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A bi-objective stochastic model for emergency medical services network design with backup services for disasters under disruptions: An earthquake case study

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ABSTRACT

In the event of a disaster such as natural and human-made, high demand for medical supplies and a large number of injured people will emerge at the affected areas in a short time period. Rapid distribution of medical supplies and the speed of transferring injured to the hospital play an important role in assuring the effectiveness and efficiency of the emergency medical service (EMS). In this paper, a bi-objective stochastic optimization model is developed for location of transfer points and medical supplies distribution centers (MSDCs). When a disaster happens, resources are usually insufficient for all to be treated immediately. For this reason, determining the priority of injured treatments based on the severity of their condition is one the most important issue on EMS, called as triage system. Therefore, for approaching the model to the real world, triage system and failure probabilities of MSDCs and routes are considered. To enhance efficiency of services during such event, backup MSDCs are also utilized. Furthermore, the proposed bi-objective model is converted to a single-objective mixed-integer programming model applying the ε-constraint method. Finally, to show applicability of the model, a case study of earthquake disaster in an urban district in Iran is examined. The proposed model can help interdisciplinary agencies both to prepare and respond to disaster considering the disruption in an efficient manner.

1. Introduction

Extreme events such as natural and human-made can strike human with little or no warning and leave most victims and damages on societies behind. For instance, In 2014, 324 triggered natural disasters were registered that have left 140.8 million victims, 7832 casualties and over 99 billion dollars of loss in assets [1]. In the same year, according to Swiss Re, 147 man-made disasters occurred and left more than 10,000 casualties, missing and homeless people and billions of loss in assets [2]. Such events have raised not only the worldwide shock about the news of victims and damages but also the growing awareness of the issues on scientific methods which can prevent victims and damages. One of the important scientific methods to reduce consequences of a disaster is facility location problem in EMS [3]. This method intends to determine the optimal locations of facilities for EMS to address the needs which arise from disasters.

With regard to the type of a disaster, the impact of the event on the affected people can be various, but there are typical needs. We address three of these vital needs including urgent medical services, medical supplies, and triage system.

The first need to be addressed is urgent medical services. When a disaster happens, a wide range of injured people urgently needs aids to survive (need help and should be treated immediately). Meanwhile, response time is a critical factor in the delivery of emergency medical care. Safar [4], studied the earthquake of 1980 in southern Italy and concluded that if first aid had been rendered immediately 25–50% of those who were injured and died slowly could have been saved. In the same vein, research by Pretto et al. [5,6] of earthquakes in Armenia (1988) and Costa Rica (1991) concluded people whose deaths might have been prevented, they received medical attention in the first six hours after the disaster. It can be argued that the greatest demand for patient care after a massive large-scale disaster with large numbers of casualties occurs during the first 24–48 h [7].

The design of an efficient logistics network for EMS is the key to overcome the problems under the condition of disasters [8]. A major element for designing this logistics network is to improve the speed of transferring injured to the hospital/health center playing an important role in mitigating serious injuries that occur in a disaster. For this

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purpose, similarly to Berman et al. [9] some transfer points are considered. In fact, the injured people are transferred based on time criterion from the affected areas (AAs): (1) to a helicopter pad (transfer point) at normal speed, and from there to the hospital at increased speed. Or (2) directly to the hospital at normal speed.

The second need to be addressed is medical supplies. for example, the medicine and protective equipment. In the event of a disaster, high demands for medical supplies will appear at AAs within a short time period, and, therefore, large quantities of medical supplies should be brought to the AAs [10]. On the other hand, the medical supply shortage can lead to additional suffering and death; therefore, it is necessary to design strategies for timely supply of required medical supplies. Preparing the pre-positioning MSDCs at AAs represents one of the main noticeable logistical strategies allowing a rapid distribution of medical supplies and for effective management of the EMS [3]. It has a critical role in assuring the effectiveness and efficiency of the healthcare system [10]. Consequently, finding appropriate locations of MSDCs is one of the other important issues which has been considered in the design of logistics network for EMS. On the other hand, it is possible that MSDCs are disrupted by a disaster because they have been established close to the disaster-prone areas. In addition, the faults or delays in the supplier's deliveries lead to supplies shortage, increase risks, and subsequently increase damages and victims of disasters. Thus, to reduce such tragic consequences of disrupted MSDCs, backup MSDCs are considered, such that must be established in a safe place. At the same time, it is possible that roads conditions are affected by a disaster [11,12]. For example, an earthquake may destroy a segment of a freeway; thus, it is explicitly necessary to address failure probability of routes in that it makes a valuable contribution to the flexibility of the model.

