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Evaluation of Dynamic Ambulance Routing for the Transportation of Patients with Acute Coronary Syndrome in Saint-Petersburg

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Abstract
Effective treatment of acute coronary syndrome (ACS) patients depends on the transportation time to a hospital. But selection of an optimal route and target hospital for an ambulance within a large city is a complex problem. It requires taking into account the dynamical nature of an urban environment. Such dynamic factors as traffic flow, changing road graph, population mobility, and hospital capabilities are sources of uncertainty in decision making on hospitalization, and eventually they influence the functioning quality of emergency medical services (EMS) in a city. This work is devoted to the analysis of this problem for the city of Saint-Petersburg (Russia) with the use of statistical data, public geographic information services (OpenStreetMap), and real-time data on traffic flow (Yandex.Maps). It is shown that dynamic traffic conditions influence selection of a hospital and have to be considered within the task of ambulance routing. The results may be applied in order to design a more efficient EMS decision support system for ambulance personnel and dispatchers.

Keywords: emergency medical services, ambulance routing, geographic information systems, acute coronary syndrome, traffic flow dynamics

1 Introduction

According to World Health Organization, coronary artery disease has the highest cause of death frequency: more than 7 million people (12.8% of all deaths) die per year from coronary artery disease

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(World Health Organization, 2014). Acute coronary syndrome (myocardial infarction) with ST segment elevation (STEMI), with the pathophysiological basis of total coronary artery thrombosis, is characterized by having the highest mortality rates in the early stages of the disease. Providing proper care with minimal delays during the first stage of acute myocardial infarction is critical. Decreasing the "system delay," which lasts from the first medical contact to reperfusion therapy, is an important task, as it has a strong influence on treatment outcomes (Steg, et al., 2012). Depending on the type of reperfusion therapy, this time delay should not exceed 30 minutes in case of fibrinolysis, and 90 minutes for primary percutaneous coronary intervention (PCI). Ambulance EMS has a crucial role in providing medical help to acute myocardial infarction patients. It not only affects the transportation time, but, at the same time, it is involved in processes of initial diagnosis, sorting and treatment. There are significant differences in emergency medical service organizations across different countries. The European system enables a doctor and EMS to evaluate and treat a patient on the scene of a medical emergency. The patient can be taken to a hospital or clinic if further evaluation is required. The American model consists of ambulances with emergency medical technicians and paramedics trained in basic and advanced life support. They provide pre-hospital emergency care, including stabilization, intervention and the transport of the patient to a hospital for further evaluation by emergency physicians (Roessler, 2006), (Black, 2005). Elements of different models can be combined in a particular regional system. The EMS model is one of the key factors for regional STEMI network.

EMS management provides a rich area for the application of decision support systems. In the case of ACS, a set of decisions are required to be made by different stakeholders in order to provide proper medical assistance. The processes of transportation, diagnosis, and treatment involve doctors, paramedics, drivers, dispatchers, and administration staff in hospitals. The decision making is performed in conditions characterized by a high level of uncertainty because of the complex and dynamic environment of the city. EMS operation depends on multiple dynamic factors referred to both service supply and demand: hospitals' load, stakeholders' working schedule, medical equipment, medical staff, city's population mobility, road traffic, dynamic road network. In order to cope with the uncertainties related to all of these factors, an ambulance routing decision support system based on actual data and model-based forecasts should be built.

In this work we consider the case of Saint-Petersburg, Russia. The global aim of this research is designing a model-based decision support system for EMS operation for all stakeholders working with ACS patients. Contribution of this work is in evaluation of the need in dynamic routing with taking into account the specifics of Saint-Petersburg, and in evaluation of the influence of changes in traffic conditions on EMS performance. In particular, this work seeks to answer the following questions. Is there a need to take into account current traffic conditions while assigning ambulance to addresses, or city can be split into several areas connected to certain hospitals? How do hospital selection criterion influence the redistribution of hospitals service areas?

2 Background

Saint-Petersburg is a large city with a population of over 5 million residents. Motorization rate for the city is evaluated as 295 automobiles per 1000 inhabitants. Together with complex road graph topology, this leads to severe problems with traffic jams on the way in and out of center during rush hours. Also, Saint-Petersburg has a system of drawbridges which are open at night in the summer season, which leads to a loss of the connectivity for different parts of the city. This factor complicates driving in the city and should be taken into account by ambulance routing.

