International Journal of Medical Informatics 111 (2018) 24–36

Contents lists available at ScienceDirect

International Journal of Medical Informatics

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

Combining spatial information and optimization for locating emergency medical service stations: A case study for Lower Austria

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A R T I C L E I N F O

Keywords:
EMS location
Covering model
Case study
Maximal coverage location problem
Emergency medicine

A B S T R A C T

Objectives: Emergency medical services have been established in many countries all over the world. Good first care improves the outcome of patients in terms of hospital stay duration, chances of full recovery and of treatment costs. In this paper, we present an integrated approach combining spatial information and integer optimization for emergency medical service location planning. The research is motivated by a recent call for bids to restructure the location of emergency medical services in the Austrian federal state of Lower Austria by the local state government.
Methods: Our framework allows for constraints on the places where an emergency care physician is stationed, accounting for the fact that – for economical reasons – it might not be feasible to arbitrarily place emergency care physicians. We use maximum coverage linear programs to get accurate solutions for the problem instances (depending on the maximum allowed number of emergency care physicians and the constraints of their placement). We optimize for the maximum number of covered residents given certain parameters. The travelling distances are calculated by means of a digital road graph. Moreover we analyze the coverage of the day population as there are significant shifts in the number of persons present at daytime. For every problem instance we have calculated the ten best solutions and examined the variance among them. For the demand point aggregation we have used a cell grid.
Results: Using our method we can show that with less emergency care physicians more residents can be covered. This is highly applicable to low populated areas where the coverage becomes better. There is little variance from the best to the second best solution: There are only small changes (usually only one cell is shifted) between the best and the second best solution. The coverage of the day population – except for a few problem instances – is always better than the coverage of the residents (reflecting the fact that many residents commute to more densely populated areas).
Conclusions: In our study, we show that our solutions provide better coverage of residents with fewer emergency care physicians than the current status quo.

1. Introduction

Emergency medical services (EMS) have been established in many countries. Depending on the country, usually one of the following two strategies is commonly used: (i) Emergency doctors on duty try to provide first care. This includes stabilizing vital functions, resuscitation, a preliminary diagnosis, the selection of an appropriate hospital, as well as the means of transport. (ii) Paramedics provide first care and try to take the patient to the nearest hospital as fast as possible after having stabilized the vital functions. While it is not clear which of these two strategies is preferable [10], good first care improves the outcome of patients in terms of hospital stay duration, chances of full recovery and of treatment costs [27,34].

Since reaching patients in emergency situations as fast as possible is a crucial aspect of EMS [22], there is vast research on optimal planning of EMS/ambulance location and related decisions (cf. Section 3.1). In this paper, we present an integrated approach combining spatial information and integer optimization for EMS locations planning. The research is motivated by a recent call for bids to restructure the location of EMS in the Austrian federal state of Lower Austria by the local state government [18]. Our solution framework is driven by the constraints given in the call. We present a case study for this region using up-to-

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https://doi.org/10.1016/j.ijmedinf.2017.12.008
Received 24 July 2017; Received in revised form 10 December 2017; Accepted 12 December 2017
1386-5056/

date spatial data. The problem of finding the optimal location of EMS is formulated as an Integer Programming problem (IP) known as *maximal coverage location problem* (MCLP) [7]. The MCLP is NP-hard [23]. We expand on this approach by producing not a single solution, but a set of near-optimal solutions to provide alternatives to decision makers. Our solutions framework also allows for constraints in places where an emergency care physician is stationed, accounting for the fact that – for economical reasons – it might not be feasible to station emergency care physicians arbitrarily.

Outline of the paper. In the next section, we first describe the current situation of EMS in Lower Austria (Section 2.1) and then the respective region of interest (Section 2.2). In Section 3 we give an overview of previous literature on EMS/ambulances location problems as well as a description of the constraints given in the call of the local government. Section 4 presents our solution framework, discusses the data used in our case study and explains our model assumptions. In Section 5, the results are shown and discussed. Finally, Section 6 summarizes the paper and points out possible further work.

2. EMS in Lower Austria – description of the region of interest and the current situation

2.1. EMS in Lower Austria

In Lower Austria EMS is organized at several levels: The lowest level is the *first responder* which is contacted by the emergency operating center in case of an emergency. First responders are volunteers, have received special training and have no shifts. Therefore – if available – more than one first responder is alarmed in case of an emergency. General practitioners are rooted at this level as well. In remote areas they provide a valuable support to the emergency medical system. First responders have only basic equipment. The next level are *first aid posts*, where ambulances are stationed. Two or three paramedics try to reach the person in need by ambulance. Ambulance personnel can either be volunteers or employees. Finally, emergency care physicians are stationed at selected ambulance posts, hospitals and airfields. Together with a paramedic who has received special training they reach the patient by car or helicopter. They carry the necessary equipment to treat a wide variety of emergencies. In Lower Austria the EMS is run by governmental, private and non-profit organizations. The State of Lower Austria also maintains several emergency call dispatch centers.

