

A multi-actor multi-objective optimization approach for locating temporary logistics hubs during disaster response

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Abstract

Purpose – The purpose of this paper is to develop a mathematical model that determines the location of temporary logistics hubs (TLHs) for disaster response and proposes a new method to determine weights of the objectives in a multi-objective optimization problem. The research is motivated by the importance of TLHs and the complexity that surrounds the determination of their location.

Design/methodology/approach – A multi-period multi-objective model with multi-sourcing is developed to determine the location of the TLHs. A fuzzy factor rating system (FFRS) under the group decision-making (GDM) condition is then proposed to determine the weights of the objectives when multiple decision makers exist.

Findings – The interview with decision makers shows the heterogeneity of decision opinions, thus substantiating the importance of GDM. The optimization results provide useful managerial insights for decision makers by considering the trade-off between two non-commensurable objectives.

Research limitations/implications – In this study, decision makers are considered to be homogeneous, which might not be the case in reality. This study does not consider the stochastic nature of relief demand. **Practical implications** – The outcomes of this study are valuable to decision makers for relief distribution planning. The proposed FFRS approach reveals the importance of involving multiple decision makers to enhance sense of ownership of established TLHs.

Originality/value – A mathematical model highlighting the importance of multi-sourcing and short operational horizon of TLHs is developed. A new method is proposed and implemented to determine the weights of the objectives. To the best of the authors' knowledge, the multi-actor and multi-objective aspects of the TLH location problem have not thus far been considered simultaneously for one particular problem in humanitarian logistics.

Keywords Humanitarian supply chain, Multi-objective optimization, Facility location problem, Fuzzy factor rating system under group decision making, Temporary logistics hub, Weighted sum method
Paper type Research paper

Nomenclature

Sets

T	set of time periods
I	set of supply points
J	set of temporary logistic hubs (TLHs)
K	set of affected area demand points

Parameters

TC_{ijt}	transportation cost of shipping one unit of the relief package from supply point i to TLH j in period t (USD per unit)
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TC_{jkt}	transportation cost of shipping one unit of relief package from TLH j to the affected area's demand point k in period t (USD per unit)
FC_j	Fixed cost of opening a TLH in the candidate location (USD)
QS_{it}	maximum available quantity of emergency relief materials at supply point $i \in I$ in period t (kg)



QH_{jt}	maximum available quantity of emergency relief materials at TLH $j \in J$ in period t (kg)	q_{jkt}	amount of emergency relief materials shipped from TLH $j \in J$ to the affected area's demand points $k \in K$ in period $t \in T$
d_{kt}	demand of the affected area's demand point k in period t (kg)	y_j	binary variable that equals 1 if the facility at j is selected as a TLH and 0 otherwise
P	total number of TLHs	z_{jkt}	binary variable that equals 1 if TLH j serves demand point k in period t and 0 otherwise
n_{kt}	number of TLHs allocated for demand point k in period t		
M	a very large number		
<i>Variables</i>			
r_{ijt}	amount of emergency relief materials shipped from supply point $i \in I$ to TLH $j \in J$ in period $t \in T$		

1. Introduction

The location of facilities, particularly distribution centers, warehouses, medical centers, and shelters, plays a significant role in ensuring the success of emergency humanitarian relief operations. From a logistics point of view, an effective response to a crisis demands setting up logistics hubs and/or distribution centers in appropriate locations. In the pre-disaster stage, facility location planning includes finding tentative locations for warehouses, distribution centers, and evacuation centers based on assumed scenarios, while in the post-disaster stage, such planning includes locating emergency shelters, medical centers, relief distribution centers, and logistics hubs for a particular disaster-affected area.

While vulnerable countries should ideally prepare designated spaces for these facilities along with safety stockpiles in advance of any disaster occurring, the situation in reality is often different. Although no specific correlation between investment in disaster preparedness and a country's GDP has been established, developed countries are typically better prepared to tackle the consequences of disasters compared with developing nations. If we examine the earthquakes that have recently impacted developed countries such as New Zealand and Japan, namely, the earthquake in Christchurch in 2011 and the Great East Japan earthquake in 2011, respectively, although they caused widespread damage, the resulting fatality rate was relatively modest (Lubkowski, 2014). By contrast, even relatively moderate earthquakes in developing nations still lead to large losses of life. The earthquakes in Haiti in 2010 and Nepal in 2015 are prime examples (Lubkowski, 2014).

The lack of advance preparedness in emerging countries suggests the need for an appropriate, effective, and efficient response. Moreover, the unpredictability of disasters prevents authorities from determining an exact location for emergency facilities beforehand and given that permanent facilities alone may be insufficient, emergency temporary facilities become especially important in developing countries where disaster preparedness falls short. Temporary facilities have been deployed in recent emergency humanitarian response operations such as the April 2015 Nepal earthquake and April 2016 Ecuador earthquake. One important feature of these facilities is their short operational horizon (i.e. they are removed soon after the response stage is over) (World Food Programme (WFP), 2016).

Selecting where to locate temporary facilities for emergency operations is an important task. This is often complicated by the growing number of humanitarian actors, prevalence of multiple and often conflicting objectives, and inherent complexity and uncertainty of the situation. The inclusion of multiple actors is important to build a sense of ownership of the established facilities, a lack of which was identified to be one of the bottlenecks in the successful operation of regional logistics hubs during the April 2015 Nepal earthquake (WFP, 2016). While the humanitarian code of conduct prioritizes minimizing victims'

suffering, the budgetary limitations and organizational and environmental constraints create a trade-off situation. In reality, relief organizations commonly plan and execute logistics activities within the confines of a limited budget (Cook and Lodree, 2012) highlighting the importance of minimizing operational costs. These challenges necessitate the inclusion of multiple objectives and participation of multiple decision makers from different humanitarian organizations in the location selection process.

Moreover, current guidance suggests that within the humanitarian coordination architecture, decisions should be made by a group rather than by individuals (Inter-Agency Standing Committee, 2009; IASC, 2015). As the number of actors involved in disaster response operations has continued to grow, a complex network that often struggles to efficiently coordinate efforts has emerged (Balcik *et al.*, 2010; Bharosa *et al.*, 2010; Bealt *et al.*, 2016). Indeed, Ortuno *et al.* (2013) concluded the need to use a decision support system incorporating optimization tools to enhance applicability in real life. However, existing studies that focus on temporary facilities (Afshar and Haghani, 2012; Lin *et al.*, 2012; Khayal *et al.*, 2015; Stauffer *et al.*, 2016; Cavdur *et al.*, 2016) formulate their problems as single objective optimization problems only. The amalgamation of optimization models and decision-making approaches with group decision theories to determine the location of temporary facilities for emergency operations is lacking in the literature.