A level of mortality from cardiovascular disease in Saint-Petersburg is higher than mean value over Russia: in 2014 it was responsible for 50.6% of all deaths. This indicates that the direction of EMS traveling optimization is an actual task, particularly for ACS cases. PCI and coronary artery bypass surgery have been available in Saint-Petersburg since the 1980s, however, the system of hospitalization for emergency interventions in ACS only developed in the few last years. Since 2008, the Russian Government launched a federal "vascular" program for creating so-called "vascular centers" designed to provide the emergency PCI for patients with ACS across the country. Saint-Petersburg was included in this program in 2010, and by 2011 the six centers was opened. In the years following, some other city hospitals were connected to the system, and in 2013 several federal university clinics were included in the network. By the end of 2014, the ACS network included 15 hospitals, 10 of which operate 24/7, and 8 of them have cardiac surgery departments with the ability to perform on-pump surgery. Today in Saint-Petersburg, there is approximately one 24/7 center per 500 000 inhabitants, which ensures the availability of this type of medical care. In total, there are 19 hospitals in Saint-Petersburg, which may receive ACS patients (fig. 1a). Relying on statistical data, 20504 cases of acute coronary syndrome have been registered in 2014 in Saint-Petersburg. The distribution of number of patients among hospitals (specialized in ACS) is shown in figure 1b. The first four places are kept by hospitals working all day in peripheral districts.

The transportation of STEMI patients is one of the key stages of care significantly affecting the outcome. In Saint-Petersburg, STEMI is causing more than 1000 deaths per year, more than 600 of which can be prevented by improving the system of regional care with optimal routing of patients.

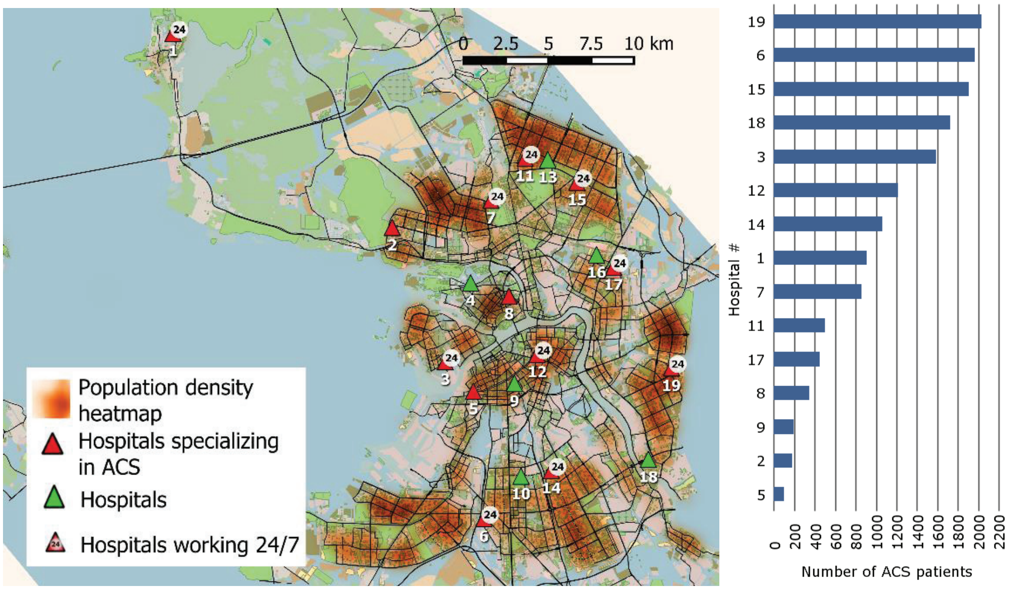


Figure 1: (a) Location of hospitals on the Saint-Petersburg map, population density heat map is rendered with the use of statistical data fetched from population database provided by the Federal Migration Service; (b) number of ACS patients treated in different hospitals of Saint-Petersburg in 2014

3 Related Works

Decision making tasks which correspond to the EMS operation may be divided into three levels (Kergosien, 2015): strategic, tactical, and operational. Reviewed works in the domain of EMS decision making were classified according to these three levels, and by type of task, which is under investigation.

Strategic level covers the long-term solutions: location of stations or emergency call centers, the type of management (centralized, decentralized), size of the fleet ambulance, the determination of the number of staff, and splitting the territory into autonomously managed districts. *The task of optimal ambulance fleet structure* is targeted on the determination of minimum number of ambulances capable for providing a fixed level of service, and examination of quality of EMS. For example, the number of ambulance crews, waiting places in emergency rooms, treatment rooms, emergency rooms, receiving offices, medical equipment, as well as the number and composition of the staff are examined in the work (Brailsford, 2004) using the system dynamics approach. *The task of the hospital emergency department layout*. A detailed review of the solutions for the classical optimal placement problem are presented in (ReVelle, 1989). In (Huang, 2010) the variation of the p-centers search in a graph is proposed. The task is solved using the dynamic programming approach, taking into account the possible loss of the functionality of a receiving department in connection with large-scale emergency cases. *Ambulance management task*. In (Kergosien, 2015), the authors study the effectiveness of dividing the ambulance fleet into two independent parts: the crews responsible for the known transportation tasks, and the crews dynamically taking urgent requests. (Chick, 2003) compares the effectiveness of central planning management of the emergency crews (e.g. decisions taken by each crew depend on the state of the whole system), and decentralized, using a discrete event simulation model based on real observations. The results prove greater efficiency of central planning.

