FUZZY DISASTER RELIEF PLANNING WITH CREDIBILITY MEASURES

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Abstract: We propose a disaster relief planning model that can handle unclear information while maximizing the credibility of the relief organizations in the most cost efficient way. Considering the uncertainty and incompleteness of the disaster data, we propose a novel non-linear fuzzy credibility measure based on the timely arrival of the relief items. By using fuzzy linear programming, theoretical performance of the relief effort is optimized for the desired level of credibility and more effective asset utilization is provided. The applicability of the model is justified with real data to demonstrate its use for organizations to establish accountable and more credible status in the eyes of donor countries and vulnerable communities.

Keywords: disaster management; emergency logistics; fuzzy linear programming.

1. Introduction

As the world population is getting denser, natural disasters result in significant amount of lives and economical resources every year. With an increased consciousness, the preparation efforts for better relief and humanitarian assistance became more important. In this context, we propose a disaster relief planning scheme that can handle the unclear information while maximizing the credibility of the relief organizations in the most cost efficient way. The main difference between mounting a disaster relief plan and an ordinary transportation plan is the uncertainty in the available information about demand, supply, and cost. In the most of situations, the trusted and accurate information can not be obtained. Therefore, considerable amount of research in the literature suggest making some assumptions on the information. Our way in this research is to use fuzzy logic theory for modeling this uncertainty. While we handle the uncertainty via fuzzy logic theory, for the desired level of credibility, theoretical performance of the relief effort can be obtained and more effective utilization of assets can be provided. Hence, this would help organizations in establishing accountable and more credible status in the eyes of donor countries and vulnerable communities. First, the performance of the relief effort is evaluated based on the timely arrival of the relief items by introducing “non-linear fuzzy credibility” measure. Thus, we contribute a new quantitative key performance indicator to disaster management. Integration of these processes with the fuzzy credibility using fuzzy linear programming should also be noted.

2. Literature Review

Disasters are defined as large intractable problem that tests the ability of communities and nations to effectively protect their populations and infrastructure, to reduce both human and property loss and to rapidly recover, [1]. Besides the frequently observed natural disasters such as hurricanes, earthquakes, floods, drought, epidemics, there also exist man-made disasters such as terrorist attacks or nuclear explosions. With the purpose of eliminating the devastating impact of disaster events, the disaster management field experienced a rapid growth during the last decade. Literature in this field consists of research articles related to statistics, economics, geophysics, engineering and operations research disciplines.

Recent studies [9], [3], [14], [15] focus on operations research approaches for solving planning problems in disaster relief and emergency logistics. A two-step heuristic solving vehicle routing and dispatching for multi-commodity problem is proposed by Yi et al. [21]. In [7], the authors consider dynamic assignment of multiple emergency response and evacuation traffic flows and propose a cell transmission based linear program model. Chang et al. [6] use stochastic programming and propose a
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decision support system for emergency logistics network planning under uncertainty. Implementation of fuzzy logic in disaster relief and emergency logistics is introduced by Sheu et al. in [10]. A fuzzy multi-objective programming method for relief distribution problem is developed by Tzeng et al. [20]. The authors integrated a fuzzy measurement for fairness to eliminate unfair distribution. In a more recent study [19], the authors present a novel approach to emergency logistics distribution for quickly responding to the affected areas in a three-day crucial rescue period. Considering time-varying relief demand forecasts, they propose a multi-objective dynamic programming approach with affected-area grouping, determination of distribution priority, group-based relief distribution and dynamic relief supply. Based on a three-layer national relief supply network, fuzzy clustering is used to group the affected areas and to assign their distribution priority. While minimizing setup and transportation costs associated with a given type of relief, their model maximizes the relief demand fill rate, which is crisp.

Few research studies address the emergency logistics issues in the context of real disasters. In [13], authors propose a centralized management of logistics operations through a single organization like United Nations. Transportation management problem after a devastating earthquake in Mexico City has been studied in [2]. Following the 1999 earthquake in Taiwan, Tzeng et al. [20] propose a relief-distribution design model at the national level. The model includes three objectives: minimizing the total cost, minimizing the total travel time, and maximizing the minimal satisfaction during the planning period. Although operations research approach for international emergency logistics is proposed as a future research topic in a few study including [19], a scenario based system design for quick response in international setting is considered in [17].

