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A two-stage optimization model for emergency material reserve layout planning under uncertainty in response to environmental accidents

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HIGHLIGHTS

- A two-stage framework is developed for emergency material reserve layout planning.
- The framework is formulated based on an integration of two developed models.
- Warehouse location and material reserve scheme are obtained in pre-accident phase.
- The results are considered to satisfy rescue requirements in post-accident phase.
- The framework is applied to emergency management system in Jiangsu province, China.

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ABSTRACT

In the emergency management relevant to pollution accidents, efficiency emergency rescues can be deeply influenced by a reasonable assignment of the available emergency materials to the related risk sources. In this study, a two-stage optimization framework is developed for emergency material reserve layout planning under uncertainty to identify material warehouse locations and emergency material reserve schemes in pre-accident phase coping with potential environmental accidents. This framework is based on an integration of Hierarchical clustering analysis – improved center of gravity (HCA-ICG) model and material warehouse location – emergency material allocation (MWL-EMA) model. First, decision alternatives are generated using HCA-ICG to identify newly-built emergency material warehouses for risk sources which cannot be satisfied by existing ones with a time-effective manner. Second, emergency material reserve planning is obtained using MWL-EMA to make emergency materials be prepared in advance with a cost-effective manner. The optimization framework is then applied to emergency management system planning in Jiangsu province, China. The results demonstrate that the developed framework not only could facilitate material warehouse selection but also effectively provide emergency material for emergency operations in a quick response.

1. Introduction

Various types of environmental accidents, such as chemical leaks, oil spills and heavy metal pollutions, threaten water supply security, cause huge loss of properties and highlight the need to improve our capabilities to minimize the damage caused by an emergency pollutant accident in a quick response [1,2]. Although special attention has been gained to emergency treatment technologies selection and evaluation to alleviate the negative impacts on the environment, it often occurs that there are emergency treatment technologies but no available treatment materials and equipments [3,4]. Due to the lack of the necessary information for emergency material reserve and material supply ability, effective environmental emergency management will be hindered from providing differentiated emergency materials to satisfy the requirements of emergency rescues before the pollutants disperse in large-scale.

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In general, environmental emergency management can be divided into pre-accident and post-accident phases, which associates with different levels of pressure, complexity, uncertainty, and response time [5]. Emergency material reserve layout planning, as pre-accident phase, are supposed to be reasonably worked out in harmony with post-accident phase which always requires fast and often real-time responses [6]. It is indispensable to select warehouse locations and make emergency materials be prepared, keeping the materials in ready-to-be-used state in pre-accident phase in order to save emergency response time, enhance integrative rescuing ability, and reduce property losses for emergency management system [7,8]. Therefore, it is of vital importance to determine material warehouse locations as well as emergency material reserve schemes in advance in dealing with potential environmental accidents.

In recent years, the location-allocation theory has attracted significant research effort to make decisions in pertaining to facility locations in many practical applications. Most of the location researches focus on discrete location-allocation planning (LAP) problems to locate a (given) number of facilities to serve the demand points [9]. Lin [10] considered a stochastic single-source capacitated facility location problem and selected a set of capacitated facilities to provide service to demand points; Durmaz et al. [11] formulated the discrete approximation of the problem in which facilities can be located on a set of candidate points; Albareda-Sambola et al. [12] presented several models to obtain the exact solution for discrete capacitated plant location problem; Zhang et al. [13] solved a multiple resources and multiple emergency response depots problem considering multiple secondary disasters; Verma et al. [14] presented a two-stage stochastic programming approach which tackled both the location and capability of oil-spill response facilities. In general discrete LAP cases, the facilities can be located at a given subset of the plane, in particular at a finite list of candidate sites. However, the discrete LAP models are subject to a set of predetermined alternative warehouse sites which must be distributed within the range of critical distance to guarantee an effective emergency rescue in a quick response. Otherwise, the emergency rescue would delay supplying emergency materials to the risk source.