Tactical level includes medium-term solutions associated with the location of the potential reserve for waiting places, selection of personnel management strategy, as well as distribution of the type of tasks for ambulance (emergency or static), and the possible distribution of the waiting areas. *The task of the pre-arrangement of the crew (covering)*. In order to minimize response time the method of the pre-arrangement of crews, which are available near the potential locations of new requests is investigated. In (Meinzer, 2014) this is modeled by a greedy algorithm in the process of which each free ambulance rides to the station. The authors demonstrate the effectiveness of K-method used for the strategy of free movement of crews. In (Maxwell, 2010), the same problem is solved by a classical p-center problem in weighted graph. *The task of dynamic reallocation of calls* is solved in order to minimize the average travel time of the crews by effective transition of the already assigned request to anther crew. In (López, 2005) the task of dynamic reallocation of orders is solved for cases caused by emergency situations or the appearance of obstacles for EMS movement. For this purpose, authors propose an auction-based approach for transferring requests. In (Gendreau, 2001), the authors examine the effectiveness of different tactics for appointment redistribution in cases where a call with a higher priority already received.

Operational level consists of short-term solutions related to management rules such as: dispatching solutions, choice of hospital, the relocation policy, and planning breaks for staff. *The task of finding the shortest path to or from patient*. In the work (Gayathri, 2014) authors propose a solution based on the Dijkstra algorithm while taking into account current traffic conditions. In (Nordin, 2011) adaptation of a more effective A* algorithm for this task is described. In (Maxwell, 2010) the shortest path is sought via an approximate dynamic programming method. In work (Gendreau, 2001) the problem of finding ways for the crew to the call is solved by a heuristic search algorithm with restrictions.

Over the last decade, ***geographic information systems*** (GIS) have been being used in public health and medicine. A large review on existing works in this domain can be found in (Patel & Waters, 2012). Taking advantage of GIS technologies led to the development of STEMI network maps, which provide web-based presentation facilities for information about STEMI hospital network functioning (Rokos, et al., 2013). Assessment of usage of observations on traffic flow is performed in (Panahi, 2009) in order to improve the ambulance's travel path finding. The authors have proposed a methodology of path adjustment and achieved a 20% reduction of travel time for the small area of the city of Teheran.

4 General Problem Statement and Methods

The following formal problem statement is used within this work (scheme is presented in the figure 2). There is a flow of call events incoming from patients. These calls are distributed in space and time according to a certain *demand model*. Patients can be stratified by their state and diagnosis. In the city there are hospitals with their treatment capabilities, working schedule, and quality of service. Dispatchers receive calls from patients and assign a certain ambulance by some dispatching algorithm (d1). The chosen ambulance takes the call and travels to patient address. At this point the decision on the certain route has to be made on the level of the dispatcher or ambulance itself (d2). At patient's the state and diagnosis of patient are evaluated (d3), the patient is classified, and the decision on the treatment tactics are made (d4). These two decision may require involvement of support system with the use of external specialist and telemedicine capabilities. Next, if the patient requires hospitalization, then on the base of his/her diagnosis and state, the decision on what hospital to choose is made by dispatcher or EMS crew (d5). Then, travel to the hospital requires route selection (d6). After the patient is delivered to the hospital, the ambulance becomes available.