Multi-objective optimization is capable of handling the non-commensurable nature of different types of objectives through three stages: model building, optimization, and decision making (preference articulation). The decision-making step (involving either single or multiple actors) can happen either before the optimization (*a priori* articulation of preferences) or thereafter (a posteriori articulation of preferences). The vagueness and ambiguity that surround decision making during emergencies often increase the complexity of the location selection problem. Hence, different approaches must be employed. Among the approaches capable of incorporating multiple actors into the decision-making process, the fuzzy factor rating system (FFRS), which is applicable to both individual and group decision making (GDM) (Chou *et al.*, 2008), is an effective method for solving problems in a fuzzy group decision environment (Ou and Chou, 2009). Such a fuzzy approach is suitable for GDM problems under uncertainty because of the vagueness and imprecision inherent in decision making during emergencies.

Based on the foregoing, the existing literature on temporary facilities fails to take account of the temporary nature, multi-objective nature, or multi-actor nature of disaster response facilities. Therefore, to address the gaps in the literature, this study develops a multi-period multi-objective optimization model with multi-sourcing and a short operational horizon to determine the location of temporary logistics hubs (TLHs) in the post-disaster stage. The objectives are minimizing total costs and minimizing total unsatisfied demand. We use the weighted sum method to solve the multi-objective optimization model and an FFRS under GDM to determine the weight of the objectives under the *a priori* articulation of preferences. The FFRS under the GDM condition enables combining the decision opinions of a multitude of actors prevalent in disaster relief operations.

The contribution of this study is manifold. First, the study provides a new dimension to the TLH location problem by incorporating the conflicting objectives and diverse preferences of multiple decision makers in addition to its temporary nature and need for multi-sourcing. Second, the study develops a multi-period multi-objective optimization model for the TLH location problem. Third, the study uses a fuzzy multi-attribute GDM approach to calculate the weight of objectives in a multi-objective optimization problem. The difficulty in calculating the weight of objectives is one of the largest challenges preventing the use of the weighted sum method; thus, the application of the FFRS under GDM is a novel feature of this study among those focusing on humanitarian operations. Fourth, the fuzzy approach uses fuzzy linguistic variables to illicit the preferences of

decision makers for different objectives. This approach is suitable for multi-actor GDM problems given the uncertainty and complexity inherent in decision making during disasters. Finally, to our knowledge, this study is the first of its kind to use a decision support system incorporated with the optimization problem to solve the TLH location problem while highlighting the significance of its short operational horizon.

The remainder of this paper is organized as follows. In Section 2, we review the relevant literature on the multi-objective optimization approach used in humanitarian operations with a special focus on temporary facilities. In Section 3, we describe the problem under consideration. Section 4 explains the multi-period multi-objective optimization model and an FFRS under GDM to calculate the weight of the objectives used in the multi-objective optimization model. In Section 5, we present the results of a numerical experiment based on the April 2015 Nepal earthquake. Finally, Section 6 concludes.

2. Literature review

In the study conducted by Afshar and Haghani (2012), temporary facilities receive, arrange, and ship the relief commodities through a distribution network during the initial response stage for deployment to lower levels. The authors model integrated logistics disaster operations by minimizing total weighted unsatisfied demand. Their model considers vehicle routing, pickup/delivery schedules, and the optimal location of temporary facilities. Lin *et al.* (2012) define temporary depots as an intermediary between the central depot and demand points. They propose a two-phase heuristic approach to locate temporary depots and allocate covered demand by minimizing logistics and penalty costs. Khayal *et al.* (2015) develop a network flow model for the dynamic selection of temporary distribution facilities and allocation of resources for emergency response planning by minimizing logistics and penalty costs. In their study, they allow for the transfer of excess resources between temporary facilities operating in different time periods to reduce deprivation.

In Cavdur *et al.* (2016), temporary disaster response facilities serve disaster victims until central disaster response units arrive. The authors develop a two-stage stochastic program for allocating temporary disaster response facilities in short-term disaster operations by minimizing the total distance traveled, unmet demand, and the cost of facilities. Finally, in Stauffer *et al.* (2016), a single objective dynamic hub location model with the option for temporary hubs for managing the vehicle fleet is developed. The model minimizes total vehicular costs over the planning period to determine the location of temporary hubs for vehicles. The temporary hub only opens after a mega disaster and operates as a regional hub for vehicles if sufficient vehicles are in the disaster location. Nevertheless, it is important that a single temporary facility can provide the minimum services for short-term storing, sorting, and handling that involve consolidating and deconsolidating emergency relief materials.

Despite the popularity of single objective optimization models, many studies have used the multi-objective approach to model different types of problems within humanitarian logistics (Serrato-Garcia *et al.*, 2016; Uster and Dalal, 2016; Jha *et al.*, 2017; Haghi *et al.*, 2017; Tayal and Singh, 2017; Zhou *et al.*, 2017). Several studies (Tzeng *et al.*, 2007; Bozorgi-Amiri *et al.*, 2013; Abounacer *et al.*, 2014; Zhang and Jiang, 2014; Barzinpour and Esmaeili, 2014; Rath and Gutjahr, 2014; Chanta *et al.*, 2014; Khodaparasti *et al.*, 2015; Yilmaz and Kabak, 2016; Haghi *et al.*, 2017; Trivedi and Singh, 2017) have used the multi-objective optimization approach to solve the location problems of various facilities, using different forms of costs and human suffering as objective functions, thus highlighting the popularity of this approach. Moreover, multiple objectives are a distinguishing feature of humanitarian logistics operations unlike in the commercial sector where the minimization of logistics costs is the primary motivation.

However, these studies using the multi-objective approach do not consider the temporary nature of disaster response facilities. Furthermore, decision aid models that involve multiple actors are rarely used to address temporary facility location problems. From a practical perspective, the many actors involved in disaster management must thus be included in location selection. According to Kovacs and Spens (2007), the typical actors involved in disaster response operations include aid agencies, donors, governments, the military, logistics providers, and other non-governmental organizations, which makes the presence of multiple actors another distinctive feature of humanitarian logistics operations.

