Information Sciences 373 (2016) 527–538

Contents lists available at ScienceDirect

Information Sciences

journal homepage: www.elsevier.com/locate/ins

A new partial coverage locating model for cooperative fire services

Jian Wang, Han Liu, Shi An*, Na Cui

School of Transportation Science and Engineering, Harbin Institute of Technology, Harbin, China

ARTICLE INFO

Article history:
Received 12 September 2015
Revised 20 April 2016
Accepted 21 June 2016
Available online 21 June 2016

Keywords:
Emergency facility location
Maximal covering location problem
Partial coverage
Cooperative fire services

ABSTRACT

The location and allocation of fire service facilities, especially for those facilities expecting high demand and severe conditions, require consideration of the cooperative behavior of multi-type fire vehicles in different fire station locations, the gradual decline of coverage with increasing distance, and the sufficient number of fire vehicles given specific requirements of the Urban Fire Rescue Specification (UFRS) of China. This paper presents a mixed integer nonlinear program (MINLP) model that integrates a cooperative mechanism of multi-type vehicles, partial distance coverage of single-type vehicle (PDC-S), and partial quantity coverage of single-type vehicle (PQC-S) into an integrated maximal covering location model for cooperative fire services, therein offering partial distance and quantity coverage of multi-type vehicles (PDQC-M). Numerical experiments with a testing example validate our model and demonstrate that the BARON algorithms can be used to effectively solve the problem. An empirical case study of Harbin (China) and a series of sensitivity analyses are conducted to illustrate the effects of station size and total budget on PDQC-M provided by cooperative fire services.

1. Introduction

Fire station location design is a strategic problem that has been, and will continue to be, a significant challenge to practitioners and researchers. As China's urbanization continues to develop, buildings with a variety of features (e.g., nuclear power plants, civil airports, and large warehouses) have been rapidly constructed in recent years. To provide critical guidance for fire services in cities, the Urban Fire Rescue Specification (UFRS) of China classifies each building as a fixed severity level according to its materials, function and size in terms of people. For each level, the specification also stipulates the essential vehicle types and quantity needed to perform a cooperative task. Generally, a building with higher weighted demands may be categorized with a higher severity level and require a more complex combination of fire vehicles. As such, the planning of fire station locations should be conducted cautiously to ensure satisfactory fire services quality in China cities. In such planning, cooperative mechanisms, response time and vehicle sufficiency within an integrated fire service framework are maximized.

Research has been conducted to address fire station location design problems using a variety of methodologies such as mathematical programming, simulation, and other modeling methods. Farahani et al. [13] surveyed models, solutions and applications related to covering problems in facility location design. Yin et al. [29] presented recent developments in

---

* Corresponding author.
E-mail addresses: wang_jian@hit.edu.cn (J. Wang), liuhanhit2013@gmail.com (H. Liu), anshi@hit.edu.cn (S. An), cuina1231@gmail.com (N. Cui).

http://dx.doi.org/10.1016/j.ins.2016.06.030
0020-0255/

data-based techniques focused on modern industry. Li et al. [28] reviewed covering models and optimization techniques for emergency response facility location and planning in the literature from the past few decades.

To our knowledge, the Location Set Covering Problem (LSCP) proposed by Toregas et al. [27] is the first model for emergency facility location coverage. Their model is a mandatory covering model, and its objective is to find the minimum number of facilities required to cover all demand points. Ball and Lin [3] incorporated a linear constraint to achieve a given reliability level and developed an extension of LSCP named Rel-P. However, LSCP could hardly cover all demand points due to its fixed cost limited by budgetary constraints. Church and Revelle [9] proposed another classic emergency facility locating model called the Maximal Covering Location Problem (MCLP). The MCLP attempts to fully utilize a given number of emergency facilities and maximize the demand coverage under predefined critical time or distance restrictions.

