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An Effective Transportation Planning in Disaster Response Management System

VikashKumar[1]* and SandeepSinghal[2]

[1,2]Mechanical Engineering Department National Institute of Technology, Kurukshetra, Haryana, India
E-mail: [1]vikky3758@gmail.com, [2]sandeep_singhal_reck@rediffmail.com

Abstract—*The number and scale of humanitarian operations has significantly increased during the past decades due to the rising number of humanitarian emergencies and natural disasters worldwide. Therefore, the development of appropriate transportation planning methods for optimization of the supply chains is constantly gathering importance. Emergency transportation is the most important part of disaster relief supply chain operations, and its planning problem always involves multiple objectives, complex constraints, and inherent uncertainties. To efficiently solve the problem, we develop a cooperative optimization method that divides the integrated problem into a set of subcomponents, evolves the sub-solutions concurrently, and brings together the sub-solutions to construct complete and effective solutions. We propose a optimization problem of emergency transportation planning in disaster relief supply chains, which takes into consideration three transportation modes viz air, rail, and road modes. The proposed method is effective, scalable, and robust, and thus contributes greatly to the performance of emergency transportation planning in disaster management.*

Keywords: *Disaster relief supply chains, Transportation planning, Multi-objective optimization, and Cooperative evolution.*

1. INTRODUCTION

We are now facing increasing threats from natural and man-made disasters like hurricanes, floods, earthquakes, infectious diseases, terrorism, etc., which often cause serious damage to lives and property. Efficient planning and scheduling of emergency supply chain operations is the most important factor in successfully managing and controlling the damage. However, in comparison with regular business supply chain operations, emergency supply chain operations are subject to the following special requirements and constraints:

- The operations often require the coordination of multiple organizations / agencies, including non- profit and government organizations such as police departments, fire departments, medical departments, military forces, and those for profit organizations such as vendors, transportation providers and warehousing providers.
- The main goal in emergency supply chain is to reduce and contain the losses caused by disasters as much as possible, meanwhile controlling the cost and risk of emergency operations. However, it is not easy to specify the objectives with some simple mathematical functions.
- Quick response and fast delivery are of vital importance to the success of operations.
- The available resources for the supply chain, such as transportation capability and warehouse facilities, are often very limited and cannot meet the overwhelming demands of the operations.
- The operations often involve more than one transportation mode (e.g., air, rail, road, etc.), and the decision maker needs to effectively coordinate multimodal transportation services.
- In the disaster areas, the environment of the supply chain may change quite frequently, and thus the emergency operations should be flexible enough to cope with the changes.
- The required information is often ambiguous, uncertain, incomplete, and sometimes even inconsistent and erroneous, and thus it becomes difficult to precisely model and solve the operational problems using classical mathematical approaches.

Transportation is a key function in both regular and emergency supply chains. During emergencies, the responders often face significant problems for delivering various kinds and huge amounts of relief supplies to different targets in the disaster areas in a timely and accurate manner. Typically, the emergency transportation decision making is a multistage process, and it is essential to evaluate and improve the transportation plans continuously. The main purpose of the paper is to propose an integrated model of emergency transportation planning in disaster relief supply chains, and develop an efficient solution method for the problem model. The proposed model can be considered as a heavily constrained and multi-objective optimization problem.

2. THE INTEGRATED MODEL OF EMERGENCY TRANSPORTATION PLANNING

The goal of emergency transportation in disaster relief supply chain is to deliver all the required relief supplies to demand targets timely and accurately. A comprehensive transportation plan consists of a set of sub-plans, including the task allocation plan and the resources (capacity) allocation plan at the strategic level, and the delivery scheduling and vehicle routing plans for individual service locations (sources), as shown in Fig. 1

2.1 Task Allocation

Suppose there are ‘m’ sources, ‘n’ targets, and ‘p’ kinds of relief supplies (goods), at the strategic level, we need to decide the quantity of each good ‘k’ to be delivered from each source ‘i’ to each target ‘j’, denoted by x_{ijk} ($0< i \leq m$, $0<j \leq n$, $0<k \leq p$).

