American Journal of Emergency Medicine xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

American Journal of Emergency Medicine

journal homepage: www.elsevier.com/locate/ajem

Original Contributions

A mathematical model for efficient emergency transportation in a disaster situation

Takwa Tlili*, Sofiene Abidi, Saoussen Krichen

LARODEC Laboratory, Institut Supérieur de Gestion, Université de Tunis, 41 Rue de la liberté, Le Bardo 2000, Tunisia

ARTICLE INFO

Article history:
Received 2 March 2017
Received in revised form 12 January 2018
Accepted 12 January 2018
Available online xxxx

Keywords:
Ambulance routing problem
Optimization
Emergency medical services
Healthcare
Genetic algorithm

ABSTRACT

This work focuses on a real-life patient transportation problem derived from emergency medical services (EMS), whereby providing ambulatory service for emergency requests during disaster situations. Transportation of patients in congested traffic compounds already time sensitive treatment. An urgent situation is defined as individuals with major or minor injuries requiring EMS assistance simultaneously. Patients are either (1) slightly injured and treated on site or (2) are seriously injured and require transfer to points of care (PoCs). This paper will discuss enhancing the response-time of EMS providers by improving the ambulance routing problem (ARP). A genetic based algorithm is proposed to efficiently guide the ARP while simultaneously solving two scenarios.

1. Introduction

Ambulance routing problem (ARP) is a significant challenge for EMS as it plays a vital role in saving lives which can reduce the mortality rate during a disaster. The sensitivity of decision making for EMS attracted the attention of operations research experts who studied numerous solutions to problems arising in the management of EMS systems (e.g. Kadri et al. [1], Bozorgi-Amiri et al. [2], and Molenbruch et al. [3]). The ARP, known as emergency logistics, is about managing and controlling the flow of ambulances to assist individuals affected by disasters. The response time of EMS is crucial for managing emergency response. Whether the emergency is a result of mother nature (earthquakes, floods, hurricanes) or caused by man (accident, terrorist attacks), An emergency dispatch center (EMC) needs to decide how many ambulances should be sent to the emergency point. Thus, the emergency logistic network should be carefully modeled to provide reliable and cost-effective services to assist those injured in a disaster.

In recent literature, EMS establishes emergency facilities, rescues survivors, provides medical assistance, transfers injured patients to hospitals, and coordinates activities across multiple organizations. Wren and Holliday [4] classified the response to a disaster into five categories: (1) Transportation planning: Programming the suppliers' delivery without directing the ambulance. (2) Ambulance assignment: Allocating the ambulances to the appropriate emergency point. (3) Routing: Giving the ambulance routes to rescue the patients. (4) Road repair: Repair damaged roadways and restore lifelines to affected areas. (5) Integrated problems: Solving a set of individual problems with one or more common objective. As we follow the strategy in which patients are transported between pickup and drop-off points, the ARP addresses the routing issue.

This paper will perform an ambulance management literature review in Section 2, a detailed description of the problem and its different modeling in Section 3, the solution approach is explained in Section 4, the experiments of the real-case study and the corresponding results based on the proposed methods in Section 5, and finally Section 6 concludes the results and discusses possible future work.

2. Ambulance management literature

Early work in ambulance management by operations engineers was mainly related to either the minimum or maximum coverage model. Toregas et al. [5] proposed a minimum covering model which minimizes the number of ambulances needed to cover all call points. Church and ReVelle [6] proposed the maximal covering model that tries to maximize total demand coverage given a fleet of fixed size. Bakuli and Smith [7] designed a queuing network model for designing an emergency evacuation plan. A linear programming

* Corresponding author.
E-mail address: takwa.tlili@isg.rnu.tn (T. Tlili).

https://doi.org/10.1016/j.ajem.2018.01.039
0735-6757/© 2018 Published by Elsevier Inc.

approach is described in Chiu and Zheng [8] who treat multi-priority group evacuation in sudden onset disasters.

More recently, Beaudry et al. [9] consider dynamic patient demand for transportation between different hospitals. They take into account the emergency requests, isolated transportation and restrictions in vehicle assignments. Tabu search approach is proposed to minimize a weighted sum of an operational objective. In Molenbruch et al. [3], the patient transportation problem is modeled as a bi-objective dial-a-ride problem. To deal with the problem, the authors developed a multi-directional local search algorithm taking into account the fundamental tradeoff between operational efficiency and service quality. Ozdamar and Demir [10] designed a hierarchical cluster and route procedure. Patients' transportation is represented as capacitated network flow models that are solved optimally. In Kadri et al. [1] the authors proposed a decision support system that predict strain situations in emergency departments to improve their management by the hospital system. Oran et al. [11] proposed a location-routing model for emergency response which considered the priority of calls. The model ensures that the most urgent calls are prioritized. Using a geographical information system, Lam et al. [12] proposed a mathematical programming approach to reallocate efficiently the available ambulances minimizing the ambulance response times. A real-case study in Singapore validated the proposed model. Shahriari et al. [13] developed a bi-objective optimization approach that minimized the travel time and maximized the service level. Results show that low-accessibility emergency points should be the principal motivation of the proposed problem. Another variant of the problem has been tackled by Bozorgi-Amiri et al. [2] that is about helicopter emergency medical service.