An important assumption in all of the studies mentioned above is the availability of not only demand and supply data but also availability of precise financial data regarding the procurement and transportation costs to be minimized. Relaxing the assumption on the availability of the financial data, in this study, we propose an alternative disaster relief-planning model with nonlinear fuzzy credibility measure.

3. Assumptions for Disaster Relief Model

In this study, we assume that disaster relief network consists of three stages and two echelons. First stage is the set of relief item supply points, the second stage contains relief distribution centers and the last stage consists of areas affected by disaster. Provided relief items are picked up from supply points and then consolidated at distribution centers to be shipped to the locations where relief items are demanded. Based on this network configuration, we propose an optimal planning scheme that can handle the unclear information while maximizing the credibility of the relief distribution at the most cost efficient way. We assume that all transportation channels are accessible and relief items are durable. We assume that different relief items have different delivery due dates, which are not strict, however, the earlier the more credible.

\[
\mu_i(q) = \begin{cases} 
0, & q \leq q^1_i \\
\left(\frac{q - q^1_i}{q^b_i - q^1_i}\right)^{1/b}, & q^1_i \leq q \leq q^b_i \\
\left(\frac{q^b_i - q}{q^b_i - q^1_i}\right)^{1/b}, & q^b_i \leq q \leq q^0_i \\
0, & \text{else}
\end{cases}
\]

Fig. 1. Fuzzy membership function for supply

Accurate, real-time demand information for relief items are assumed to be inaccessible, which is always the case as pointed out in [19]. It is generally assumed that how much and what kind of relief items is supplied is known a priori with certainty. In a real situation, quantities of these aids are characterized by strong uncertainty. Therefore we assume that supply of item \( r \) available at supply point \( i, q_{ir} \) is characterized by a nonlinear fuzzy number with the membership function \( \mu_{q_{ir}}(q) \) given in Fig. 1.
In our model, we assume that each relief item \( r \) has a threshold value until which delivery of the item is most credible. When the threshold value is exceeded, credibility gradually falls down. For example, after an earthquake, rescue teams and operators are necessary at most for two weeks. After two weeks, rescue operations usually become useless. To integrate this reality to our model, we construct a fuzzy number denoting the credibility of delivery of the item with respect to time.

\[
\mu_{d_0}(t) = \begin{cases} 
1, & 0 \leq t \leq t_0 \\
e^{-\frac{(t-t_0)}{t_1}}, & t_0 \leq t \leq t_1 \\
0, & \text{else} 
\end{cases}
\]

![Fig. 2. Nonlinear fuzzy membership function for the credibility of the delivery of item \( r \)]

We employ two parameters in constructing the fuzzy credibility; \( t_0 \) is the threshold value until which the necessity of the item is maximum. Between \( t_0 \) and \( t_1 \) the necessity of the item falls down and after \( t_1 \), it is equal to zero as the membership function \( \mu_{d_0}(t) \) is illustrated in Fig. 2 and formulation is presented next to the figure.

\[
\mu_{\tilde{p}_r} = \begin{cases} 
0, & m \leq m^1_r \\
\left( \frac{m - m^1_r}{m^2_r - m^1_r} \right)^{1/b}, & m^1_r < m \leq m^0_r \\
\left( \frac{m - m^0_r}{m^2_r - m^0_r} \right)^{1/b}, & m^0_r < m \leq m^2_r \\
0, & \text{else} 
\end{cases}
\]

![Fig. 3. Fuzzy membership function for price](image)

Although disaster relief items are usually collected by donation, items required for the first aid can be procured from any supplier either by donor countries or by the government of the stricken country. Since it is highly uncertain, price of the relief items are usually not taken into account in the disaster planning literature. However, the true cost relief items should be considered while planning the disaster relief operations. Note that the price of a relief item will be different at different countries or at different suppliers. In this study, we assume that unit price of item \( r \) at supplier \( i \), \( \tilde{p}_r \) is a nonlinear fuzzy number with membership function presented in Fig. 3.

