Research on Location-Allocation Problem of Emergency Logistics Based on Supply Chain Collaboration

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Abstract. The location of relief distribution centers and allocation of relief commodities are two of the most challenging issues in emergency logistics. This paper develops a multi-objective robust stochastic optimization model to determine the optimal location-allocation for emergency logistics problem considering the priority of demand points, the equity level between two demand points and the average removal time and cost for each relief commodity. In our model, not only demand, but also supplies and the state of roads in the post-disaster phase are considered as uncertain parameters. The proposed model simultaneously attempts to minimize the average of the weighted response times and the sum of the expected value and the variance of the total cost in the preparedness and response phase. Considering the global evaluation of two objectives, a compromise programming model is formulated and solved to obtain a non-dominating compromise solution. A case study of our robust stochastic optimization approach for disaster planning for the Great Sichuan Earthquake in China is presented to demonstrate that the proposed model can help in making decisions on both facility location and resource allocation in cases of disaster relief efforts.

Introduction

Over the past 30 years, earthquake has been proven to be a global challenge because of its unpredictable nature and potential scale of impact represented by fatalities and economic costs (Alfredo et al., 2016). Especially over the past decade, the earthquake often happens everywhere in the world, and brings enormous loss to people's lives and properties. Examples in the last decades include the Great Sichuan earthquake which killed nearly 70 thousand people in May 2008 (Fawu et al., 2009), the Haiti earthquake in January 2010 killing approximately 230,000 lives (Patrick & Anna, 2012), the Chile earthquake with at least 708 victims in February 2010 (BBC News, 2010), and the east Japan earthquake in March 2011 with 15,883 confirmed deaths (Christine, 2013). When the earthquake occurs, immediate distribution of emergency resources is pivot in minimizing the damage and the fatality and therefore the priority of post-earthquake relief operations. The emergency logistics decision-makers have to make optimal decisions in the distributions of the resources. Therefore, the disaster relief logistic problems have attracted a lot of attention in the recent years.

In our paper, demand, supply, disruption of roads, priority of demand points and the proportion of usable inventories are all viewed as the uncertain parameters. To our knowledge, it is the first time to consider these five sources of uncertainty at the same time for emergency logistics. The purpose of the present paper is to proffer a multi-objective robust optimization model to address the location-allocation problem under uncertainty in emergency logistics. Different from the recent development trends in this topic, the model tackles the location-allocation problem in a multi-objective, multi-stage and multi-commodity, while considering the inherent uncertainties involved in disaster situations, such as the demand, supply and the proportion of usable inventories. The uncertainty of the disaster is obtained by using a multitude of possible earthquake intensity scenarios. The formulation considered some real concerns of emergency logistics under each disaster scenario, such as considering disruption of roads, priority of demand points and average removal time and cost for each commodity. This model includes two objective functions, which minimize the
expected total cost of relief logistics and the risk reflected by the variability of the total cost and the average of the weighted response time. The equity level between two demand points is also an important consideration in this paper, which can ensure the distribution of relief items among demand points in an equitably way. The problem is solved by using the Lp-metrics technique.

Model Assumption

The model is based on the following assumptions:

1. The suppliers can provide more than one type of relief commodity.
2. Each RDC can serve more than one AA, and each supplier can afford more than one RDC.
3. The supplier has capacity limitations for providing each type of relief commodity.
4. There are predefined nodes for locating the RDCs.
5. Different types of relief commodities are permitted to be loaded in the same vehicle.
6. There is no limit to the transportation vehicles, and the disaster areas can be still reachable through the current road network.
7. Shortages and inventory of relief commodities are penalized.

Model Formulations

Notations and Definitions

Indices

- $i$: Index of suppliers ($i = 1, \ldots, I$)
- $j$: Index of potential locations for RDCs ($j = 1, \ldots, J$)
- $k$: Index of affected areas for AAs, i.e., demand points ($k = 1, \ldots, K$)
- $r$: Index for storage capacity levels of RDCs ($r = 1, \ldots, R$)
- $c$: Index of relief commodity ($c = 1, \ldots, C$)
- $s$: Index for probable disaster scenarios ($s = 1, \ldots, S$)

Deterministic Parameters

- $FC_j^r$: Fixed cost for opening a new RDC $j$ at capacity level $r$.
- $CT_{ij}^c$: Transportation cost per unit of relief commodity $c$ from supplier $i$ to RDC $j$.
- $CT^c_{ij}^s$: Transportation cost per unit of relief commodity $c$ from supplier $i$ to RDC $j$ in scenario $s$.
- $CT^c_{jr}^s$: Transportation cost per unit of relief commodity $c$ from RDC $j$ to AA $k$ under disaster scenario $s$.
- $Ts_{ij}^r$: Transportation duration time from supplier $i$ to RDC $j$ in pre-disaster.
- $Tra_{jk}^r$: Transportation duration time from RDC $j$ to AA $k$ in pre-disaster.
- $TR^c_{jr}^s$: Average removal time for each commodity type $c$ at RDC $j$ in scenario $s$.
- $CR^c_{jr}^s$: Removal cost for each commodity type $c$ at RDC $j$ in scenario $s$.
- $S_{ic}$: Capacity of supplier $i$ to supply relief commodity $c$.
- $v_c$: Unit volume of the commodity $c$.
- $Cap_r$: Type of capacity of RDC $r$ that has been opened.
- $G$: Available budget for establishing RDCs.