The authors applied their model to the Lorestan Province case study and determined the placement of helipads and helicopter stations that minimize the transfer time. In another paper, Jotshi et al. [14] developed an integrated EMS routing and dispatching system for disaster management based on simulation and data fusion. The dispatching decisions are divided into the patient pickup problem and the patient delivery problem. They consider the priority of calls and clustering criteria. The ambulance routes are designed based on real-world road networks, existing road damage, and congestion. Talarico et al. [15] developed two mathematical formulations to obtain route plans by minimizing the latest service completion time among the people waiting for help. They proposed that a large Neighborhood Search approach produced high quality solutions for a large number of test instances with very short response times. Numerous review papers, about solving the ARP, have been proposed as Aringhieri et al. [16]. After a thorough examination of the literature, its apparent the authors were interested in optimizing the response time but did not focus on travel costs.

3. Ambulance routing problem

The proposed ARP mathematical model is based on the vehicle routing problem formulation stated in Wang and Lu, 2009. An emergency call may start with elementary triage, where personnel of an EMC determine the urgency of the injuries and assign an ambulance to the emergency point. Fig. 1 illustrates the ambulance routing problem by optimizing response time.

ARP is focused on deploying the ambulance fleet among the waiting emergency points efficiently and cost effectively to rescue patients. Formally, ARP is defined as an undirected graph $G = (A, E)$ where a node $j \in A$ corresponds to either a patient or a PoC and an edge $e \in E$ expresses a path between a pair of nodes. Let $E = \{1, \ldots, n\}$ be the patients set and $F = \{1, \ldots, m\}$ the set of PoC. Each ambulance has a maximum budget C^k_{max}. The ARP aims to minimize the travel cost while fulfilling structural constraints such as visiting each patient once, path continuity, subtour elimination, and circuit requirements.

The following glossary details the variables used in defining the mathematical model.

Parameters and decision variable	
A	The set of patients and PoCs
V	The set of PoCs
E	The set of patients
P	The set of ambulances
$UnitC$	The unit cost of traveling
C^k_{max}	The maximum travel cost of an ambulance k
d_{ij}	The distance between customers i and j
c_{ij}	The travel cost between customers i and j
where $c_{ij} = UnitC \times d_{ij}$	
$x_{ijk} = \begin{cases} 1 & \text{if the arc } (i,j) \text{ is traversed by the ambulance } k \\ 0 & \text{elsewhere} \end{cases}$	

Inspired by the formulation of the vehicle routing problem [17], the following mathematical formulation is proposed. The objective function $Z(x)$ aims to minimize the total travel cost using Eq. (1).

$$Min \quad Z(x) = \sum_{i \in A} \sum_{j \in A} \sum_{k=1} c_{ij} x_{ijk} \tag{1}$$

A set of structural constraints should be fulfilled in order to generate a feasible solution of the problem.

- Visiting each patient once: Each patient is visited exactly once by one of the ambulances.

$$\sum_{j \in A} \sum_{k=1} x_{jik} = 1, \text{forall} i \in E \tag{2}$$

$$\sum_{j \in A} \sum_{k=1} x_{ijk} = 1, \text{forall} i \in E \tag{3}$$

- Path continuity: An ambulance visiting a patient also has to leave that patients' location. The ambulance route concludes at one of the hospitals.

$$\sum_{j \in E} x_{ijk} = \sum_{j \in E} x_{jik}, \text{forall} 1 \le k \le P, i \in V \tag{4}$$

- Cost constraints: The ambulance travel cost (budget) should not be exceed.

$$\sum_{i \in A} \sum_{j \in E} x_{ijk} c_{ij} \le C^k_{max}, \text{forall} 1 \le k \le p \tag{5}$$

- Circuit requirements: Each ambulance originates from the PoC where it is initially located.

$$\sum_{i \in F} \sum_{j \in E} x_{ijk} \le 1, \text{forall} 1 \le k \le P \tag{6}$$

4. Optimization approach

In the Combinatorial Optimization Field, a metaheuristic, is a higher-level procedure designed to find, generate, or select a method that may provide a sufficiently good solution to an optimization problem, especially real-world problems that are of a complex nature such as the ambulance routing problem. The proposed approach is a nature-inspired metaheuristic that imitates the biological evolution of Charles Darwin's theory of natural selection. This method is called Genetic Algorithm (GA) that attempts to emulate the way living species evolve and adapt to their environment in order to

Please cite this article as: T. Tlili et al., A mathematical model for efficient emergency transportation in a disaster situation, American Journal of Emergency Medicine (2018), https://doi.org/10.1016/j.ajem.2018.01.039