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Reconfiguring a set of coverage-providing facilities under travel time uncertainty

Oded Berman [a,*], Iman Hajizadeh [b], Dmitry Krass [a], Alireza Rahimi-Vahed [c]

[a] Rotman School of Management, University of Toronto, 105 St. George Street, Toronto, Ontario M5S 3E6, Canada
[b] Graduate School of Management & Economics, Sharif University of Technology, Azadi street, Tehran, Iran
[c] Sears Holding Corp, Hoffman Estates, IL, USA

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ABSTRACT

We study networks of facilities that must provide coverage under conditions of uncertainty with respect to travel times and customer demand. We model this uncertainty through a set of scenarios. Since opening new facilities and/or closing existing ones is often quite expensive, we focus on optimal reconfiguration of the network, that is finding a facility set that achieves desired thresholds with respect to expected and minimal coverage, while retaining as many of the existing facilities as possible. We illustrate our model with an example of Toronto Fire Service. We demonstrate that relocating just a few facilities can have the same effect as opening a similar number of new ones. We develop exact and approximate solution approaches and test them with computational experiments. Algorithm based on Tabu Search (with certain novel components) appears to be particularly successful for this problem. We also analyze the multi-objective version of the problem, where the expected and minimum coverage levels are treated as objectives in addition to the objective of maximizing the number of pre-existing facilities in the final location set.

1. Introduction

We focus on facilities that provide coverage to clients within a given travel time radius. Examples of such facilities range from fire stations and hospitals to supermarkets and fast-food outlets. These facilities typically operate as a network and strive to ensure adequate coverage for all customers within a designated service region. The network of fire stations operated by a given municipality provides a good example.

Two distinguishing characteristics of such networks are: (1) they often operate under the conditions of large uncertainty in travel times and customer demand, and (2) since locating new facilities is often very expensive, one must focus on optimally reconfiguring an existing network of facilities rather than creating a new "optimal network" from scratch. In this paper we propose a model that accommodates both of these characteristics.

Travel time uncertainty comes from a variety of sources, ranging from predictable hourly variations in traffic flows in most major cities to relatively rare weather-related events such as large snowstorms. In this paper, we model travel time uncertainty as different scenarios, where a "scenario" is a snapshot of the transportation network with regard to link travel times and customer demands. We assume that probability of occurrence can be attached to each scenario, though for some scenarios this probability may be very close to 0.

Since the facility locations typically cannot be adjusted for different scenarios, the same set of locations must provide "adequate" service under all scenarios. The meaning of "adequate" depends on the facility type. For some facilities, such as supermarkets, it may be sufficient to focus on maximizing the expected coverage over all scenarios. This, of course, effectively ignores rare or catastrophic scenarios for which prior probabilities are quite small and are often impossible to estimate accurately *a priori*. On the other hand, fire stations and other emergency service facilities must provide some level of coverage under all scenarios, no matter how unusual they might be. In fact, adequate service during rare events, such as snowstorms, may be especially important.

Due to changes in demand distribution and traffic patterns over time, it is highly unlikely that any network of currently existing

* Corresponding author.
E-mail addresses: Berman@rotman.utoronto.ca (O. Berman), Hajizadeh@gsme.sharif.edu (I. Hajizadeh), Krass@rotman.utoronto.ca (D. Krass), Alireza.Rahimi-Vahed@searshc.com (A. Rahimi-Vahed).

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facilities occupies an optimal location set. Thus, at any given time the management has two options to improve network coverage: adding new facilities or relocating some existing ones. While there are significant cost implications to both options, adding new facilities is typically more expensive. The exact costs of each action are often hard to estimate in advance (they are often site- and time-dependent). However, a reasonable objective is to minimize the "disruption" to the existing network, i.e., to keep as many of the existing facilities as possible in the new configuration. This also speaks to the common question asked by the decision-makers: What can be achieved by better use of the available resources?

We propose a Robust Expected Covering Reconfiguration Problem (RECRP) Model, with the objective of maximizing the number of pre-existing facilities while creating a network of m facilities subject to two main constraints:

(1) ensure the total *expected* coverage is above a certain threshold ρ_E, and
(2) ensure the *minimum* coverage in any scenario is above another threshold ρ_M,

where the coverage thresholds ρ_E, ρ_M are specified by the decision-maker.

Of course the objective, as well as constraints (1) and (2) can be viewed as three different objective functions: instead of specifying coverage thresholds, the left-hand sides of the constraints can be maximized. One could then analyze the set of efficient solutions and the trade-offs between the three objectives.