Nevertheless, it is often very difficult to precisely define the quantity b_{jk} of each good k required by each target j, and it is more appropriate to depict the quantity using a fuzzy number $\overset{*}{b}_{jk}$. However, the lower limit of the required quantity must be satisfied such that:

$$\sum_{i=1}^{m} x_{ijk} \geq \inf(\overset{*}{b}_{jk}) \qquad \text{(i)}$$

On the other hand, the available quantity a_{ik} of good ‘k’ stored at source ‘i' is deterministic, but in some cases the current storage is not enough to satisfy the total demand, and thus we should consider the quantity a'_{ik} that source i needs to acquire during the early stages of disaster response:

$$a'_{ik}=\left(\sum_{j=1}^{n} x_{ijk} - a_{ik}\right) \text{ if } \left(\sum_{j=1}^{n} x_{ijk}\right)>a_{ik} \qquad \text{(ii)}$$
$$= \quad 0 \qquad\qquad \text{else}$$

Typically the quantity a'_{ik} has an upper limit $\overset{*}{b}_{ik}$, which can also be defined as a fuzzy number. Therefore, for all i and k we have:

$$\sum_{j=1}^{n} x_{ijk} \leq (a_{ik}+\overset{*}{a}_{ik}) \qquad \text{(iii)}$$

And for each a’ik , the acquisition cost can be evaluated using a cost function $\overset{*}{n}$ik which returns a fuzzy number, and the total acquisition cost $\overset{*}{C}$Q is calculated as:

$$\overset{*}{C}_{Q}=\sum_{i=1}^{m}\sum_{k=1}^{p}\overset{*}{n}_{ik}(a'_{ik}) \qquad \text{(iv)}$$

According to its importance and urgency, each required supply item has its own priority wjk and expected arrival times $\overset{*}{Ʈ}_{jk}$.$\overset{*}{Ʈ}_{jk}$ is a fuzzy number, since the supply item is sually expected to arrive in a given time period. The estimated arrival time of xijk, denoted by $\overset{*}{t}$ijk , is also a fuzzy number because the travel time of vehicles is always uncertain due to the variation of environment. Thus, the time delay of the subitem is $\Delta\overset{*}{Ʈ}_{jk} = \overset{*}{t}_{ijk} - Ʈ_{jk}$. The first objective function of the integrated problem is defined as the total delay weighted by the priority:

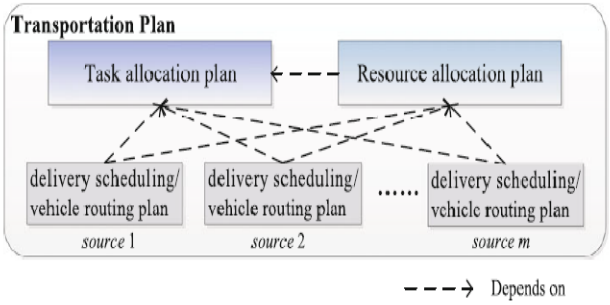

Fig. 1: The Components of a Comprehensive Transportation Plan

$$\overset{*}{T}=\sum_{j=1}^{n}\sum_{k=1}^{p} w_{jk}\left(\sum_{i=1}^{m}\Delta\overset{*}{Ʈ}_{ijk}\right) \qquad \text{(V)}$$

2.2 Transportation Resource Allocation

In almost all of the disaster response operations, more than one transportation mode is to be used, which makes the problem a multimodal transportation problem. For convenience, here, we consider three basic modes of transportation capacity: air, railway and road. However, the description, here, can be easily modified to other special cases. For example, if the disaster area is an island, we can replace road transportation with sea transportation, and simply ignore the railway transportation capacity. Here, we make a general assumption that air and railway transportation is scheduled uniformly by government departments, and the vehicles for road transportation are to be scheduled by the sources independently. The road vehicles can be divided into two categories: general-purpose vehicles and special-purpose vehicles. Accordingly, the relief supplies can be categorized into ordinary goods and special goods: general-purpose vehicles are used to transport ordinary goods, and each type of special-purpose vehicle are used to transport one or more types of special goods (such as explosive devices ,dangerous chemicals , special equipments etc).

Suppose there are N^G types of general-purpose vehicles and N^S types of special-purpose vehicles, we denote the capacity of a general-purpose vehicle of type l as Ψ_l^G, denote that of a special-purpose vehicle as Ψ_l^S, and denote the set of goods that can be transported by special-purpose vehicle type ‘l’ as G_l.