In the continuous/planar LAP models, facilities can be located anywhere in the plane. Planar LAP models are particularly useful when there is uncertainty or lack of detailed data regarding a set of alternative facility sites [15]. Ohsawa [16] developed quadratic Euclidean distance bi-criteria model defined in the continuous space; Drezner et al. [17] proposed a solution algorithm for the location of a facility in a planar network minimizing nuisance; Katz and Vogl [18] formulated an extension of the Weiszfeld algorithm to solve location–allocation problems in the plane; Murat et al. [19] presented an alternative methodology where the market demand is modeled as a continuous density function; Iyigun and Ben-Israel [9] proposed a generalized Weiszfeld method in dealing with the multi-facility location problem. The continuous LAP models can locate the material warehouses in an effective area to guarantee the emergency materials can be allocated in a quick response, but yield to put forward reserve scheme of material types and amounts due to the limited availability of data and inherent uncertainty and imprecision in emergency management.

When there is uncertainty in the parameters or a lack of data, a planar model can be used in a first stage, followed by a discrete model in a second stage based on the solution of planar model, yielding a complementary strategy [20]. Therefore, a solution strategy for the LAP of emergency management is to prioritize locations over allocation decisions and assume allocation decisions are decided subsequent to location decisions. The continuous LAP, especially the continuous multi-facility LAP, can also be considered as a clustering problem with a clustering criterion to be minimized. Clustering analysis [21–24] is widely used in many real applications, such as market analysis, pattern recognition, image processing and information retrieval [25–29]. Despite all valuable application of clustering methods in many areas, it has not yet employed in emergency management aiming to identify a set of reasonable warehouse locations. In addition, there are some characteristic studies using center of gravity location theory for planar location-allocation problems [30–34], taking transportation distance and demand into consideration. However, the locations of newly-built emergency material warehouses are supposed to be influenced on risk source and emergency material demand. Therefore, it is necessary to develop an improved center of gravity location model taking risk source level and emergency material demand level into consideration. In this study, the integration of hierarchical clustering analysis (HCA) and improved center of gravity (ICG) location theory are considered to be used in the first stage to locate newly-built emergency material warehouse in the plane. Meanwhile, a discrete multi-facility LAP model is supposed to be developed in the second stage to provide emergency material reserve planning among all the potential emergency material warehouses based on the solution of the first stage.

However, in real-world planning problems, such as emergency rescue for environmental accidents, many system parameters/variables and their interrelationships are often associated with multiple uncertainties. However, most of the studies had difficulties in handling interval-format uncertainties when dealing with emergency material reserve layout planning among emergency material supply, transportation and demand. In addition, dynamics of material warehouse location under uncertainty were complicated in environmental emergency management system. In fact, uncertain parameters and impact factors in many regional emergency management systems could hardly be obtained as deterministic numbers and their distribution information is not known. However, issues of emergency material reserve and warehouse location were desired to be addressed. This is particularly true for emergency management system in Jiangsu province.

In recent decades, Jiangsu province has experienced high-speed economic development, accelerated industrialization process, and incremental population growth. However, a large amount of hazardous chemical industries, such as pesticide chemical, medicine chemical, smelting chemical and so on, are located in Jiangsu province and have become potential environmental threats. Currently, Jiangsu province is facing the challenge of transformation toward a sustainable emergency management system supported by the south-to-north water transfer project. To meet such task, emergency management system in Jiangsu province is desired to be effective planned with emergency material reserve being tackled and dynamics of warehouse location being addressed.

Therefore, the objective of this study is to develop a two-stage LAP framework for emergency material reserve layout planning under uncertainty to generate decision alternatives and thus help decision makers identify appropriate material warehouses and obtain emergency material reserve schemes to satisfy the requirements of different emergency management phases and different types of emergency environmental accidents. An integration of Hierarchical clustering analysis – improved center of gravity (HCA-ICG) location model is developed for realizing the selection of appropriate material warehouses in the first stage, and material warehouse location – emergency material allocation (MWL-EMA) planning model is formulated to provide emergency material reserve planning in the second stage. The obtained results are beneficial for decision makers to not only guarantee the implementation of the emergency rescue in a quick response, but also minimize the damage caused by an emergency pollutant accident both in economic and environmental aspects. The paper is organized as follows: Section 2 presents the development of a two-stage