The factor rating system, which is also known as a multi-factor rating system or scoring method, is a popular and easily applied subjective decision-making method under the multi-attribute decision-making approach (Heragu, 1997; Chou *et al.*, 2008). The chaotic and often turbulent nature of disaster management necessitates a simple yet efficient method that includes decision makers' preferences. Although conventional factor rating system approaches have been successfully applied for rating different criteria, these approaches are less effective when dealing with the inherent imprecision of linguistic valuation in the decision-making process (Liang and Wang, 1991; Chen, 2001; Kahraman *et al.*, 2003; Chou *et al.*, 2008). To overcome the shortcomings of traditional approaches, fuzzy set theory, which allows for vague and/or imprecise boundaries, provides a mechanism to use fuzziness in the subjective or imprecise determination of preferences, constraints, goals, and group decisions (Kahraman *et al.*, 2003; Yager, 1982; Ou and Chou, 2009) and is integrated with the factor rating system in this study.

The review of the literature reveals the integration of many concepts and approaches with fuzzy set theory to enhance its capability of handling multi-attribute decision-making problems with imprecise attributes. While existing studies have used statistical approaches, scaling approaches, and multi-attribute approaches, the weights obtained through multi-attribute methods are considered to be more stable than those produced by direct evaluations (Maggino and Ruviglioni, 2009). Additionally, a fuzzy approach is more suitable for GDM problems given the uncertainty inherent in disaster management operations. The FFRS is thus an effective method for solving problems in a fuzzy group decision environment (Ou and Chou, 2009).

3. Problem description

The problem under consideration is determining the location of TLHs. Figure 1 shows the structure of a typical humanitarian supply chain and the positioning of TLHs within.

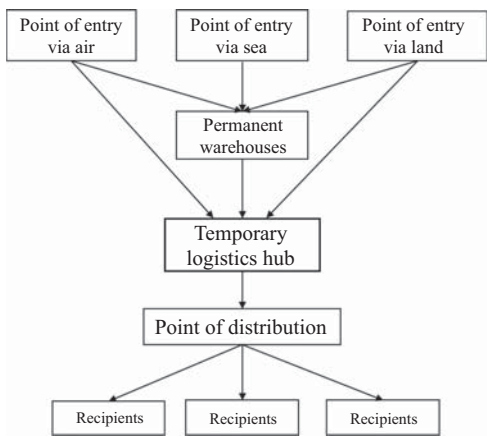


Figure 1.
Structure of
humanitarian
supply chain

In our study, a TLH is defined as a place designated for storing, sorting, consolidating, deconsolidating, and distributing emergency relief materials to disaster-affected areas in the short term. It thus acts as an intermediary between the central warehouse or relief supply points and areas in need. Hence, TLHs are often established after the disaster has occurred in the response stage of disaster management. Nonetheless, TLHs play a key role in ensuring an efficient and effective disaster response.

The supplies from permanent warehouses or entry points typically come in larger vehicles, which might be unable to access affected areas because of partial or complete damage to roads and bridges. In the absence of logistics hubs, the congestion created by larger vehicles using vulnerable road networks may cause delivery times to increase significantly. In particular, the temporary nature of hubs is important in developing countries where infrastructure facilities are poor and disaster preparedness usually falls short. The two major decisions regarding temporary hubs are to determine their optimal number and location while considering the length of their operational horizon.

Determining the location of TLHs in the immediate aftermath of a disaster is a complicated task because of the multi-actor and multi-objective nature of the decision-making process. The two objectives considered in this study are minimizing total costs and minimizing total unsatisfied demand, which are non-commensurable. Since it is impossible for a single organization to meet the demand of all affected people in need, no single organization can be the sole decision maker. Therefore, involving multiple humanitarian organizations in the disaster response is crucial for making location selection decisions. Furthermore, it is also important to consider the dynamic nature of cost attributes and demand of affected areas. The dynamic nature of demand is a common feature of humanitarian operations, in which, within the operational horizon, costs, available resources, and demand may vary (either increase or decrease) in each time period.

Several factors affect the short operational horizons of TLHs such as the number of people affected or injured, location of the demand points, pattern of relief demand, number of houses damaged or destroyed, socioeconomic situation of the affected areas, type of disaster, and accessibility conditions within and outside the affected area. The main goal here is to identify how long it will take for society to return to normal functioning so that the TLHs can be decommissioned and made ready for their next disaster response mission.

How to prioritize the demand points in the affected area is another aspect of the location selection problem that arises because of the nature of disaster impact. Disaster impacts are non-uniform: some areas are highly affected, while others receive only mild effects. This variation necessitates the allocation of emergency relief materials to affected areas' demand points based on the severity of disaster impact. Multi-sourcing ensures that the number of TLHs assigned to serve an affected area depends on the severity of the disaster impact in that area. The higher the disaster impact, the larger is the number of TLHs assigned. The main decision is to determine the number of hubs required to supply emergency relief materials, select their locations, and allocate demand to open hubs in such a way that the total objective is minimized without exceeding the capacity of facilities over the entire planning horizon.

4. Methodology

4.1 Mathematical model formulation

The proposed multi-period multi-objective TLH location model with multi-sourcing and a short operational horizon allows us to accurately capture the changing levels of relief demand and costs over the planning horizon. Multi-sourcing helps ensure agility while addressing priority needs, which means that even if one of the hubs fails to meet the

demand of affected areas, another hub will be able to fulfill this demand without distress. Multi-sourcing thus refers to the situation where demand in each affected area can be split between open facilities. The operational horizon refers to the length of time the TLH will be functioning.

We formulate a multi-objective optimization problem that minimizes total costs and total unsatisfied demand under dynamic demand, costs, and available units of emergency relief. Each district or demand point has an associated demand for emergency relief materials. Along the discrete time horizon, demand from the affected zone changes in a known way related to changes in the number of affected people and recovery of affected people, as a result of which demand can either increase or decrease or be stable.

The establishment of logistics hubs is required to meet the demand of affected people over the entire relief time horizon. Each logistics hub has a known threshold of emergency relief supplies that can be supplied. This threshold depends upon the available units of emergency relief supplies, which in turn depends on factors such as resource availability, the quality of the disaster response, and in addition to the capacity of TLHs. The amount of emergency relief materials available in TLHs can be either less than or equal to the capacity of TLHs but cannot exceed their capacity.