Stochastic parameters
Transportation duration time from supplier $i$ to RDC $j$ in scenario $s$ $(T_{sr_{ij}^s} = \kappa_{ij}^s \cdot T_{r_{ij}})$.

Transportation duration time from RDC $j$ to AA $k$ in scenario $s$ $(Tra_{jk}^s = \kappa_{jk}^s \cdot Tra_{jk})$.

Amount of demand for commodity $c$ at AA $k$ under disaster scenario $s$ $(D_{kc}^s)$

Demand priority for commodity $c$ at AA $k$ in scenario $s$ $(\pi_{kc}^s \geq 1)$.

Occurrence probability scenario $s$ $(\sum_{s} p_s = 1)$.

First-stage decision variables

$X_{jr}^s$: 1 if the $j$th candidate RDC is opened at capacity level $r$; 0 otherwise.

$O_{ijc}^s$: Amount of commodity $c$ purchased from supplier $i$ and stored at RDC $j$.

Second-stage decision variables

$P_{ijc}^s$: Amount of commodity $c$ to be delivered from supplier $i$ to RDC $j$ in scenario $s$.

$Q_{jkc}^s$: Amount of commodity $c$ to be delivered from RDC $j$ to AA $k$ under disaster scenario $s$.

$P_{kc}^s$: Inventory level of commodity $c$ at AA $k$ in scenario $s$.

$U_{kc}^s$: Amount of shortage at AA $k$ in scenario $s$.

Mathematical Model (P1)

The first objective function (1) minimizes the average of the weighted response times for all of the scenarios. The first and second terms in the numerator calculates the transportation duration time of the commodities from supplies to RDCs and from RDCs to AAs, respectively, which depend on the distance and traffic conditions, and the last part in the numerator presents the removal time of commodities at RDCs.

\[
\text{Min } obj_{1}^{p1} = \frac{\sum_{s} p_s \left( \sum_{i \in I} \sum_{j \in J} T_{sr_{ij}^s} P_{ijc}^s + \sum_{j \in J} \sum_{k \in K} \sum_{c \in C} Tra_{jk}^s Q_{jkc}^s + \sum_{j \in J} \sum_{k \in K} TR_{jk}^s Q_{jkc}^s \right)}{\sum_{k \in K} \sum_{c \in C} D_{kc}^s} \quad (1)
\]

The second objective function (2) minimizes the total expected cost consisting of the preparedness phase and the response phase costs. The preparedness phase costs include the setup costs, procurement costs, transportation costs from suppliers to RDCs, and unused inventories costs in RDCs. The response phase costs cover the procurement costs, the transportation costs from suppliers to RDCs, the removal costs of commodities from RDCs, the transportation costs from RDCs to the affected areas, the inventory holding costs in AAs, and the unmet demand costs in AAs.

\[
\text{Min } obj_{2}^{p2} = YC + PC + SRTC + RUI + \sum_{s} p_s \left( PC_s + SRTC_s + RATC_s + TC_s + AIC_s + ASC_s \right) \quad (2)
\]
Constraint (3) guarantees that the amount of commodity $c$ procured from supplier $i$ cannot have more than the supplier’s capacity in the preparedness phase. Constraint (4) ensures that the amount of commodity $c$ procured from supplier $i$ cannot exceed the remaining usable commodity $c$ in the response phase under scenario $s$. Constraint (5) is the flow conservation at RDC $j$ which shows that the sum of the amount of the remaining usable commodity supplied to a specific RDC from suppliers in preparedness phase and the shipped commodity $c$ from suppliers to RDCs in response phase are equal to the amount of commodity transferred to affected areas from the RDCs. Constraint (6) indicates the available budget for the establishment of RDCs. Constraint (7) determines the number of open RDC at node $j$ to one. Constraint (8) restricts the amount of commodity supplied to a RDC from suppliers in preparedness phase does not exceed the capacity limits of the specific RDC. Constraint (9) and (10) ensure suppliers and RDCs from dispatching commodity to AAs where RDC has been opened. Constraint (11) is the flow conservation for AAs. Without loss of generality, inventories and initial shortages are considered zero. Constraints (12)-(14) represent the type of the decision variables.