Because these two classic models considered only one type of vehicle, ReVelle and Marianov [23] presented a fire protection system including fire engines and fire trucks. They assumed that a demand point can be considered as covered if and only if both types of vehicles are sited within a certain time window. However, they did not classify the disaster level, which may directly affect the number and type variation of fire vehicles dispatched. Mandell [18] considered server availability through a two-dimensional queuing model and developed a covering model for two-tiered emergency medical services (EMS) systems. Belciug and Gorunescu [5] integrated the well-known hypercube queuing model into a complex EMS system to analyze the healthcare resource allocation. The hypercube queuing model was also extended to analyze the dispatching policies of French SAMU's in Brazil with multiple priority classes for users [15,26]. A new hybrid optimization method called the Hybrid Evolutionary Firefly-Genetic Algorithm was proposed to solve the capacitated facility location problem by Rahmani and MirHassani [21]. However, the approach was not tested for large-scale cases. To address the ambiguity and vagueness of facility location problems, Kahraman et al. [16] attempted to use four different fuzzy multi-attribute group decision-making approaches. Concerning multi-objective multi-facility location problems, interactive integrated possibilistic linear programming and fuzzy set theory were effectively used to address the imprecise nature of input data by Ozgen and Gulsun [19].

To date, various extensions of MCLP have been developed to solve the above proposed problems. Erkut et al. [12] presented the Maximum Survival Location Problem (MSLP). By incorporating a monotonic survival function into the covering model, they mapped response time to survival rate. Paul et al. [20] proposed a multi-objective hierarchical extension of MCLP and explored non-inferior solutions with comparable coverage and fewer unit moves. Salman et al. [25] incorporated dependent link failures into the emergency facility location model to obtain significantly improved coverage. An et al. [1,2] explored location design models for several types of emergency service facilities under probabilistic facility disruption risks to reduce the expected cost of losing service. By formulating a compact model for reliable location design under imperfect information, Yun et al. [31] provided managerial insights into optimal location design and cost tradeoffs. In the Ambulance Allocation Capacity Model (AACM), Shiah and Chen [24] considered not only the ambulance service capacity but also the population distribution and road conditions. The Dynamically Available Coverage Location (DACL) model was formulated by Rajagopalan et al. [22] to satisfy time-varying demands. Yin et al. [30] proposed a real-time optimization method for system performance optimization.

In a classical sense, if a demand point is sited within the distance threshold of a facility, it is assumed to be covered completely; otherwise, it cannot be covered at all. Such an assumption may lead to erroneous results. Berman and Krass [6] applied a non-increasing step function to consider different levels of partial coverage. The authors provided integer programming formulations and reported computational evidence of the solvability under a variety of conditions. Berman et al. [7] considered the level of partial coverage that is determined by the coverage decay function and developed an alternative formulation that possessed all the advantages of the uncapacitated facility location problem (UFLP). Drezner et al. [10] addressed the discontinuity in the definition of coverage and proposed a branch-and-bound procedure. Karasakal and Karasakal [17] developed the MCLP in the presence of partial coverage (MCLP-P) and relaxed the "all or nothing" assumption in the MCLP. In their model, service decays with the increasing distance from a "fully covered" level to a "partially covered" level and drops to a no-service level beyond the maximal coverage range. Eiselt et al. [11] investigated gradual coverage models as extensions of the basic LSCP model and carefully compared the size and feature factors. Because a large number of coverage models are limited to deterministic demands and distances, Batanovic et al. [4] developed another gradual coverage model that imitated the reality of a wide class of facility locating tasks.

Despite all these efforts in the above areas, to our best knowledge, no previous study has captured the inherent complexity of national conditions in China's fire services. Specially, the impacts of a multi-type vehicle cooperative mechanism, partial distance coverage and partial quantity coverage have generally been ignored in the fire station location literature. However, these factors significantly affect the efficiency of a fire service system. Separate considerations of these factors, as in prior studies, may result in sub-optimal decisions or inaccurate coverage estimation.

First, a high level hazard demand (e.g., nuclear power plants or inflammable or explosive hazardous goods warehouses) may require specific combinations of professional fire vehicles (e.g., fire pumpers, foam vehicles, fire-fighting turntable ladders) to form a cooperative rescue team. As such, fire vehicle allocation should be properly selected to provide cooperative coverage for a specific level demand point. In China, the UFRS stipulates the essential vehicle types for each level. If any type of essential vehicle stipulated in the UFRS is absent, the cooperative mission for the specific level demand point cannot be conducted. In that case, the demand point is completely annihilated. In other words, a demand point has a chance to be saved only when at least one vehicle of each essential type is available. As such, ignoring the cooperative aspect would not