Due to the fuzziness in supply and delivery operations, the satisfaction of the requested demand quantity should be expressed by a soft equation whose membership function \( \mu_{d_0}(d) \) is given in Fig. 4. With \( \pm \delta_r \) being an acceptable tolerance level for the demand of each relief item \( r \), we can illustrate the membership function for fuzzy demand satisfaction equation as in Fig. 4.

![Fig. 4. Fuzzy membership function for demand satisfaction equation](image)
4. Multi-objective model for disaster relief planning

This section presents the model with the notation. Let $i \in I$, denote the supply point; $j \in J$, denote the relief distribution point; $k \in K$, represent the affected area where aid will be delivered to; $r \in R$, be the relief item requested and $t \in T$ denote the time period. The notation and the model are as follows:

- $\tilde{s}_{ir}$: fuzzy supply quantity for item $r$ available in time period $t$ at supply point $i$;
- $d_{kr}$: demand for item $r$ at demand point $k$;
- $\tilde{c}_{ij}, \tilde{c}_{jk}$: unit fuzzy transportation cost from supply point $i$ to distribution center $j$ and from $j$ to $k$;
- $q_{ij}, q_{jk}$: available transportation capacity between points $i, j$ and $j, k$;
- $\tilde{p}_r$: unit fuzzy price of relief item $r$ at supply point $i$;
- $\theta_{kr}$: credibility level about the satisfaction for relief item $r$ at demand point $k$;
- $g_{jk}$: travel time from distribution center $j$ to demand point $k$;
- $h_j$: potential delay period at relief distribution center $j$;
- $F_l$: fixed cost for allocating transportation vehicle of type $l$;
- $x_{ijrt}$: the amount of item $r$ transported from supplier $i$ to distribution center $j$ in period $t$;
- $y_{jkrt}$: the amount of item $r$ transported from distribution center $j$ to demand point $k$ in period $t$;
- $z_{jkrt}$: is 1 if the item $r$ is shipped to point $k$ through distribution center $j$ at time $t$; 0 otherwise;
- $u_{ij}, w_{jk}$: number of transportation vehicles between points $(i, j)$ and $(j, k)$ in period $t$;
- $a_{jkrt}$: period in which item $r$ arrives to the demand point $k$, shipped from distribution center $j$ at time $t$.

\[
\min f_1 = \sum_{ijrt} (\tilde{p}_r + \tilde{c}_{ij}) x_{ijrt} + \sum_{jkrt} \tilde{c}_{jk} y_{jkrt} + \sum_{ijlt} F_l u_{ijt} + \sum_{jklt} F_l w_{jk}\tag{1}
\]

\[
\max f_2 = \min \theta_{kr}\tag{2}
\]

subject to

\[
\sum_j x_{ijrt} = \tilde{s}_{ir} \quad \forall i, r, t \tag{3}
\]

\[
\sum_t x_{ijrt} = \sum_y y_{jkrt} \quad \forall j, r \tag{4}
\]

\[
\sum_t y_{jkrt} = d_{kr} \quad \forall k, r \tag{5}
\]

\[
\sum_i \sigma r_{ijrt} \leq q_{ij} u_{ijt} \quad \forall i, j, t \tag{6}
\]

\[
\sum_{ij} \sigma r_{jkrt} \leq q_{jk} w_{jk} \quad \forall j, k, t \tag{7}
\]

\[
a_{jkrt} = (t + h_{r} + g_{jk}) z_{jkrt} \quad \forall j, k, r, t \tag{8}
\]

\[
\mu_{d_{kr}} (a_{jkrt}) \geq \theta_{kr} \quad \forall j, k, r, t \tag{9}
\]

\[
z_{jkrt} \leq My_{jkrt} \quad \forall j, k, r, t \tag{10}
\]

\[
y_{jkrt} \leq Mz_{jkrt} \quad \forall j, k, r, t \tag{11}
\]

\[
x_{ijrt}, y_{jkrt} \geq 0 \quad \forall i, j, k, r, t \tag{12}
\]

\[
u_{ij}, w_{jk} \in \mathbb{Z} \quad \forall i, j, k, t \tag{13}
\]

