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Original Contribution

Dynamic ambulance reallocation for the reduction of ambulance response times using system status management☆,☆☆

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ABSTRACT

Objectives: Dynamically reassigning ambulance deployment locations throughout a day to balance ambulance availability and demands can be effective in reducing response times. The objectives of this study were to model dynamic ambulance allocation plans in Singapore based on the system status management (SSM) strategy and to evaluate the dynamic deployment plans using a discrete event simulation (DES) model.
Methods: The geographical information system–based analysis and mathematical programming were used to develop the dynamic ambulance deployment plans for SSM based on ambulance calls data from January 1, 2011, to June 30, 2011. A DES model that incorporated these plans was used to compare the performance of the dynamic SSM strategy against static reallocation policies under various demands and travel time uncertainties.
Results: When the deployment plans based on the SSM strategy were followed strictly, the DES model showed that the geographical information system–based plans resulted in approximately 13-second reduction in the median response times compared to the static reallocation policy, whereas the mathematical programming–based plans resulted in approximately a 44-second reduction. The response times and coverage performances were still better than the static policy when reallocations happened for only 60% of all the recommended moves.
Conclusions: Dynamically reassigning ambulance deployment locations based on the SSM strategy can result in superior response times and coverage performance compared to static reallocation policies even when the dynamic plans were not followed strictly.

1. Introduction

Prehospital emergency medical services (EMS) play a pivotal role in providing personnel, facilities, and equipment toward an effective and coordinated delivery of medical care under emergency conditions. The quality of an EMS system is determined by many factors, such as the proficiency of EMS personnel, effectiveness of care delivery processes, and organizational communications and control.

Response time is often used as a key process performance indicator and industry benchmark for an EMS system [1-4]. The importance of this indicator is driven by the need to treat time-sensitive medical conditions without delay. Examples of such conditions include out-of-hospital cardiac arrests (OHCA) [5-8], acute myocardial infarction, stroke, and severe trauma cases [9-11].

Apart from the relation to clinical outcomes, EMS response time is also an important public expectation and quality of service benchmark. In this study, we defined EMS response time as the time interval between ambulance dispatch and arrival on-scene [12]. Because resources are often constrained and EMS providers cannot continuously expand their ambulance fleet, a more optimal deployment of ambulances to meet the demands for ambulance services is an attractive option to achieve faster response. Discrete event simulation (DES) models have been implemented for the evaluation of different static deployment policies to reduce ambulance response times [12,13]. Dynamically reassigning ambulance deployment locations to balance ambulance availability and demands can be a more effective strategy. In this study, the performance of a dynamic ambulance reallocation strategy

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based on the idea of system status management (SSM) will be evaluated. System status management is an operational technique of deploying ambulances in anticipation of where they will be needed next [14,15].

The objectives of this study are to develop efficient ambulance allocation plans in Singapore based on the SSM strategy and to evaluate its performance using the DES model. Two approaches were proposed to develop the ambulance allocation plans—geographical information system (GIS) and mathematical programming (MP). The DES model was used to compare the performance of the dynamic SSM strategy vs the static reallocation policies [12,13].

2. Materials and methods

2.1. Emergency medical system in Singapore

The EMS system of Singapore is managed by the Singapore Civil Defence Force, which operates the national "995" emergency telephone service. The system is supported by a centralized dispatching unit that uses computer-aided dispatch, medical dispatch protocols, global positioning satellite–based automatic vehicle locating systems, and road traffic monitoring systems.

The Singapore EMS system operates a fleet of 46 ambulances to answer approximately 280 to 320 emergency calls per day [12,16]. The ambulances are deployed in various fire stations or fire posts across the island [12,16]. A static reallocation policy is used by the EMS provider where redeployments of ambulances occur only across different shifts, that is, ambulance deployments are not dynamically reconfigured within each shift [12,13]. Operationally, the closest ambulance is dispatched to respond to an emergency call received by the centralized dispatching system. During an emergency, patients are first treated if necessary. Subsequently, they are assigned a triage status based on the Patient Acuity Category Scale (PAC scale) ranging from PAC-1 to PAC-4, with PAC-1 representing the most severe medical/trauma cases and PAC-4 representing the least severe [12]. All patients with PAC-1 to PAC-4 are taken to 1 of the 6 public hospitals nearest to the incident scene, except for maternity or pediatric patients who are transferred to a specialized hospital. After the patients are transferred to the hospital, the ambulance returns to its original station.