Each demand point can be served from one or more TLHs, a decision determined based on the severity of the disaster impact. The shipment of emergency relief materials between supply points, TLHs, and demand points incurs a variable transportation cost proportional to the quantity, distance, capacity of vehicles, and time period. Further, the establishment of a new facility incurs a fixed opening cost, which represents the initial investment for the mobile storage units, procurement cost, cost of leasing land, and cost of transporting the mobile storage units from the supply sources to the candidate TLHs. Our model is deterministic in that the location of the disaster and affected areas is known before the decision to open a TLH is made. The following subsection provides the mathematical model and its notations, parameters, and variables.

4.1.1 Formulation. The multi-objective optimization problem is formulated as follows: Minimize:

$$\text{Objective 1 : } O_1 = \sum_j FC_j y_j + \sum_i \sum_j \sum_t TC_{ijt} r_{ijt} + \sum_j \sum_k \sum_t TC_{jkt} q_{jkt} \quad (1)$$

$$\text{Objective 2 : } O_2 = \sum_k \sum_t d_{kt} - \sum_j \sum_k \sum_t q_{jkt} \quad (2)$$

Constraints:

$$\sum_k q_{jkt} = \sum_i r_{ijt} \quad \forall j \in J, t \in T \quad (3)$$

$$\sum_j r_{ijt} \leq QS_{it} \quad \forall i \in I, t \in T \quad (4)$$

$$\sum_i r_{ijt} \leq QH_{jt} \quad \forall j \in J, t \in T \quad (5)$$

$$\sum_k q_{jkt} \leq QH_{jt} \quad \forall j \in J, t \in T \quad (6) \text{ Locating TLHs during disaster response}$$

$$\sum_j y_j \leq P \quad (7)$$

$$\sum_j q_{jkt} \leq d_{kt} \quad \forall k \in K, t \in T \quad (8)$$

$$z_{jkt} \leq y_j \quad \forall j \in J \quad (9)$$

$$\sum_j z_{jkt} \leq n_{kt} \quad \forall k \in K, t \in T \quad (10)$$

$$q_{jkt} \leq Mz_{jkt} \quad \forall j \in J, t \in T \quad (11)$$

$$r_{ijt} \geq 0 \quad \forall i \in I, j \in J, t \in T \quad (12)$$

$$q_{jkt} \geq 0 \quad \forall j \in J, k \in K, t \in T \quad (13)$$

$$y_j \in \{0, 1\} \quad \forall j \in J \quad (14)$$

$$z_{jkt} \in \{0, 1\} \quad \forall j \in J, k \in K, t \in T \quad (15)$$

The objective function (1) minimizes total costs, which include the fixed cost of opening a TLH, transportation cost from the supply point to the TLH, and transportation cost from the TLH to the affected area's demand points. Objective function (2) minimizes total unsatisfied demand.

Constraint (3) ensures that the flow of emergency relief materials from the supply points to TLHs should be equal to the flow from the TLHs to the affected area's demand points. Constraints (4)-(6) are the availability constraints. Constraint (4) ensures that the quantity of emergency relief materials moved from the supply points to the TLHs should be less than or equal to the maximum available quantity of emergency relief materials in the supply point in each period. Similarly, constraints (5) and (6) ensure that the quantity of emergency relief materials moved from the supply points to the TLHs and from the TLHs to the affected area's demand points should be less than or equal to the maximum available quantity of emergency relief materials in the TLHs in each period. Constraint (7) limits the number of opened hubs to P . Constraint (8) ensures that the quantity of emergency relief delivered for each demand point does not exceed its demand. Constraint (9) ensures that a demand point is served by the TLH only if that TLH is open. Constraint (10) enforces multi-sourcing, ensuring that each demand point is served by a prespecified number of TLHs. Constraints (11) ensures emergency relief distribution only between the assigned TLH and the demand point. Constraints (12)-(15) express the nature of the decision variables used in the model.

4.2 Solution strategy for the multi-objective TLH location model

The weighted sum approach is a frequently used method for combining different objective functions in a multi-objective optimization problem. This approach, also known as the scalarization method, minimizes the positively weighted convex sum of the objectives that represents a new optimization problem with a unique objective function. The theorem of the weighted sum method states that “if x^* is a Pareto-optimal solution of a convex multi-objective optimization problem, then there exists a non-zero positive weight vector w such that x^* is a solution.” This theorem suggests that for a convex multi-objective optimization problem, any Pareto solution can be found by using the weighted sum method (Miettinen, 1998). The solutions obtained by using different weight settings represent the points on the Pareto front, meaning that the solutions are Pareto-optimal. The only requirement is the weight factors $w_i \geq 0$ and sum of $w_i = 1$. Therefore, we use the weighted sum method in this study.

The simplicity of using this method to solve multi-objective optimization problems is often complicated by the difficulty in determining the weight of the objectives. The weights used represent decision makers’ preferences and priorities, while the relative value of the weight reflects the relative importance of the objectives. Typically, infinitely many Pareto-optimal solutions exist for a multi-objective problem. Thus, it is often necessary to incorporate decision makers’ preferences for these objectives to determine a single suitable solution. By employing methods that incorporate the a priori articulation of such preferences, the user indicates his or her preferences before running the optimization algorithm and this subsequently allows the algorithm to determine a single solution. Alternatively, with the a posteriori articulation of preferences, one manually selects a single solution from a representation of the Pareto-optimal set (Marler and Arora, 2010). This study focuses on the use of the weighted sum method that incorporates the a priori articulation of preferences.

Given the multi-actor nature of disaster management, it is necessary that the weight assigned to the objectives comply with the preference of multiple decision makers. When decisions made by more than one person are modeled, two differences from the case of a single decision maker can be considered: first, the goals of the individual decision makers may differ such that each places a different ordering on the alternatives; second, the individual decision makers may have access to different information upon which to base their decision. Theories known as n -person game theories deal with both these considerations, team theories of decision making deal only with the second, and group decision theories deal only with the first (Kahraman *et al.*, 2003). This study focuses on GDM to determine the weight of the objectives.