\[
z_{jkrt} \in \{0,1\} \quad \forall j, k, r, t \tag{14}
\]
There are two objectives; minimizing the total cost of procurement and transportation (1), and maximizing the credibility (2). Fuzzy constraint (3) ensures the transportation of the supplied relief items. Equation (4) is flow conservation constraint for every item and supply points. Equations (6, 7) represent the capacity limitation of the available transportation assets on each route to collection points in every time period. Note that, in an emergency transfer, air is the most frequently used mode and airlift is strictly limited. Constraint (5) represents the demand satisfaction, which is a fuzzy constraint because of uncertainty. Although we assume that the demand is known in the beginning of relief process, the credibility of the demand of a certain item changes together with time. Equation (8) gives us the time period that the relief item arrives to the corresponding demand point. The credibility of delivery of relief item is calculated based on the arrival time in Equation (9).

5. Solution Algorithm

Since any disaster relief item can be supplied by any donor country at different cost, we try to supply a disaster relief item from the country in which the price of the item is lower. At the solution stage, by obtaining the total cost as a fuzzy number, the above model is transformed into parametric model by following the steps given below.

**Step 1.** Initialize the possibility levels \( \alpha \) and \( \gamma \), credibility level \( \theta \) and acceptable tolerance level \( \varepsilon \).

**Step 2.** Defuzzify supply constraint (3) for the given possibility level \( \alpha \), ie., replace (3) by

\[
\sum_{j} x_{s_{ijr}} \leq s_{ir} + \alpha^{\varepsilon} \quad \text{and} \quad \sum_{j} x_{s_{ijr}} \geq s_{ir} - \alpha^{\varepsilon}.
\]

**Step 3.** Defuzzify demand satisfaction constraint (5) for the given possibility level \( \alpha \), ie., replace (5) by

\[
\sum_{j} y_{jkr} \leq d_{kr}(1 - \delta_{i}(1 - \alpha)) \quad \text{and} \quad \sum_{j} y_{jkr} \geq d_{kr}(1 - \delta_{i}(1 - \alpha)).
\]

**Step 4.** Defuzzify the objective function by replacing cost functions first with

\[
\sum_{j} x_{s_{ijr}} (p_{ijr}(1 + \eta_{ir}(1 - \gamma^{\delta}_{i})) + c_{ij}(1 + \eta_{ir}(1 - \gamma^{\delta}_{i}))) \quad \text{and} \quad \sum_{j} y_{jkr}(c_{jk}(1 + \mu_{jk}(1 - \gamma^{\delta}_{i})))
\]

then

\[
\sum_{j} x_{s_{ijr}} (p_{ijr}(1 - \eta_{ir}(1 - \gamma^{\delta}_{i})) + c_{ij}(1 - \eta_{ir}(1 - \gamma^{\delta}_{i}))) \quad \text{and} \quad \sum_{j} y_{jkr}(c_{jk}(1 - \mu_{jk}(1 - \gamma^{\delta}_{i})))
\]

**Step 5.** For the current values of \( \alpha \) and \( \theta \) obtain the solution set by solving the resulting mixed integer linear programming problem and go to Step 6.

**Step 6.** Update the values of \( \alpha \) and \( \theta \). Proceed to Step 2 until all combinations of parameter values are exhausted.

**Step 7.** Fuzzify the objective function value and decision variables in the solution.

6. Numerical Results

Using above algorithm, for possibility and credibility levels \( \{0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0\} \), we obtain 121 fuzzy numbers that demonstrate fuzzy total cost values for different possibility (\( \alpha \)) and credibility (\( \theta \)) combinations. We present only two of them in Fig. 5. The shapes of these fuzzy numbers are similar to fuzzy membership functions for price and transportation costs because of the linearity of the objective function. We interpret these results as follows. While credibility is 0.8 and...
possibility level for demand is 0.2, carrying out this disaster relief operation most possibly costs 1,586,500, and while credibility level is 0.2 and possibility level is 0.8, carrying out the optimal disaster relief operation most possibly costs 1,661,000.

7. Conclusion

The model is run for 7 relief items, 5 supply points, 2 demand areas and for two weeks. After the optimization is run, the maximum level of credibility is reached. The proposed model can be used to analyze the required effort for the desired level of credibility and possibility. Even though, it is not possible to determine market price of an item, the total cost analysis gives an idea whether endeavoring to find lower price makes sense or not.

References