Therefore, also at the strategic level, we need to decide for each source i:

- The air transportation capacity Ψ_i^A allocated to source i, which is subject to the constraint

$$\sum_{i=1}^{m} \Psi_i^A \leq \Psi^A$$

where Ψ^A is the total available air transportation capacity (if there is no airport around the source then Ψ_i^A is fixed to zero).

- The railway transportation capacity Ψ_i^T allocated to i, which is subject to the constraint

$$\sum_{i=1}^{m} \Psi_i^T \leq \Psi^T$$

where ΨT is the total available railway transportation capacity (if there is no railway station around the source then WT i is fixed to zero).

- The numbers of different types of vehicles $n_{li}^G (0<l< N^G)$ and nSli$(0<l< N^S)$ allocated to i, all of which are subject to the available numbers of the vehicles.

2.3 Delivery Scheduling and Vehicle Routing

After allocating the transportation task and the resources, at each source i, we need to determine the transportation mode and delivery sequence of its supply items. This can be divided into the following steps:

1. If available, try to arrange high-priority items to air transportation capacity and then to railway transportation capacity as much as possible.
2. Fill up the available vehicles with remaining delivery items.
3. Determine the routes for the vehicles.

The second objective function of the integrated problem is the total transportation cost. Usually, the air and railway transportation capacity is fully utilized, and the corresponding parts of the cost can be evaluated, respectively, as follows:

$$C^A=\sum_{i=1}^{m}\sum_{j=1}^{n} c^A d_{ij}^A \Psi_{ij}^A \qquad \text{(vi)}$$

$$C^T=\sum_{i=1}^{m}\sum_{j=1}^{n} c^T d_{ij}^T \Psi_{ij}^T \qquad \text{(vii)}$$

where C^A is the unit cost of air transportation and c^T is that of railway transportation, d_{ij}^A and d_{ij}^T are, respectively, the air distance and the railway distance between source i and target j, Ψ_{ij}^A and Ψ_{ij}^A are, respectively, the air and railway capacity arranged for transportation from i to j. Since the routings of general-purpose vehicles and special-purpose vehicles are independent to each other, the problem can be further divided into two CVRPTW sub problems. After obtaining the result routing solution, we can easily calculate the travel distance d(l) and the travel time $\overset{*}{t}(l)$ of each vehicle l (the former is a normal function but the latter is a fuzzy one). The total cost of road transportation can then be calculated as follows:

$$C^{*R}=\sum_{i=1}^{m}\left(\sum_{l=1}^{N^G}\sum_{t=1} c_l^G \overset{*}{t}(l)+\sum_{l=1}^{N^S}\sum_{t=1}^{n_{li}^S} c_l^S \overset{*}{t}(l)\right) \qquad \text{(viii)}$$

where c_l^G and c_l^S are the unit costs of general-purpose and special-purpose vehicle types l, respectively.

Thus, the objective function of the total cost is calculated as:

$$C^{*}=C^{*Q}+C^A+C^T+C^{*R} \qquad \text{(viv)}$$

It should be noted that the load all relief supplies allocated to source i, or only part of supplies. That is, there are two different cases:

- In the first case (e.g., for most short-term disasters), the total transportation capacity is enough to deliver all supplies in a single run. Even in this case, bad allocation plans may result in that the capacity of some sources cannot satisfy their demands, which should be avoided as much as possible.
- In the second case, (e.g., for some long-term or very large disasters), the total transportation capacity is not enough. However, here, we still regard the VRP for each source as a single-period problem, because for the next period the vehicles need to be rearranged among the sources instead of returning back to the original sources. That is, we need to re-establish new instances of the whole transportation problem.

2.4 Summary

Now we can summarize the integrated transportation planning problem as a multi objective fuzzy optimization problem, which needs to minimize the total time delay, total transportation cost and total transportation risk simultaneously. The difficulty of the problem mainly lies in the following facets:

- The values of the three objective functions are all fuzzy variables.
- All the three objectives need to be evaluated based on not only the strategic task and resource allocation plans, but also the tactic delivery scheduling and vehicle routing plans.
- The integrated problem is subject to a number of constraints including the available relief supplies, the available transportation capacities, and the mandatory requirements that the lower limits of all demand items must be satisfied.

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