A GDM process can be defined as a decision situation where there are two or more individuals’ different preferences but the same access to information, each characterized by his/her own perceptions, attitude, motivations, and personalities; all recognize the existence of a common problem; and all attempt to reach a collective decision (Bui, 1987). The concept of GDM is used to incorporate multiple decision makers’ decision opinions. Fuzzy multi-attribute methods are often coupled with GDM to address the vagueness and imprecision inherent in location decisions. We use the FFRS under the GDM condition to determine the weight of the objectives in the a priori articulation state. This allows us to incorporate multiple decision makers’ decision opinions.

4.3 Fundamental of fuzzy set theory

Fuzzy set theory uses approximate rather than precise reasoning (Saaty and Tran, 2007) and can process data by using partial set membership functions. Fuzzy logic allows impersonating ambiguous and uncertain linguistic knowledge and offers a robust framework for model designers dealing with systems that contain high uncertainty (Aguilar-Lasserre *et al.*, 2009). Trapezoidal fuzzy numbers are the most widely used form of

fuzzy numbers because they can be handled arithmetically and interpreted intuitively (Chou *et al.*, 2008). Hence, the linguistic terms assessing scarcely quantifiable variables are represented by trapezoidal fuzzy numbers in this study.

A fuzzy set $\tilde{A} = (a, b, c, d)$ on $R, a \leq b \leq c \leq d$, is called a trapezoidal fuzzy number if its membership function is:

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{(x-a)}{(b-a)}, & a \leq x \leq b, \\ 1, & b \leq x \leq c, \\ \frac{(x-d)}{(c-d)}, & c \leq x \leq d, \\ 0, & \text{otherwise,} \end{cases} \quad (16)$$

where a, b, c , and d are real numbers (Dubois and Prade, 1978; Keufmann and Gupta, 1991). The main operations of two fuzzy numbers can referred from previous studies (Keufmann and Gupta, 1991; Liang and Wang, 1991; Chen and Hwang, 1992).

In the fuzzy set theory, conversion scales are applied to transform linguistic terms into fuzzy numbers. Determining the number of conversion scales is generally intuitive: while too few conversion scales reduce analytical discrimination capability, too many conversion scales make the system overly complex and impractical (Chou *et al.*, 2008). In this study, a scale of 1-5 is used for the importance weight following Liang (1999). Given the fuzzy nature of this weight selection problem, the importance weights of the individual objectives are used as the linguistic variables in this study. Table I lists the linguistic variables and fuzzy numbers used.

4.4 Algorithm of an FFRS under the GDM condition

In the following section, we explain the algorithm of the proposed method by using the concepts of fuzzy set theory and factor rating system under the GDM condition. The decision makers are assumed to act in the best interests of the affected people. The proposed method derives its insights from Chou *et al.* (2008) and Ou and Chou (2009):

- Step 1. Selection of decision makers.
Under the GDM scenario, multiple decision makers can be chosen. The choice of decision maker also varies case to case and country by country. However, the effectiveness of GDM is influenced by group size. Yetton and Botter (1983) point out that a group of five, and to a lesser extent, seven, is the most effective. A committee of decision makers can be formed based on their overall role in the disaster management activity. The nature of these decision makers and their decision opinions can lead to the generation of four situations: when the decision makers are homogeneous and their decision opinions are also homogeneous; when the decision makers are homogeneous but their decision opinions are heterogeneous; when the decision makers are heterogeneous but their decision opinions are homogeneous; and when the decision makers are heterogeneous and their decision opinions are also heterogeneous.

Linguistic variables	Fuzzy numbers
Very low (VL)	(0, 0, 0, 3)
Low (L)	(0, 3, 3, 5)
Medium (M)	(2, 5, 5, 8)
High (H)	(5, 7, 7, 10)
Very high (VH)	(7, 10, 10, 10)

Table I.
Linguistic variables and fuzzy numbers

- Step 2. Collecting decision opinions and establishing decision matrices.
The next step is to collect their decision opinions and determine if decision makers are homogeneous or heterogeneous. If the degree of the importance of decision makers is equal, then the group of decision makers is deemed to be a homogeneous group.
In a committee of k decision makers ($D_t, t = 1, 2, \dots, k$) responsible for assessing n objectives ($O_j, j = 1, 2, \dots, n$), the degree of the importance of the decision makers is $I_t, t = 1, 2, \dots, k$, where $I_t \in [0, 1]$ and $\sum_{t=1}^k I_t = 1$. If $I_1 = I_2 = \dots = I_k = (1)/(k)$, the group of decision makers is called a homogeneous group; otherwise, the group is called a heterogeneous group.
- Step 3. Constructing the aggregated fuzzy rating of the individual objectives.
Subsequently, we construct the aggregated fuzzy rating of the individual objectives. Table I shows the linguistic variables and corresponding fuzzy numbers for the decision makers to access the importance of the objectives. Let $\tilde{W}_{jt} = (a_{jt}, b_{jt}, c_{jt}, d_{jt}), j = 1, 2, \dots, n; t = 1, 2, \dots, k$, be the linguistic rating given to objectives $O_1, O_2, \dots, O_n$ by decision maker D_t . The aggregated fuzzy rating, $\tilde{W}_j = (a_j, b_j, c_j, d_j)$, of objective O_j assessed by the committee of k decision makers is defined as follows:

$$\tilde{W}_j = (I_1 \otimes \tilde{W}_{j1}) \oplus (I_2 \otimes \tilde{W}_{j2}) \oplus \dots \oplus (I_k \otimes \tilde{W}_{jk}), \quad (17)$$

where $a_j = \sum_{t=1}^k I_t a_{jt}, b_j = \sum_{t=1}^k I_t b_{jt}, c_j = \sum_{t=1}^k I_t c_{jt}$, and $d_j = \sum_{t=1}^k I_t d_{jt}$.

- Step 4. Computing the weight of objectives.

To compute the weight of objectives, defuzzify the fuzzy rating of the individual objectives, compute the normalized weights, and construct the weight vector. To defuzzify the rating of the fuzzy objectives, the signed distance is adopted. The defuzzification of $\tilde{W}_j$, denoted as $d(\tilde{W}_j)$ is therefore given by:

$$d(\tilde{W}_j) = \frac{1}{k}(a_j + b_j + c_j + d_j) \quad (18)$$

The crisp value of the normalized weight for objectives O_j , denoted by W_j , is given by:

$$W_j = \frac{d(\tilde{W}_j)}{\sum_{j=1}^n d(\tilde{W}_j)}, \quad (19)$$

where $\sum_{j=1}^n W_j = 1$. The weight vector $W = [W_1, W_2, \dots, W_n]$ is therefore formed.

