \qquad \forall i \in I, j \in J, r \in R, k \in K, t \in T, o \in O \tag{18}$$

$$fti_{io}^{kt} \leq f_{io}^{kt} \qquad \forall r \in R, k \in K, t \in T, o \in O \tag{19}$$

$$fti_{io}^{kt} \leq T_{ir}^{t} \qquad \forall i \in I, j \in J, r \in R, k \in K, t \in T, o \in O \tag{20}$$

$$fti_{io}^{kt} \geq f_{io}^{kt} + T_{ir}^{t} - 1 \qquad \forall i \in I, j \in J, r \in R, k \in K, t \in T, o \in O \tag{21}$$

$$Qx_j^k \leq Q_j^k \qquad \forall j \in J, k \in K \tag{22}$$

$$Qx_j^k \leq M x_j \qquad \forall j \in J, k \in K \tag{23}$$

$$Qx_j^k \leq Q_j^k - M(1 - x_j) \qquad \forall j \in J, k \in K \tag{24}$$

$$Qz_r^k \leq Q_r^k \qquad \forall r \in R, k \in K \tag{25}$$

$$Qz_r^k \leq M z_r \qquad \forall r \in R, k \in K \tag{26}$$

$$Qz_r^k \leq Q_r^k - M(1 - z_r) \qquad \forall r \in R, k \in K \tag{27}$$

$$x_j \in \{0,1\} \qquad \forall j \in J \tag{28}$$

$$y_i, z_r \in \{0,1\} \qquad \forall i \in I, \quad r \in R \tag{29}$$

$$T_{ir}^{t}, T_{ij}^{t} \in \{0,1\} \qquad \forall i \in I, j \in J, t \in T \tag{30}$$

$$Q_j^k, Qx_j^k \geq 0 \qquad \forall j \in J, k \in K \tag{31}$$

$$Q_r^k, Qz_r^k \geq 0 \qquad \forall r \in R, k \in K \tag{32}$$

$$fti_{io}^{kt} \geq 0 \qquad \forall i \in I, o \in O, k \in K, t \in T \tag{33}$$

Objective function (1) consists of three terms. The first term represents demand coverage when the primary distribution centers and routes to demand points are operational. The second term estimates demand coverage when the primary centers are unavailable, and routes to demand points are available. The third term represents demand coverage when the primary centers and their routes are unavailable while the routes to the backup centers are operational. Constraints (2) and (3) ensure that each demand point is allocated to a distribution center. Constraints (4) and (5) require that the centers be allocated only when they are available. Constraints (6) and (7) ensure that the quantity of commodity in the distribution centers above than the demand. Constraint (8) ensures that the total cost of establishment, operation, storage, and transportation is lower than the budget. Constraint (9) represents the coverage of distribution centers. Constraints (10) and (11) ensure that the relief commodities supplied to an area do not exceed the demand and can be delivered only when the area is covered. Constraints (12) and (13) indicate that relief items stored in a distribution center do not exceed the capacity. Constraint (14) indicates that a relief item can be provided by a distribution center only if it is available. Constraint (15) ensures that a backup center can be deployed only when it is available. Constraints (16-21) linearize the product of two binary variables. Constraints (22-27) linearize the product of a continuous variable and a binary variable. Constraints (28-33) constrain the ranges of the variables.

5. Numerical Results

This section provides the numerical results. Data were generated randomly at intervals obtained from [26] to solve the model. Table 2 shows the generation of random numbers.

Table 2: Generation of random numbers

Parameter	Description
d_{io}	It ranges from 6 to 12 hours from each center [26] with a random distribution.
ϕ	It ranges from 0 to 1 [27] based on the distance between a center and an affected area.
τ	It is 0.3 [27].
P^t	It is 1 for each scenario [26].
ρ^k	It is 1 [26].
B	It is 1,500,000 USD.
D_i^{tk}	It ranges from 5,000 to 100,000 (Lee et al., Year) for an area in a given scenario. The numbers have a uniform distribution.
h_o^k	It 1 USD per item [26].

Parameter	**Description**
c_{io}^{k}	It is 1 USD per time unit for delivering commodities from the primary centers and 2 USD per time unit for delivering commodities from the backup centers [2].
u^{k}	1 m^3 per commodity [26].
w_{j}^{k}	It is **1** per commodity [26].
c_{o}	It ranges from 400,000 to 2,200,000 m^3 for the primary centers and 500,000 m^3 for the backup centers [26] (random numbers of uniform distributions)
F_{o}	It ranges from 80,000 to 380,000 USD for each primary center and 50,000 USD for backup centers [26] (random numbers of uniform distributions).
p_{j}^{t}	Random numbers generated using an exponential distribution in MATLAB.
re_{i}^{j}	Random numbers generated using an exponential distribution in MATLAB.
re_{i}^{r}	Random numbers generated using an exponential distribution in MATLAB.

Table 3: Numerical results

Scenario	**Collaborative**				**Non-collaborative**				
	Established Primary Centers	Covered Areas	Coverage Rate	Established Centers Based on Reliability	Established Primary Centers	Covered Areas	Coverage Rate	Established Centers Based on Reliability	Established Primary Centers
Low-Demand	4	3	55.3%	1, 2, 3, 4	3	3	5	83%	1, 2, 3, 5, 6, 7
Medium-Demand	4	3	38.4%	1, 2, 3, 4	3	4	4	49.2%	1, 2, 3, 5, 6, 7, 8
High-Demand	4	3	21.2%	1, 2, 3, 4	2	4	3	35.4%	1, 3, 5, 6, 7, 8

As shown in Table 3, collaboration improved the demand coverage rate as backup centers have high reliability and ensure uninterrupted relief delivery to the affected areas. In the absence of collaboration, the coverage rate was higher in the low-demand scenario than in the medium- and high-demand scenarios. This implies that individual organizational efforts are more effective when there is low relief demand in an area. However, an increase in the scale of the disaster increases the necessity of organizational collaboration. Center 4 was excluded under the collaborative sub-scenario since it had poor reliability. Under the non-collaborative sub-scenario, on the other hand, Center 4 was deployed to meet the demand. In the presence of collaboration, the model prioritized the deployment of most backup centers in light of their high reliability. Thus, in both low- and medium-demand scenarios, all four backup centers would be used. Budget constraints also played a key role in the establishment of centers with higher reliability. For instance, a 60% increase in the budget enabled a 100% coverage rate in the collaborative model under the low-demand scenario.

6. Conclusion and future directions

This study proposed a mathematical model for the location and allocation of relief centers to natural disaster-affected based on the reliability of the relief centers and roads and the available budget. Three demand scenarios were studied, and the effects of collaboration between relief organizations were evaluated by comparing collaborative and non-collaborative sub-scenarios. It was found that the reliability of relief distribution centers plays a key role in the uninterrupted delivery of relief. Furthermore, the budget constraints would affect the establishment of high-reliability distribution centers. Future works can perform the model on data from a real-world disaster to assess its efficiency at a larger scale. Furthermore, more realistic results can be derived by adding upstream levels, e.g., suppliers of relief commodities to the relief distribution centers. Future works can also incorporate commodity perishability into the model.

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