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O.R. Applications

An optimization approach for ambulance location and the districting of the response segments on highways

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Abstract

In this paper we present a method to optimize the configuration and operation of emergency medical systems on highways. Different from the approaches studied in the previous papers, the present method can support two combined configuration decisions: the location of ambulance bases along the highway and the districting of the response segments. For example, this method can be used to make decisions regarding the optimal location and coverage areas of ambulances in order to minimize mean user response time or remedy an imbalance in ambulance workloads within the system. The approach is based on embedding a well-known spatially distributed queueing model (hypercube model) into a hybrid genetic algorithm to optimize the decisions involved. To illustrate the application of the proposed method, we utilize two case studies on Brazilian highways and validate the findings via a discrete event simulation model.

Keywords: Location and dispatching of ambulances; Hypercube model; Genetic algorithm; Spatially distributed queues; Highways

1. Introduction

The operation of many emergency medical systems (EMS) on Brazilian highways is under the management of private organizations as part of privatization contracts with the Brazilian government. During the last years, new EMS have been installed along Brazilian highways, and the configuration and operation of the existing EMS have been revisited. In these highway EMS, an ambulance provides the first medical treatment to the individuals involved in an accident, transports them to the nearest hospital (if necessary), and then goes back to its home base on the highway. These systems are typically zero-line capacity, and they operate within particular ambulance dispatching policies, which stipulate that only specific vehicles can be dispatched to a given region on the highway (partial backup), mainly due to the limitations of travel distance or time. In addition, some policies involve multiple dispatching, as in some cases (depending on the type of call), it is necessary to dispatch more than one ambulance to the same call location.

The mean user response time is considered the main performance measure. In general, the limitations for the response time specified in the privatization contract must be followed by the private organizations, which are responsible for managing the highway. Other performance measures to the EMS are: the balance of ambulance workloads, the fraction of calls not serviced by the EMS (loss probability), and the fraction of calls not serviced within a predetermined threshold (i.e., fraction of calls with response times exceeding T minutes). The former measure has especially been utilized by the EMS analysts. For example, the United States EMS Act of 1973 states that 95% of the emergency medical responses should be serviced within 10 minutes in urban areas and within 30 minutes in rural areas (Ball and Lin, 1993). In some EMS on Brazilian highways, this statistic is also used to evaluate the system, and these regulations are specified in the privatization contract.

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Studies by Swersey (1994), Owen and Daskin (1998) and Brotcorne et al. (2003) present revisions of the classic location models to analyze the emergency systems developed during the last few decades. In particular, the hypercube model based on spatially distributed queueing theory and Markovian analysis approximations has been one of the most effective methods for analyzing these systems (Larson, 1974; Larson and Odoni, 1981). The model implies the solution of a linear system of O (2^N) equations (N is the number of ambulances in the system), where the variables involved are the equilibrium state probabilities of the system. With these probabilities, a number of interesting and critical performance measures for managing the system can be estimated. Examples of applications of the hypercube model in urban EMS in the United States can be found in studies by Larson and Odoni (1981), Chelst and Barlach (1981), Brandeau and Larson (1986), Burwell et al. (1993) and Sacks and Grief (1994). More recently, the hypercube has been considered as a deployment model for response to terrorism attacks and other major emergencies (Larson, 2004). In Brazil, the hypercube model has been applied to analyze urban EMS (Takeda et al., 2007) and EMS on highways (Mendonça and Morabito, 2001; Iannoni and Morabito, 2007).

Some studies have extended the original hypercube model to remove its limiting assumptions for application to EMS on highways. For example, Mendonça and Morabito (2001) modified the model to consider dispatching with partial backup, Iannoni and Morabito (2007) extended that model to consider multiple dispatching of identical and distinct servers, and Atkinson et al. (2006, 2007) proposed heuristic methods based on the model in the Mendonça and Morabito (2001) study to estimate the loss probability for large-scale systems. Other studies have been focused on combining the hypercube model with optimization procedures, such as those conducted by Batta et al. (1989), Saydam and Aytug (2003), Chiyoshi et al. (2003), Galvão et al. (2005) and Rajagopalan et al. (2008). These studies present successful implementations of hypercube embedded metaheuristic search methods applied to ambulance location problems.

Recently, Iannoni et al. (2008) integrated the hypercube model into a standard genetic algorithm in order to determine the optimal primary and secondary response areas for the ambulances (districting problem), considering their current location, while taking into account different conflicting objectives such as the mean user response time, the imbalance of ambulance workloads and the fraction of calls with response times exceeding a predetermined threshold. In that study it was shown that these different objectives could be better met by simply modifying the atom sizes of the system, without relocating ambulances and without requiring additional capacity investments.

In this study, we extend the study conducted by Iannoni et al. (2008). First, we modify the districting GA/hypercube algorithm to optimize the location of ambulance bases along the highway (location problem), which we call location GA/hypercube algorithm. We assume ambulance bases can be located anywhere along the stretch of highway under study, which is quite different than locating ambulances on a set of previously determined candidate posts (nodes, points). In addition, the location GA/hypercube algorithm includes a local search procedure to evaluate the local neighborhood of each solution generated by the GA operators (hybrid GA algorithm). We show that the location GA/hypercube algorithm provides better solutions for each objective than the districting GA/hypercube proposed in Iannoni et al. (2008). Then, we extend this algorithm to optimize the two combined decisions: the location of ambulance bases (the location problem) and the districting of ambulance response or coverage areas (the districting problem), which we call the location and districting hybrid GA/hypercube algorithm. This algorithm searches for the best ambulance locations and their coverage areas, in order to minimize region-wide response times and/or ambulance workload imbalances in the system. In addition, we discuss how the algorithms can be adapted to generate trade-off curves among the conflicting performance measures.

Computational results are analyzed by applying the algorithms to two case studies. The first case corresponds to an EMS operating on a portion of an interstate highway connecting the cities of Sao Paulo and Rio de Janeiro, which was initially studied by Mendonça and Morabito (2001). The second is an EMS operated by a private firm. It is based on two busy stretches of highway located in the state of Sao Paulo and recently studied by Iannoni and Morabito (2007) and Iannoni et al. (2008). To verify the quality of the solutions produced by the algorithms, we developed a simple procedure that incorporates the hypercube model into a simple enumerative algorithm and provides the optimal configuration for smaller problems (i.e., in terms of N number of ambulances). In order to validate the performance measures obtained by the hypercube model, we compare them with the results obtained via a discrete event simulation model of the system.

This article is organized as follows: Section 2 presents a brief description of the EMS case studies, while Section 3 discusses how the hypercube model can be adapted to analyze these EMS systems. Section 4 presents the location hybrid GA/hypercube algorithm (*location problem*), and in Section 5, this algorithm is extended to support the combined decisions of regarding ambulance location and coverage area (the *location and districting problem*). Section 6 analyzes the outcomes from the application of the algorithm to the case studies. Finally, Section 7 presents concluding remarks and perspectives for future research.

2. EMS case studies on highways

2.1. The first case study

As described by Mendonça and Morabito (2001), this EMS provides emergency medical treatments on a portion