This crisp value of the normalized weight of the objectives O_j can therefore be used as the weight of the objectives in the weighted sum approach.

5. Numerical example

To support the usefulness of the proposed model as a decision-making tool for selecting the location of TLHs, we evaluate the performance of the model by using disaster data from the April 2015 Nepal earthquake.

5.1 April 2015 Nepal earthquake

The earthquake that occurred in Nepal in 2015 killed approximately 9,000 people and injured another 100,000. At the height of the emergency, some 188,900 people were temporarily displaced, 605,254 houses destroyed, and 288,255 houses damaged. Of Nepal's

75 districts, 39 were affected and 14 of those were declared severely affected. The 14 districts prioritized are located in Kathmandu, Bhaktapur, Lalitpur, Makwanpur, Nuwakot, Rasuwa, Dhading, Gorkha, Kavrepalanchok, Sindhupalchok, Sindhuli, Dolakha, Ramechhap, and Okhaldhunga. Approximately 5.4 million people live in these 14 districts, which are located in the Western and Central regions of Nepal. Of these, 2.8 million people were estimated to need assistance. The Government of Nepal declared a state of emergency in the country on 25 April and called upon the international humanitarian community for support. More than 450 aid organizations responded to the emergency (United Nations Office for the Coordination of Humanitarian Affairs, 2015). The humanitarian supply chain during the immediate aftermath of the earthquake faced many challenges such as the lack of vehicles, congestion in the airport, the lack of coordination and cooperation, and operational and location issues related to the use of regional logistics hubs.

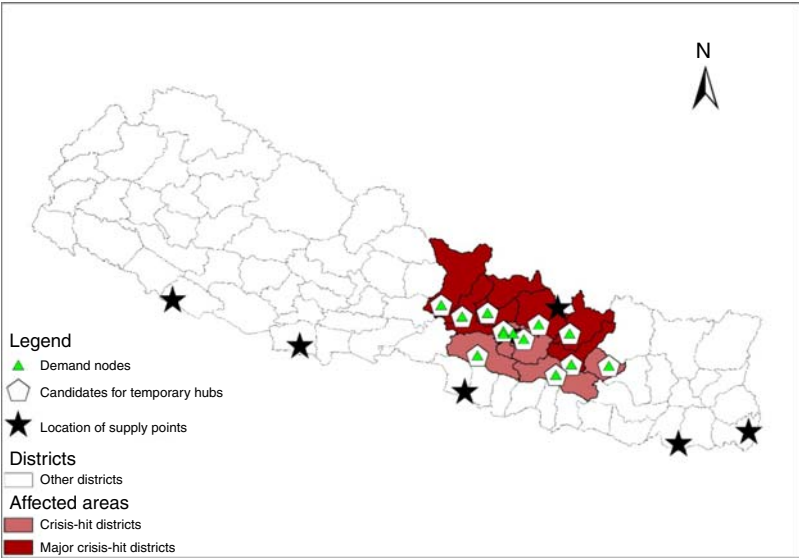
5.2 Nature of the data

In this example, the supply points are the points of entry to Nepal from neighboring countries via land and air. We did not consider seaports because Nepal is a landlocked country. We selected seven entry points: the Mechi Customs Office, Jhapa; Biratnagar Customs Office, Morang; Bhairawa Customs Office, Kapilbastu; Kodari Customs Office, Sindhupalchok; Nepalgunj Customs Office, Banke; Birgunj Customs Office, Parsa; and Tribhuvan International Airport, Kathmandu. We ensured the selected entry points had warehouses in place to handle the sudden upsurge in emergency relief materials. The amount of emergency relief materials available in the supply points was assumed to be known. In all, 11 candidates in Dhading, Dolakha, Gorkha, Kathmandu, Kavrepalanchok, Makwanpur, Nuwakot, Okhaldhunga, Ramechhap, Sindhuli, and Sindhupalchok were selected for locating TLHs. The opening of a TLH incurs a fixed opening cost. The capacity of a candidate TLH is restricted by the available units of emergency relief materials.

Among the 14 severely affected districts, 13, namely, Bhaktapur, Dhading, Dolakha, Gorkha, Kathmandu, Kavrepalanchok, Lalitpur, Makwanpur, Nuwakot, Okhaldhunga, Ramechhap, Sindhuli, and Sindhupalchok, were used as the demand points in this study. One district in Rasuwa was not considered because of the lack of distance-related data. Figure 2 shows the spatial location of the supply points, candidate TLHs, and affected areas' demand points. The demand points represent the location of the aggregated demand arising in each district. The demand points and candidate hubs overlap with each other. Demand was estimated based on the severity of the disaster impact. According to Salmeron and Apte (2010), the degree of severity differentiates the demand in each zone. A larger proportion of the population is assumed to require relief in major crisis-hit areas compared to crisis-hit areas. Rasuwa, Gorkha, Nuwakot, Dhading, Sindhupalchok, Dolakha, and Ramechhap were identified as major crisis-hit areas and Kavrepalanchok, Sindhuli, Okhaldhunga, Makwanpur, Lalitpur, Bhaktapur, and Kathmandu as crisis-hit areas. Similarly, major crisis-hit districts were allocated two TLHs, whereas crisis-hit districts were assigned a single TLH. The nature of the demand is assumed to be increasing initially and then stagnating after a while. This assumption is in reference to the numerical results of Sheu (2010).

As discussed earlier, the operational horizon of TLHs is affected by many factors; as such, the operational horizon was assumed to be five weeks in this numerical example. We considered a single package relief delivery system. A single emergency relief package was assumed to weigh 10 kg and include essential items such as meals, a basic medical kit, blankets, baby supplies, and clothing. We assumed that a single emergency relief package was sufficient to sustain an individual for a week.

Figure 2.
Location of
supply points,
candidate TLHs, and
demand points



5.3 Results

In this section, we first calculate the weight of the objectives by using an FFRS under the GDM condition and then present the results of the optimization model. We ignore the first 72 hours of critical importance, acknowledging the reality of real-life emergency responses. Assuming that TLHs could be established within 72 hours is unrealistic because of the time needed and complexity of finding an appropriate location. Hence, our model is valid for the response situation after the first 72 hours. The distribution planning is considered for 35 days divided into five weekly periods.