To demonstrate the main features and benefits of our approach we apply it to the example of Toronto Fire Service (TFS), which has been dealing with the need to improve coverage for some time. As discussed in Section 2 below, TFS consistently fails to meet the required response time standards. To address this, the Master Fire Plan developed in 2007 called for addition of four new stations. However, due to large capital commitments required, the political will to execute this option has been lacking – 10 years later not a single one of these stations have been opened (though the commitment remains on the books). We show that coverage improvements that can be expected from adding four new stations can be achieved by relocating a similar number of existing stations – arguably, a more politically acceptable option.

We also address the solvability for out model. We develop an Integer Programming (IP) formulation, allowing us to solve small to moderate instances to optimality. For larger instances we develop several heuristic approaches. The algorithm based on Tabu Search (with several novel features) combined with a location-allocation heuristic appears to have excellent performance in our computational experiments.

The analysis of covering location models originates with the maximal covering location problem (MCLP) introduced by [9]. Interested readers are referred to [21] and [12] for a discussion of the MCLP and to [29] and [26] for a review of the literature on facility location problems under uncertainty. There is also a body of literature on optimal fortification of facilities to protect against natural disasters (network fortification) or intentional attacks (network interdiction); see, for example, [10]. Multi-objective analysis of facility location models is reviewed in Refs. [13] and [23]. We note that the vast majority of previous papers on multi-facility models follow a "design from scratch" framework, i.e., assume that p new facilities are to be located. We are not aware of any previous papers that aim to optimally reconfigure the current system by keeping as many of the existing facilities as possible in the stochastic context.

In a related paper, [6] study three variations of the MCLP on a network with travel time uncertainty considering combinations of average and worst case coverage objectives; scenario-based representation of uncertainty is used. This general modeling framework is also employed in the current paper. One of the models defined in Ref. [6] has similar "robust expected coverage" structure to ours (i.e., the thresholds ρ_E and ρ_M, as well as the corresponding constraints are defined). However, that paper follows the standard "design from scratch" framework. The model sought to maximize the expected coverage while ensuring a specified level of minimal coverage, given a pre-fixed number of facilities. Thus, the model structure is quite different from ours (in particular the Lagrangian Dual was tight for their model but appears to be quite loose for ours), leading to different solution approaches.

The paper includes some aspects of stochastic and robust optimization. In stochastic optimization an objective function that involves random parameters is maximized (see Refs. [7,28]). In robust optimization the decision maker typically looks for solutions that will be perform adequately for any realization of the random parameters (see e.g., [4,22,30]; as well as [20]). Our requirement of achieving a specified minimal level ρ_M of coverage over all scenarios is related to the concept of "strict robustness" in the literature. Our general approach of finding minimally-disruptive reconfiguration of the current system that achieves the required levels of both expected and minimal performance can be applied outside of the facility location area as well.

As mentioned earlier, to illustrate our model we apply it to the possible re-location of fire stations by Toronto Fire Service in Toronto, Canada. There is a rich prior literature on the application of locational analysis and, in particular, location coverage models to optimize the performance of fire protection services – please see Ref. [24] for a recent review. Interesting applications are described in Refs. [2,8] and [1]; among others. However, all of these employ deterministic models and consider only deterministic coverage. We note that [27], one of the earliest papers to apply maximal coverage to the location of fire stations, did use maximization of the number of existing facilities in the final configuration as one of the key objectives. However, their treatment is deterministic as well. Finally, we note a recent paper [33] that considers the improvement of a system of healthcare facilities by both relocations of existing facilities and addition of new ones. However, their setting – a P–median objective with no stochasticity in travel times – is quite different from ours.

The remainder of the paper is organized as follows. In Section 2 we illustrate the key issues and results with the Toronto Fire Service example. Next, in section 3 we formulate our model and prove a localization result deriving a finite dominating set for out model. In Section 4 we develop algorithmic solution techniques based on a Lagrangian Relaxation, a Greedy-Type Heuristic and Tabu Search. Results of the computational experiments are reported in Section 5. Concluding remarks are presented in Section 6.

2. Network reconfiguration example: relocating fire stations in Toronto

In this section we describe an application of the key ideas of the current paper to a specific example: re-configuring the network of fire stations in Toronto, ON. At the heart of this example is the issue of improving system performance through realignment of the available resources and (possibly) adding a few new service facilities to an already existing network (parts of this example were also discussed in Ref. [6] in a somewhat different context).

Toronto Fire Services (TFS), the largest fire service in Canada and the 5th largest fire service in North America, is responsible for providing emergency service to (as of 2016) 2.73 million residents of Toronto. TFS currently operates 82 fire stations. While TFS strives