2.2. Study protocol

Six months of emergency calls data (January 1, 2011, to June 30, 2011), which included call times, dispatch times, scene arrival times, hospital conveyance times, base return times, and locations of incident scenes (with latitude and longitude information), were reviewed for this study. This included a total of 52 512 valid "995" emergency calls received by the national EMS provider. Exclusion criteria were (1) calls that did not require an ambulance to be dispatched, (2) "false" calls for which no ambulance was dispatched, or (3) calls that had insufficient information on incident locations. In this study, PAC-0 was used as a triage status for casualties who were declared dead on scene.

The Cardiac Arrest and Resuscitation Epidemiology (CARE)-3 Study had shown that EMS "995" calls were not random events but occurred in patterns and trends over different periods and locations [17,18]. The consistent patterns and trends of the spatiotemporal distribution of emergency calls showed potential for the application of SSM, which could help to match ambulance availability with the spatiotemporal variations in demand profiles [15,18].

2.2.1. System status management

The term *SSM* was first introduced to describe the process of dynamically reconfiguring EMS ambulance deployments to balance ambulance availability and demands across time and space [14,15]. This strategy has been used to improve response time performance without the need to deploy more ambulances and to set up new ambulance base locations [14,15]. The foundation of SSM is the development and implementation of the systems status plan (SSP); an SSP matches the deployment of system resources (ie, ambulances) with demands (ie, emergency calls) and can be realized through a set of "posting pyramids."

System status management leverages on the relationship between call volumes and ambulance deployment to derive deployment plans that dynamically assign ambulance resources according to projected ambulance demand patterns. During operations, the SSP will guide the assignment of ambulances to bases according to the number of ambulances that are available within the system. Given the dynamic nature of ambulance deployments, there is a possibility of compliance issues. System state is the total number of ambulances available to respond to calls. Complete compliance is defined by the strict implementation of relocation decisions whenever the system state changes to necessitate relocations [19]. Incomplete compliance occurs when the redeployment decisions are not implemented strictly for all system state changes. For instance, 80% compliance implies that the ambulance operator may decide not to relocate according to the posting pyramids for 20% of the time when the system state changes. Decisions to not achieve full compliance can be deliberate either because of operational considerations that may restrict redeployment moves, or in anticipation of imminent system state restoration that makes redeployments impractical.

In a typical SSP, there could be a number of posting pyramids across different times of the day that are adapted to emergency call volumes that fluctuate across time. To derive an optimal SSM strategy that aims to achieve maximal demand coverage with a given number of ambulances, 2 approaches are proposed in this paper: (1) GIS-based analysis and (2) the MP approach.

2.2.2. Geographical information system–based analysis

Geographical information system technology [20,21] has been used to analyze the spatiotemporal heterogeneity of emergency call volumes for different purposes [17,18,22]. Being a system that is capable of capturing, analyzing, and presenting data that is associated with geographical locations, it allows the precise mapping and display of emergency call volumes and candidate base locations. Moreover, it facilitates the estimation of travel times across the existing road networks. Geographical information system can thus provide a more rigorous basis for constructing the deployment plans.

The GIS-based analysis leverages the Getis-Ord Gi* statistics [23,24] and visualizations of travel time polygons. The Gi* statistic is essentially a z-score that can facilitate the statistical test for identifying statistically significant hot and cold spots [24]. This statistic can be plotted onto the geographical map of Singapore to visualize the change in geospatial distributions of hotspots for emergency call volumes over different times of the day and days of the week. To account for fluctuations of emergency call volumes and variations in traffic conditions in the same day [12,17,18], detailed analysis was performed for different times of the day for weekdays and weekends. Statistical tests for hotspots were performed, assuming interactions between nearby features are stronger vs features that are further apart, based on the inverse distance relationship with a distance band of 4 km (estimated from the Global Moran's I statistics) [24,25].

Apart from the hotspot analysis, travel time polygons, which describe the coverage of deployment locations according to travel time thresholds, are also useful for ambulance deployment. Given a set of candidate base locations, the coverage for each location can be visualized using travel time polygons as shown in Fig. 1. Travel time projections together with the hotspot analysis and the geospatial visualization of emergency call volumes were evaluated using ArcGIS 10 (ESRI, Redlands, CA). Volume of emergency calls visualized using hotspot analysis or geospatial mapping of call volumes across postal districts can be evaluated simultaneously (eg, by map overlays) for the development of SSPs.

2.2.3. Mathematical programming approach

Mathematical programming is a more rigorous quantitative approach to determine the ambulance deployment locations according to the projected demands and available ambulance resources [26-28].