5.3.1 *Calculating the weight of the objectives.* Step 1: a committee of four decision makers, D_1 , D_2 , D_3 , and D_4 , from four humanitarian organizations active in disaster management in Nepal is formed. Objective O_1 represents minimizing total costs and O_2 represents minimizing total unsatisfied demand.

Step 2: Table II shows homogeneous and heterogeneous decision opinions of the decision makers from different humanitarian organizations. From this, two situations can be generated: when the decision makers are homogeneous and when they are heterogeneous. However, in this study, we only explore the situation when the decision makers are homogeneous because of the complexity of determining their importance without bias.

Step 3: the importance rating of each objective is assessed by using the linguistic variables and their respective fuzzy numbers. The aggregated fuzzy rating of the individual objective when the decision makers are homogeneous is constructed (see Table III) by using Equation (17).

Table II.
The importance rating
of the objectives

Objectives	Decision makers (homogeneous)			
	D_1	D_2	D_3	D_4
O_1	<i>H</i>	<i>M</i>	<i>H</i>	<i>M</i>
O_2	<i>VH</i>	<i>VH</i>	<i>VH</i>	<i>H</i>

Step 4: the defuzzified values of the aggregated fuzzy rating (Table IV) are obtained by using Equation (18) and the crisp value of the normalized weight is calculated by using Equation (19).

5.3.2 Optimization results. The model was coded in Lingo 17.0 Optimization modeling software. All the experiments were run on a personal computer with an Intel (R) Core (TM) i3-3220 CPU (3.30 GHz) and 8 GB of RAM. All the test problems were computed in 10 minutes.

To determine the optimal number of TLHs, the model was run without constraint (7). The model results in eight optimal TLHs with locations in Gorkha, Kathmandu, Kavrepalanchok, Makwanpur, Nuwakot, Ramechhap, Sindhuli, and Sindhupalchok to meet the dynamic demand over the entire planning horizon. The eight selected TLHs result in the minimum value of both objectives over the entire planning horizon. Figure 3 shows the spatial location of the eight selected TLHs in Nepal.

Locating TLHs during disaster response

Objectives	Decision makers				Aggregated fuzzy rating
	D_1	D_2	D_3	D_4	
O_1	(5, 7, 7, 10)	(2, 5, 5, 8)	(5, 7, 7, 10)	(2, 5, 5, 8)	(3.5, 6, 6, 9)
O_2	(7, 10, 10, 10)	(7, 10, 10, 10)	(7, 10, 10, 10)	(5, 7, 7, 10)	(6.5, 9.25, 9.25, 10)

Table III.
Aggregated fuzzy rating of the objectives

Objectives	O_1	O_2
Defuzzified value of aggregated fuzzy rating	6.125	8.750
Normalized weight	0.411	0.588

Table IV.
The defuzzified values of the aggregated fuzzy rating and normalized weights of the objectives

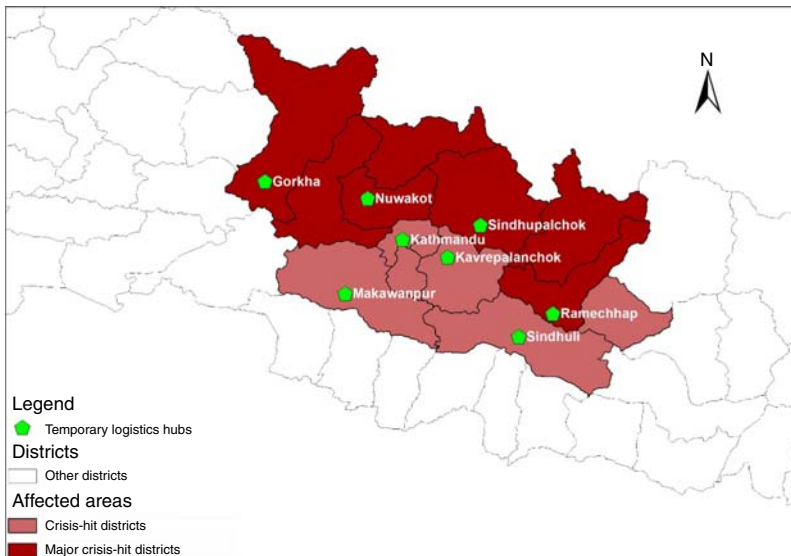


Figure 3.
Spatial location of optimal temporary logistics hubs

Furthermore, calculations were carried out to understand the impact of the number of TLHs on both the cost and the unsatisfied demand objectives. The results in Figure 4 show the change in cost attributes and total unsatisfied demand with a change in the number of TLHs. The figure shows that eight TLHs provide the minimum total cost and minimum unsatisfied demand; increasing the number of TLHs beyond eight raises the total cost, whereas total unsatisfied demand remains the same, perhaps owing to the limited availability of relief materials in the TLHs and supply points. Thus, we performed a sensitivity analysis to examine the extent to which the available quantity of emergency relief in the TLHs and supply points affects costs and demand satisfaction.

Table V shows the results of the sensitivity analysis over the available quantity of emergency relief materials in the TLHs. The table illustrates the cost attributes and total unsatisfied demand. Each scenario represents an increase in the available units of relief materials by 10,000 units in each step. In each scenario, the model resulted in eight optimal TLHs. With an increase in the availability of emergency relief materials in the TLHs, the results show that total unsatisfied demand decreases at the cost of increased total costs, while the fixed cost remains the same. This sensitivity analysis allows us to conclude that keeping the locations the same, an increase in the availability in the TLHs decreases total unsatisfied demand and increases total cost. This cost can be attributed to increases in downstream transportation costs. The sensitivity analysis of the model over the varying

