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Prepositioning emergency earthquake response supplies: A new multi-objective particle swarm optimization algorithm

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ABSTRACT

The development of an efficient emergency response plan to provide critical daily supplies to affected people facilitates efficient relief operations. In this study, we propose a multi-objective stochastic programming model for developing an earthquake response plan, which integrates pre-and post-disaster decisions. This three-objective model attempts to maximize the total expected demand coverage, to minimize the total expected cost, and to minimize the difference in the satisfaction rates between nodes. We develop a new multi-objective particle swarm optimization (MOPSO) algorithm to solve this model. Genotype-phenotype-based binary particle swarm optimization (PSO) and continuous PSO are designed to deal with the binary location and other continuous decision variables, respectively. A new strategy is employed to select two types of guides in order to enhance the search ability. Furthermore, a new adaptive inertia weight strategy and two mutation operators are used to ensure that the diversity is sufficient and to regulate the exploration and exploitation capacities, respectively. We present an illustrative real-world case study and some randomly generated instances for computational applications. The results obtained by the proposed MOPSO algorithm were compared with those obtained using a modified time-variant MOPSO, the non-dominated sorting genetic algorithm, strength Pareto evolutionary algorithm, and the exact solution method where possible.

1. Introduction

In the past decade, there have been increases in the number of natural disasters, such as earthquakes, hurricanes, and floods, and the number of people affected by them. A consideration of recent disasters, including earthquakes, floods, and various other disasters, indicates that the people affected are at high risk in the absence of comprehensive and efficient plans to facilitate the prepositioning and distribution of relief supplies.

Most previous studies of the humanitarian relief chain and emergency response have focused on the distribution of commodities, the logistics of relief items and injured persons, and facility location problems following a disaster. Many studies [1,2,3] have investigated the logistics of commodities and injured persons after a disaster, while others [4,5] have described facility location and transportation problems after a disaster. Abounacer et al. [4] proposed a deterministic multi-objective location-transportation model to make decisions a few hours after a disaster, where their model determines the locations of humanitarian aid distribution centres (HADCs) and deals with the distribution of aid from HADCs to the affected areas. By considering

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uncertain travel times, Lu and Sheu [5] investigated the optimal location of urgent relief distribution centres immediately after a disaster.

The locations and inventory levels of relief item providers are key components of an earthquake response plan [6,7], but relatively few studies have addressed the issue of a priori planning for the prepositioning of relief items. In the present study, we aim to determine the optimal policy for prepositioning and distributing emergency supplies, including the optimal numbers and locations of distribution centres, the optimal stocking levels of relief items, and the optimal amount of relief items that flow from distribution centres to the affected areas. These emergency supplies are utilized to respond quickly to the needs of affected people immediately after an earthquake.

Deterministic models for prepositioning emergency supplies have been suggested previously [8–12]. Akkihal [8] proposed a model to determine the optimal locations of non-consumable supplies that are needed immediately after a disaster. Campbell and Jones [9] studied decisions regarding the prepositioning of relief items and inventory levels in preparation for disasters. By considering some risks, they defined equations to calculate the total cost of delivering relief items to the affected areas. Jia et al. [10] developed a single-objective maximal covering model to determine the facility locations for medical supplies in response to emergencies, where they proposed three heuristics to solve the model. Ukkusuri and Yushimito [11] developed a model to identify the optimal locations of supplies by considering transportation network disruption. Their model maximizes the probability that demand nodes can be reached from at least one prepositioned facility. Viswanath and Peeta [12] proposed a maximal covering network design model for disaster relief by considering budgetary constraints. Duran et al. [13] developed a model to evaluate the effect of stock prepositioning on the emergency response plan to minimize the response time. However, they did not consider cost factors in their model, which they solved using the CPLEX solver.

Uncertainty is an inherent characteristic of disaster relief planning, especially during the preparation phase. Stochastic programming (SP) has been applied more successfully than other tools to deal with uncertainties in disaster relief planning. In [14–17] and [7], SP techniques were applied to model uncertainties. Balcik and Beamon [14] used a variant of a maximal covering location model to determine the locations and stocking levels of relief items. They also defined discrete scenarios to specify demands. In addition, they considered budgetary constraints and integrated the inventory and facility location decisions, where they assumed that the distribution centres will never experience shortages of supplies in any scenario. They solved their model using GAMS software and they suggested the development of a heuristic algorithm in future research to solve large-scale instances. Mete and Zabinsky [15] proposed a stochastic model for disaster preparation, which determines the storage locations of medical supplies and the inventory levels, as well as considering distribution and routing decisions. Rawl and Turnsquist [7] applied two-stage stochastic mixed integer programming to determine the locations and quantities of multiple emergency commodities by considering the transportation network availability and uncertainties in demand. They developed a heuristic algorithm to solve large-scale instances. Murali et al. [16] studied the problem of locating distribution centres to distribute medicine in large cities, where they formulate the problem as a maximal covering location problem by considering a distance-dependent coverage function under uncertain demand. They used a locate–allocate heuristic to solve a case study based on an anthrax attack in Los Angeles County. Noyan [17] developed a risk-averse two-stage SP model to determine the locations of facility and the inventory levels of relief items under uncertain demand, as well as based on the damage level in the network. Table 1 compares these previous studies according to seven criteria.

Evolutionary algorithms were applied to disaster response planning in [18–21] and [23]. Nolz et al. [18] developed a hybrid method to solve a multi-objective covering tour problem based on genetic algorithms, variable neighbourhood search, and path relinking. In [19], a modified particle swarm optimization (PSO) method was developed to optimize a relief chain. Zheng and Ling [20] developed a cooperative fuzzy optimization method to solve the problem of emergency transportation planning in disaster relief supply chains. Zheng et al. [21] developed a hyper-heuristic approach to solve an emergency railway transportation problem. A comprehensive overview of the application of evolutionary algorithms to disaster relief operations was provided previously [23].

The studies mentioned above indicate that previous multi-objective SP models have not considered the prepositioning and distribution of emergency supplies during disaster responses. In a review, Caunhye et al. [6] also emphasized the lack of multi-objective stock prepositioning and relief distribution models.

The problem considered in this study was introduced to us by the Tehran Disaster Mitigation and Management Organization (TDMMO). The prepositioning of emergency supplies in local areas can increase preparedness to decrease the response time in terms of the disaster logistics. Thus, the TDMMO investigated the development of an emergency preparation and response planning tool to determine the optimal locations for emergency supplies, the optimal stock quantities, and the optimal commodity flow amounts. Budgetary limitations are major challenges when developing an emergency response plan. Modelling the uncertainties in disaster data are also challenging. Thus, our proposed model and solution method were developed by considering these challenges, relevant previous studies, and the specific problem introduced by the TDMMO.

In this study, we formulate the prepositioning and distribution of relief items as a multi-objective SP model. Our model determines the optimal numbers and locations of distribution centres, the stocking levels of relief items, the multiple commodity flow amount, and the possible unmet demand for emergency supplies by considering the uncertainties in demand and transportation costs. The main goal of prepositioning relief items is to reduce suffering after disasters by providing sufficient emergency supplies. Hence, maximizing the total expected demand coverage is considered to be one of the main objectives of our multi-objective model. The second objective of our model is to minimize the total cost, including the cost of establishing distribution centres, the costs of acquiring and storing items in distribution centres, and the expected cost of transportation from distribution centres to the affected areas. During disaster relief operations, employing an egalitarian policy is an important factor when