Ground-based EMS is supported by helicopters. In Lower Austria and Vienna there are four and all but one can operate only from dawn till dusk. The fourth is able to fly day and night but due to adverse weather conditions, all four helicopters are unable to take off in roughly 25% of emergency cases. Fig. 1 provides an overview of the current situation. Hospitals are shown as green dots, blue diamonds indicate the presence of helicopters and red triangles are ambulance locations.

2.2. Description of the area of interest

The state of Lower Austria is located in the northeast of the country. It covers a surface of 19,186 square kilometers and has a population of about 1.653 million inhabitants. The geography is quite diverse: hills in the north, a lowland in the center, which is traversed by the Danube River, and an alpine area in the south. Therefore, the population is distributed rather unevenly throughout the state. The population is centered along the Danube river and gradually decreases north and south of the lowland. Fig. 2 shows the population distribution in 2016 using cells of 1 × 1 km size. Cells that are not shown are uninhabited. Lower Austria surrounds the city of Vienna (pictured as empty area in the east), which was excluded from the investigation since it is a separate state. Another unpopulated area in the northwest is a military area.

In 2015 the number of out-of-hospital emergencies treated by emergency care physicians has reached 208,486 [28]. Currently, there are 32 emergency medical service stations where an emergency care physician is present but some of these stations are not operating 24/7 (for example some operate only during the night when helicopters cannot be used). In 2015 the number of emergencies a single 24/7 EMS station was required to handle ranged between 627 and 2849 [18]. In remote areas with a lower population density, emergencies were less frequent. Although there is no official agreement, it is common use to share EMS facilities with neighboring states and countries if the facilities are located near the border. Since 2016, there has been an official agreement of reciprocal aid in case of need with the Czech Republic.

Fig. 3 shows the status quo: With a maximum of 29 emergency care physicians during daytime and 32 during nighttime, a maximum of 84.72% (86.54%)[1] of residents can be served in time by an emergency care physician. It is noteworthy that the current system offers double coverage of 39.82% (41.55%) of the residents.

3. Related work and call of the local government

3.1. Related work

EMS and ambulance planning can be partitioned in three decision levels (see Chapter 21.3 of [20]): (i) the strategic level, which consists of planning EMS station locations. Decisions made on this level are long-term decisions; (ii) the tactical level, which consists of the staffing at the EMS stations, and temporary opening/closing of stations (medium-term decisions); (iii) the operational level, which deals with dispatching EMS units.

Our work addresses the strategic level, that is, the location of EMS stations, and solve this problem using the MCLP [7]. We observe that a similar modeling approach has been used in the seminal paper [11] for EMS deployment in Austin, Texas, which allowed for savings of 3.4 million dollars. In our approach, we combine mathematical modeling with a digital representation of the Austrian road map which we use to calculate driving distances. In doing so, we were able to calculate a fine grained solution. Moreover, we did not only consider the residents, but also investigated the influence of commuting. In the area of interest, hundreds of thousands of people commute every day, influencing the demand for first medical aid substantially.

Note that *location planning* is one of the most studied areas of Operations Research, thus a comprehensive survey on this topic is out of the scope of this paper. We refer the reader to Laporte et al.'s book [20] for an overview of location science, including location science for health care. Furthermore, [6] is a survey focusing on ambulance location and reallocation models. The role of *uncertainty* in planning has received lot of attention recently (for example see [24] for ambulance location under stochastic demand). However, following the constraints in the call given by the Lower Austrian government, our model is *deterministic*. Recent papers on the tactical and operational level include [3,26], which consider reallocation of ambulances and [9], where coverage is considered on a day-to-day basis. In [19], the location of emergency units in two regions of Spain is studied using an heuristic approach.

Besides Operations Research, location planning is also a common research topic in Geographic Information Science (GIS). Location planning for health infrastructure is covered, for example, by [33]. GIS is also used for ambulance planning. For example, [29] describes a GIS based ambulance deployment model for reducing response time and [14] presents a simulation tool for emergency operators. Since their tool can be used for operational decision support, they use a time-varying model for travel times.

[1] The number in brackets refers to the day population whereas the number without brackets refers to the number of residents.