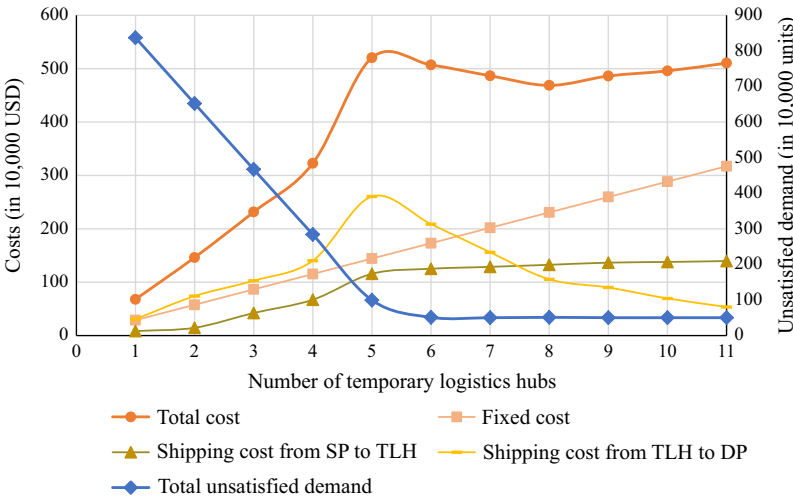


Figure 4.
Change in cost
attributes and
unsatisfied demand
with a changing
number of TLHs

Table V.
Sensitivity of the
available quantity of
relief materials
in TLHs

Scenarios	Total unsatisfied demand (in 1,000 units)	Total cost	Shipping cost from SP to TLH	Shipping cost from TLH to DP
			(in 1,000 USD)	
Original case	512.10	4,686.68	1,325.65	1,053.84
Scenario I	482.10	4,691.15	1,324.66	1,059.30
Scenario II	452.10	4,693.32	1,336.61	1,049.52
Scenario III	422.10	4,697.68	1,348.48	1,042.01
Scenario IV	392.10	4,697.82	1,361.19	1,029.43
Scenario V	362.10	4,701.76	1,375.49	1,019.09

quantity of emergency relief materials available in the supply points shows no significant reduction in total costs or unsatisfied demand upon increasing the available units.

Additionally, we investigated the model performance over the multi-sourcing constraint. Figure 5 shows the model results with and without the multi-sourcing constraint. In both cases, the optimal number of TLHs remains the same. While the other input parameters remain the same, the results highlight that multi-sourcing reduces total unsatisfied demand with a slightly higher cost compared with single sourcing. This finding indicates the significance of multi-sourcing for minimizing total unsatisfied demand.

6. Conclusions and future scope

Deciding on the best location for TLHs to aid humanitarian relief distribution often involves more than one decision maker and the trade-off between multiple objectives. In this study, we developed a mathematical model to determine the optimal location for TLHs by using a multi-objective optimization model with multi-sourcing as well as dynamic demand, cost, and capacities. We also proposed an FFRS under the GDM condition to take account of the decision opinions of multiple decision makers. This consideration is important to avoid issues with the ownership of the TLHs that may arise because of monopolistic decision making. The results of the questionnaire with humanitarian organizations show the heterogeneous nature of decision opinions. Although the humanitarian code dictates that minimizing human suffering should be given utmost priority during disaster response, this alone does not necessarily hold true. Indeed, humanitarian organizations often have to work under a tight budget, resulting in many trade-offs.

The model proposed herein was implemented by using data obtained from the Nepal earthquake in 2015. The results of the optimization model clearly highlight the trade-off relationship between minimizing total costs and unsatisfied demand. Emphasizing minimizing costs results in decreased demand satisfaction, whereas emphasizing minimizing unsatisfied demand leads to increased costs. The sensitivity analysis shows the extent to which the available quantities of emergency relief items in the TLHs and the supply points influence costs and unsatisfied demand. Higher availability in the TLHs increases demand satisfaction at the price of increased costs. Additionally, the model was

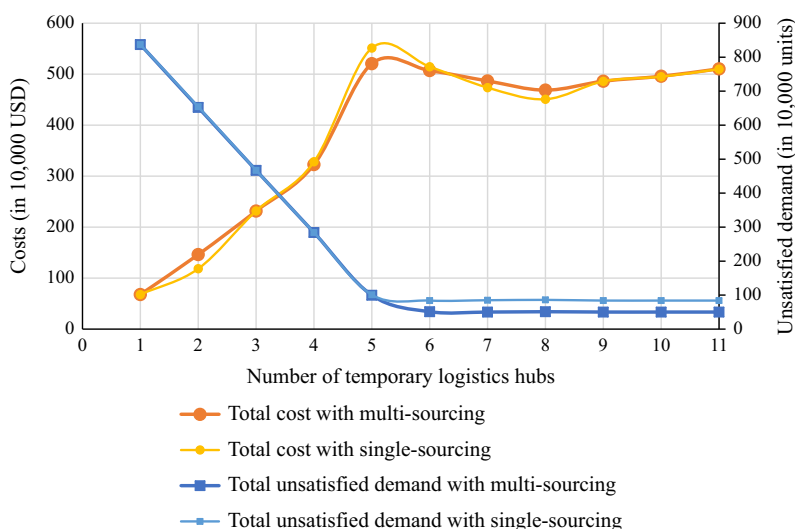


Figure 5.
Comparison of
single sourcing with
multi-sourcing

found to be less sensitive to increases in the availability of relief materials in the supply points. Further, the analysis of the multi-sourcing constraint reveals the reduction in total unsatisfied demand at the cost of increased costs in the multi-sourcing setting compared with single sourcing under the same availability restrictions. However, multi-sourcing enables supply chain agility, which is essential during disaster response.

Finally, the practical implications of involving multiple decision makers early in the location selection process might help develop a sense of ownership. This sense of ownership is important to maximize the utilization of the established hubs while enabling coordination. Moreover, the multi-actor approach used to determine the weight of objectives enables coordination among several decision makers by synthesizing a representative outcome from a decision maker's judgments. The trade-off between non-commensurable objectives provides decision makers with ample alternatives and combinations from which to choose when deciding on the available quantity of emergency relief goods as well as the number and location of the TLHs. Moreover, a sensitivity analysis helps decision makers decide where and how much emergency relief materials should be made available for minimizing the total objective.

However, the model proposed in this study assumes all decision makers have equal importance, which might not hold true in real-world disaster operations. Developing a method to determine the relative importance of decision makers and incorporating it into the model is thus a possible extension. Future research could also focus on developing ways to directly incorporate coordination between multiple actors. Other possible extensions would be determining the exact length of the operational horizon of TLHs. Future research could apply the current model in other disaster cases using the same or different types of objectives to understand the dynamics of location selection process under different scenarios.

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Further reading

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