ABSTRACT

Emergency medical services (EMS) are an important component of a modern healthcare system that aims to provide out-of-hospital emergency medical care and patient transportation. EMS systems employ ambulances with specialised equipment that enable them to respond to emergency calls and provide transportation for both urgent and non-urgent patients. EMS plays a vital role in saving lives in the case of critical emergency care such as trauma and out-of-hospital cardiac arrests. In this thesis, we address an important problem of planning for EMS in the healthcare sector that determines an optimal location of ambulances to enable quick response for urgent medical care. We consider a region divided into demand zones and served by an EMS system using a fleet of ambulances. The EMS aims to maximise the number of emergency patients served within the shortest possible response time using available ambulances. To achieve this objective, it is necessary to determine the optimal location of ambulances. Additionally, it is necessary to determine the preference order of ambulance stations for each zone in the given region to dispatch ambulances. Further, to tackle the variation that occurs in demand and travel time of ambulances, it is important to determine the possible relocations of ambulances based on the hour of the day. The planning of ambulances also depends on the different types of ambulances utilised and the level of urgency of patients. To capture the research theme sequentially, we set four objectives that address optimal location-allocation of ambulances in an EMS.

In the first objective, we present a model that considers the temporal variation in demand while determining the optimal location of ambulances. The proposed problem incorporates the dispatching decision by determining the primary and secondary stations for each demand zone. The temporal variation in demand is incorporated into the model by dividing the day into a number of periods, where each period is associated with a different call arrival rate for each zone. The problem considers the server-level arrival rate, service rate and busy probability of ambulances (servers). The problem is formulated as a mixed-integer non-linear programming (MINLP) model and then linearised to obtain a mixed-integer linear programming (MILP) model. The presented model considers an objective function based on heterogeneous performance measures combining survival function and coverage for different patient types. A memetic algorithm (MA) that utilises mixed chromosome representation of solutions is proposed to solve the problem. Our computational results show that the proposed MA produces solutions within 3% of the optimal solution obtained by CPLEX within significantly less CPU time. The proposed MA also outperformed the genetic algorithm (GA) in finding better solutions for most instances. Computational results indicate that neglecting time-dependent variation in demand can underestimate ambulances required by up to 15% during peak demand. Incorporating temporal variation in demand balances ambulance availability during peak periods and resource utilisation for periods with low demand.

In the second objective, we extend the previous model to incorporate the temporal variation in travel time along with demand. The dispatching decision is incorporated by determining the rank of ambulance stations to indicate the preference order for each demand zone. To capture the impact of variation in travel time more accurately, we use a performance measure based on the survival function for all calls in the objective function. The proposed problem is formulated as an MINLP model. We present a variable neighbourhood search (VNS) based solution approach to solve the problem that uses a relaxed solution of the original problem as an initial solution. The proposed model is tested on the problem instances developed based on the urban region of Kolkata in India. Modelling with temporal variation improves the actual survival function value and the coverage achieved. When temporal variation is ignored, the overestimation in coverage is higher for a shorter response time and decreases for a longer response time limit. We observe that the improvement in survival probability decreases with an increased number of periods, resulting in diminishing returns as more periods are considered.

In the third objective, we develop performance evaluation approaches for a multi-tiered EMS system that employs three types of ambulances, Advanced Life Support (ALS), Basic Life Support (BLS), and First Responder Vehicle (FRV). We also consider two types of patients: type A patients require ALS to be dispatched, while type B patients are expected to be served by BLS ambulances. We first discuss a hypercube queueing model (HQM) for the proposed system and then present an approximate approach for application in large EMS systems. The HQM and approximate approaches are validated by comparing them with a simulation model. The approximate approach consistently provides results within 8% of the simulation model for all the problem instances. As the approximate approach takes significantly less time and is easy to implement for even large systems, it is a more useful approach for planning such EMS systems.

In the fourth objective, we extend the location model presented in the second objective by considering a multi-tiered EMS system. Similar to the third objective, we consider three types of ambulances and two types of emergency calls. The proposed problem is formulated as an MINLP model. An adaptive variable neighbourhood search (AVNS) based approach is proposed for solving the problem. The AVNS based solution approach integrates the approximate approach developed in the third objective to estimate the busy and dispatch probabilities. The dispatch probability obtained using the approximate approach is then used to calculate the value of the objective function of an AVNS solution. The initial solution for the AVNS is obtained by solving a relaxed MILP version of the proposed problem. Two adaptive neighbourhood change procedures and multiple neighbourhood structures are proposed. The results of computational experiments indicate that proposed adaptive approaches outperform the basic VNS approach in terms of the time required to obtain the best solution. Similarly, using the solution of the relaxed problem as an initial solution results in a better final solution in relatively less CPU time. We also analyse the impact of temporal variation in parameters and the variation in the number of ambulances available on server utilisation, and the proportion of demand served.

Keywords: Emergency medical services; Ambulance location-allocation; Joint location and dispatching; Memetic algorithm; Variable neighbourhood search