In light of such needs in a disaster, it is becoming extremely difficult to ignore the importance of identification of appropriate locations for transfer points, MSDCs, and backup MSDCs.

After a catastrophic disaster, resources are usually insufficient for all to be treated immediately. For this reason, determining the priority of injured treatments based on the severity of their condition is another important issue on EMS. This process is called triage system. In the other word, triage system refers to the evaluation and categorization of the sick, wounded or injury when there are insufficient resources for the medical care of everyone at once [13]. In this system, injured people are classified into red, orange, yellow, green and blue colors. The response time of the colors are definite and if they are postponed, death probability will increase; for example, injured people with breathing damages or head and neck damages are in the red category and the response time for them is about 10 min. Given the importance of triage system under disaster condition, it has been considered in the proposed model [14]. A distinguishing characteristic of logistics network design under disaster condition is a high uncertainty in many aspects [3,15]. In fact, lack of information as well as stochastic estimates and absence of exact parameters lead to many stochastic parameters in the problem, including stochastic demand, time and failure probabilities.

Accordingly, this study presents a new mathematical model to address the aforementioned concerns under the conditions of disorder and the uncertain parameter information sourcing from AAs during the crucial rescue period of a large-scale emergency. In fact, the proposed model considers three principal issues for designing the logistics network for EMS in a disaster including identification of appropriate locations for transfer points, MSDCs, and backup MSDCs and also aims to determine the best strategy to store medical supplies in MSDCs and backup MSCDs and the best allocations between facilities considering triage system and failure probabilities of MSDCs and routs. To cope with the uncertainty parameters, a stochastic optimization model is therefore proposed. The remainder of the paper is organized as follows: Section 2 briefly provides a review of the relevant literature. The general problem description statement is given in Section 3. In Section 4 the stochastic bi-objective model for designing the logistics network for EMS in a disaster is shown. In Section 5, a solution method is presented. In Section 6, the application of the proposed model in a real world context is shown. Finally, results and conclusions and recommendations for further research in the area are presented in Sections 7 and 8, respectively.

2. Literature review

Facility location problem in EMS has been extensively studied by different practitioners and researchers. In this section, we review some of the more recent and related articles on this area. Based on the nature of location problem and our need, this review is separated into three sections: In the first section, we review the related literature on the transfer point location problem (TPLP). In the second section, we presents studies on the location and rapid distribution of emergency supplies (LRDES). In the last section, we review several key studies on the two stage stochastic programming approach for EMS in disasters; also, in the last of this section, we refer to some of the more important and recent articles associated with demand models and demand forecasting in this area.

2.1. The TPLP

One of the recently presented subcategories of facility location is the TPLP having a large number of applications in the real world problems.

In 2005, Berman et al. [9] proposed the facility and transfer points location problem (FTPLP), where investigate the location of a facility and several transfer points to serve as collector points for demand points that need the services of a central facility. They presented heuristic approaches to solve the problem considering travel time discount rate. Then, Berman et al. [16] suggested TPLP in the another work, in which the set of points to be connected to one transfer point as well as the location of the facility given; in fact, it need to find the optimal location of the transfer point. Furthermore, Berman et al. [17] also considered the multiple transfer point location problems (MTPLP) as an extension of TPLP, where the location of a single facility assumed to be known and the establishment of multiple transfer points allowed. Sasaki et al. [18] formulated MTLP as a p-median problem and also a new flow-based formulation for FTPLP presented. Hosseinijou and Bashiri [19] developed stochastic models for TPLP where the demand points were weighted and their coordinates had bivariate uniform distribution. The proposed model was to find the optimal location of transfer point such that maximum expected weighted distance for servicing to demands point is minimized. Kalantari et al. [20] presented a possibilistic unconstrained nonlinear programming approach in that coordinates of the demand points and associated weights were fuzzy random variables and their approach was designed based on a fuzzy rule-based decision support system (DSS). Ebrahimi Zade and Lotfi [21] extended FTPLP based on a given service time where the DM tends to specify an upper bound for it in the network design. Also, with respect the importance of facility capacity, they considered a soft capacity constraint for them. Their problem formulated as a linear and multi-objective model; for this purpose, a fuzzy multiple objective linear programming method applied.

2.2. The LRDES

As mentioned before, another important issue which should be addressed in facility location problem in EMS is facility location and rapid distribution models for emergency supplies.

One of the earliest studies about this area has been conducted by Toregas et al. [22], it aims to locate the optimal number of facilities which are required to cover all demand points. They applied linear programming to solve this problem. Dessouky et al. [10] argued that two important issues in designing the medical supply distribution system for disasters are facility location and vehicle routing. They