Solution Methodology

The methods of multi-objective optimization have been successfully applied in the literature. To solve the proposed multi-objective optimization model, the LP-metrics method (2011) was used to solve the proposed model. Based on this method, the proposed model should be solved for each one of these two objectives separately. Assume that the optimal values for the two objective functions are $F^*_1$ and $F^*_2$. The LP-metrics objective function $F_3$ can be written as follows:

$$
\text{Min } F_3 = [w \cdot \frac{F_1 - F^*_1}{F^*_1} + (1-w) \cdot \frac{F_2 - F^*_2}{F^*_2}]
$$

(15)
LP-metrics coefficient \( w(0 \leq w \leq 1) \) is the relative weight of components of the objective function (15). Using LP-metrics objective function and considering our model constraints, we have a single objective, mixed integer programming model, which can be efficiently solved linear programming solvers.

Case Study

Test Instances

China is a country prone to many types of natural disasters, such as earthquakes. There have been a number of earthquakes with magnitude 2 or above on the Richter scale that caused heavy casualities as well as widespread economic loses. This section presents a case study to demonstrate the effectiveness of the proposed model and solution algorithm. The main study area lies in the Sichuan Province in China, which has been a number of earthquakes with magnitude 8.0 and caused heavy casualities as well as widespread economic loses in 2008. The earthquake in Wenchuan, one County of Sichuan Province, caused about 69,227 people were killed, 374,643 injured and 17,923 missing. Many historical and recent earthquakes have affected this region. Based on the disaster-related information including the suppliers, candidate RDCs and relief demand from affected areas, the presented model is employed to design the emergency logistics network.

According to Fig.2, we assume the five suppliers, named Sup1…, Sup5 (Kunming, Guiyang, Changsha, Wuhan, Xi’an), the 10 most severely affected areas and five candidate RDCs to supply relief commodities, including the three types of emergency supplies, namely, water, food, and tents.

Five scenarios are considered in this numerical test, \( s_1, s_2, s_3, s_4, \) and \( s_5 \), with occurrence probabilities of 0.1, 0.15, 0.2, 0.25, and 0.3, respectively. On account that some data about the earthquake are not yet published by the government, man-made data are used to test the model, which will not lead to essentially different solutions. Due to the limitation of space, other specific data are not described in detail.

Computational Results

In this section, we present computational results and analyze the behavior of the proposed model. All computations were coded in GAMS 23.5 and solved by the CPLEX 12.2 solver, using a PC with Core i5 CPU, 2.2 GHz and 12 GB RAM DDR3 under Windows 10 environment. In order to present Model P2, Model P1 and P2 are solved for the same problem. The features and results will be analyzed in detail below.

<table>
<thead>
<tr>
<th>Model</th>
<th>No. of decision variables</th>
<th>No. of constraint</th>
<th>computation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>1424</td>
<td>1433</td>
<td>138</td>
</tr>
<tr>
<td>P2</td>
<td>1440</td>
<td>1454</td>
<td>867</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RDC</th>
<th>Size</th>
<th>Water</th>
<th>Food</th>
<th>Shelter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chengdu</td>
<td>Large</td>
<td>624</td>
<td>809</td>
<td>18</td>
</tr>
<tr>
<td>Deyang</td>
<td>Medium</td>
<td>292</td>
<td>-</td>
<td>48</td>
</tr>
<tr>
<td>Mianyang</td>
<td>Large</td>
<td>-</td>
<td>678</td>
<td>75</td>
</tr>
<tr>
<td>Jiangyou</td>
<td>Small</td>
<td>760</td>
<td>-</td>
<td>21</td>
</tr>
</tbody>
</table>

Model P1 is just based on the stochastic scenario programming, which does not consider the uncertainty and robustness of the problem. Conversely, a robust approach is considered in Model P2 and the complexity of the model (i.e., large amount of variables and highly constraint) increases to some extent (see Table 1).
The results of the facility size and the storage amount of commodities in pre-disaster phase are given in Table 2. Table 2 shows that Chengdu is a large RDC and stores all three items; another large facility (Mianyang) stores food and shelters; Deyang and Jiangyou store water and shelters. Totally, four RDCs store about 1.67 million units of water, 1.49 million units of food and approximately 0.162 million units of shelter. The total cost of Model P2 is approximately 385.2 million yuan. The average of weighted response time is about 17804 h.

Summary
In this paper, we present a multi-objective, robust, stochastic optimization model to address location-allocation problem for emergency logistics, which are motivated by real-world disaster relief problem. The proposed model has attempted to minimize the average of the weighted response times and the total operational cost simultaneously and taken into account the uncertainties linked to the earthquake’s occurrence. The problem is reformulated as a single objective, linear programming problem through the Lp-metrics technique. The use of a robust stochastic scenario-based approach has addressed the solution robustness and model robustness under uncertain demand, supply and the road traffic conditions. Furthermore, the equity level between two demand points has also appeared in this paper. For future research, considering the multimodal transportation and the limitations of the vehicle, and developing efficient and effective meta-heuristics to solve the large-scale problems for emergency logistics are recommended.

References