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Flexibility and real options analysis in emergency medical services systems using decision rules and multi-stage stochastic programming

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ABSTRACT

A novel approach to EMS infrastructure systems design, planning, and operations under long-term uncertainty is introduced based on multi-stage stochastic programming and decision rules, accounting for strategic flexibility (also known as real options – RO). Different from standard RO analysis, the approach mimics real-world decision-making by exercising flexibility based on conditional-go decision rules. The objective is to minimize the expected total costs over the system's life cycle, and the outputs are the optimal initial configuration and decision rules. A flexible solution provides lower expected cost than stochastically optimal rigid solutions, especially valuable when required incident coverage rate is >95%.

1. Introduction

As part of public services, Emergency Medical Services (EMS) systems are significant for the well-being of cities and societies. EMS systems aim to provide quick and efficient out-of-hospital medical care to emergency patients and transport them to the nearest hospital if needed. Ong et al. (2009) illustrated that delivering fast defibrillation in medical emergencies could significantly increase patients' survival rate. Managing such EMS systems, however, can be challenging in both the short and long term. Significant uncertainty in the short term – such as incident patterns, geographical locations, and severity of incidents – influences the daily operations of the system (e.g., how to assign an emergency vehicle to respond to an incident). At the same time, EMS systems may also suffer from longer-term uncertainty related to changes in demographics, which influences the overall need for emergency services over time (e.g., where to allocate emergency vehicles and stations over time and space), and the shorter term uncertainty patterns as well. Indeed, an EMS system designed and deployed in view of short-term uncertainty patterns may prove sub-optimal in the long term. This reality is especially true in many cities of emerging countries, such as China and India, which need to deploy EMS systems on a large scale in the future to accommodate the growing needs of their populations. Hung et al. (2009) discussed EMS systems in China and suggested a few directions (e.g., training of EMS staff) to help EMS systems adapt better to growing urbanization. The study also indicated that smaller cities and rural areas were unable to meet Chinese regulatory standards due to the costs of construction and equipment acquisition, suggesting the need for more cost-effective designs for EMS systems. Sharma and Brandler (2014) reviewed current EMS systems in India and highlighted weak points requiring potential improvements (e.g., financial/budget limitations). Although it is the second most populous country in the world, there is currently no guideline for the training

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and operation of EMS systems in India, and the EMS system in Rajasthan received a total of 28,262 complaints in 2013 due to its low efficiency (Sharma and Brandler, 2014).

EMS system designs that planned to accommodate short-term variations in incident patterns (e.g. such as the daily fluctuations in incident rates) may not account well for the variations that occur over a longer time horizon (i.e. rising incident rates over several quarters and years). Hence, while performing well in the short term, such systems may perform in a suboptimal manner in the long run due to a phenomenon referred as the "Flaw of Averages" (Savage, 2002). Indeed, EMS designs that rely heavily on the "average" or "most likely" scenario forecast for capacity planning and operations may perform well for some time when the future does not depart significantly from expectations. They may start performing badly if the future does not arise as planned, either having too much and unused capacity, or being under capacity, depending on how incident patterns evolve over time.

To deal pro-actively with this issue, one approach is to enable the system's capacity and configuration to change to future possibilities. This method is inspired from the concept of flexibility in systems design, or real options, which provides the "right, but not the obligation, to change the system easily in the face of uncertainty" (Trigeorgis, 1996). Not only does flexibility enable a system to capitalize on upside opportunities, it also helps limit potential exposure and risks to downside conditions, with the net effect of improving its overall expected performance. For example, modularity can be exploited whereby EMS stations – where emergency vehicles are operated and maintained – are initially deployed with smaller size and operational/maintenance capacity (e.g. 2 vehicles), and then expanded as needed, depending on how generation patterns evolve in the area serviced by the station. Such modularity requires careful planning for future upgrades, which is where infrastructure design and management is important. It allows the size of the station to be upgraded more easily, only if and when needed. This expansion reduces the initial capital cost, but also provides better contingencies to deploy additional capacity over time and space in a given area (i.e. city or region) to maintain or improve response time if the number of requests increases (i.e., upsides). This further deployment could be postponed if the number of incidents remains at the same level, reducing possible unused capacity and costs (i.e., downsides).

Although flexibility in engineering design sounds like a promising approach to deal with uncertainty, exercising flexibility strategies appropriately (e.g., gradually deploying the capacity of a station at the right times) can be challenging. This is because standard real options analysis (ROA) tools based on dynamic programming (DP) that are typically used to analyze flexibility and determine optimal timings for exercise, as well as design configurations, may not be fully suited for this purpose. For example, standard ROA tools typically rely on the assumption of path independence, which is not suitable to an engineering context (Wang and de Neufville, 2005) – see Section 2.3 for more details. Also, in practice, one may need to be proficient at using DP to implement the optimal policies obtained from an optimization analysis. When dealing with multiple uncertainty sources and flexibility strategies, applying standard ROA tools like multinomial lattices and approximate dynamic programming can be challenging due to the curse of dimensionality. For these reasons, standard ROA tools may prove difficult to use to analyze flexibility in EMS systems, which typically involve considerations of multiple sites (i.e. stations), vehicles, and flexibility (or real option) strategies. Thus, the potential of flexibility to generate better performances may not be fully recognized and exploited under standard ROA methods.

To alleviate concerns related to the ability to quantify the value of flexibility, finding the optimal flexible system configuration and times to exercise flexibility, a novel approach based on decision rules was recently proposed by Cardin et al. (2017a). The authors developed a multi-stage stochastic programming model to capture the decision-making dynamics, while flexibility strategies were exercised based on conditional-go decision rules. This approach is practical as it provides planners with straightforward and intuitive guidelines for operations. For example, it helps determine the stochastically optimal parameter to determine the right timing and amount to deploy additional capacity based on a conditional-go decision that is similar to an IF-THEN-ELSE statement in computer programming (e.g. *IF* incident rates reach threshold X, *THEN* upgrade station capacity to Y, *ELSE* do nothing). EMS systems are more complex in terms of the number of decision variables and interactions that are considered in the study by Cardin et al. (2017a), and typically involve deploying infrastructure and emergency vehicles over multiple sites to accommodate needs for emergency services. This provides an opportunity for further methodological improvement and application.

Considering the background above, the main contribution of this paper is to propose a novel approach based on multi-stage stochastic programming to systematically analyze real options and flexibility in EMS systems, considering long-term uncertainty in incident pattern generation. Such a time horizon is typically longer, in the order of several quarters to years for planning purposes. The design problem considers where and when to install/open new vehicle stations (strategic), where to deploy emergency vehicles (tactical), and whether to purchase new vehicles (strategic) subject to how incident patterns evolve over time. This approach also exploits a decision rule technique, with considerations of the fact that large-scale urban systems will typically require capacity deployment and operations over multiple sites and time periods. Various flexibility strategies associated with typical decision-making, such as phasing/staging deployment and capacity expansion, are taken into account and exercised using decision rules. As a demonstration of this approach, a case study is conducted in the context of a hypothetical city in an emerging country, using data for the input parameters (e.g., locations of candidate sites) from a published study, and publicly available information on incident data in major cities.

This paper is organized as follows. Section 2 presents a literature review of the relevant work in optimal capacity planning and operations in EMS systems, standard ROA tools, as well as flexibility in engineering design. Section 3 revisits standard ROA techniques and extends the tools to capacity planning problems at multiple sites that is better suited to analyze flexibility in EMS systems. The novel framework proposed in this paper is introduced in Section 4, along with related