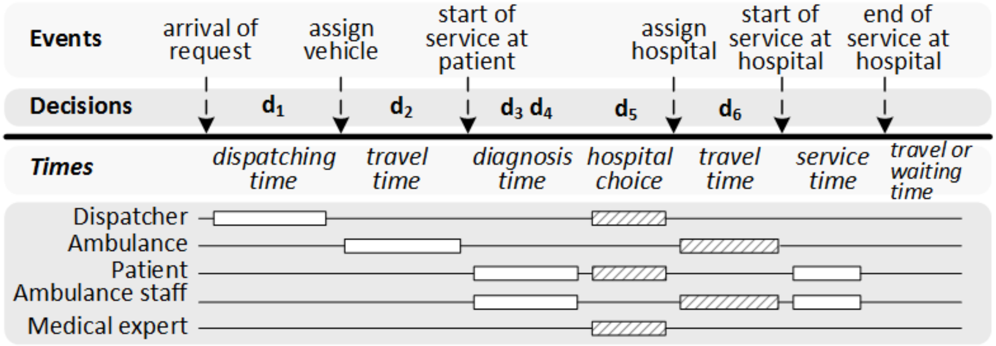


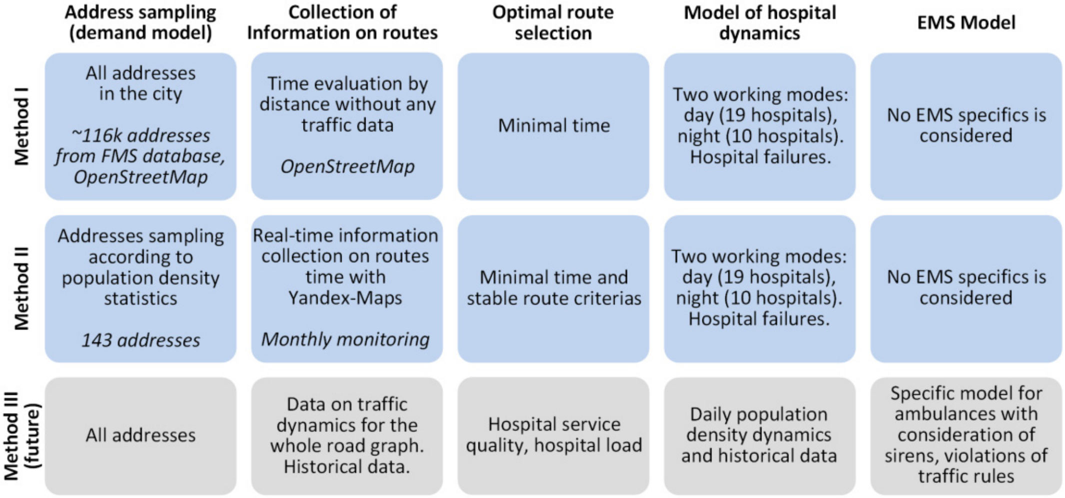
Figure 2: Scheme of EMS operation (the marked processes are investigated in this work)

In this work we consider the EMS system in Saint-Petersburg and focus on investigation of the problems corresponding to patient transportation phase: choice of hospital (d5) and choice of route (d6). In fact, in this work we evaluate the case that these two decision are made together, i.e. hospitals are assessed with taking into account road graph topology and traffic dynamics. For this purpose the following entities are considered: buildings, road graph, traffic dynamics, population density, working hospitals. In order to create a realistic EMS model for Saint-Petersburg the following data sources were used: road graph is taken from OpenStreetMap (https://www.openstreetmap.org); population data from Federal Migration Service for 2012; Yandex.Maps (https://maps.yandex.com) API is used for collection of data on optimal routes built according to current traffic conditions in the city.

Methods of data collection and analysis. In order to investigate the problem from different perspectives, several method to analysis with their own capabilities and restrictions have been applied (see figure 3). The general intention of analysis process is to fetch data on how much time it takes to get from a certain address to each hospital and finally to estimate the best option in different conditions (time of day, traffic conditions).

Method I. The first one is based on the evaluation of quality of EMS provided by system of hospitals within the city without considering the traffic dynamics. Data collection from OpenStreetMap includes graph acquisition, filtering, cleaning, and processing. The main purpose of processing is to determine large connected components and link them. Usually absence of links is caused by incorrect data in publicly edited map. Population density data consists of information about how many people live in buildings (total number of registered buildings is about 116 thousands). Routes from a certain address to each hospital is found with the Dijkstra algorithm, and edge weight is evaluated according to a simple formula for travel time – the ratio of distance to velocity.

Method II. A second approach relies on the traffic data collected with the use of Yandex.Maps service, and it consists of several steps. Firstly, data sampling for demand model has been performed. A sampling step is based on the basic principle that if more of the population lives in a municipal district then more addresses will be included into a sample (statistical data on municipal districts population was taken from government sources). Sample addresses within each district were taken randomly. The size of the sample was limited by the Yandex.Maps service user agreement in order to avoid overloading the service with requests. Sample size was set to 143 addresses (1 test address on about 35 000 inhabitants, about 60 patients with STEMI per year). Data collection was organized using the Yandex.Maps service. This service provides the information on the shortest (by travel time) route from point to point taking into account current traffic conditions. Like the TomTom navigation system the service relies on the clients' positions data fetched in real-time. Routes to each of 19 hospitals from all the sample addresses were requested in real time, once per hour. Data collection lasted for one month and resulted in a table with the following columns: from (address coordinates), to (hospital coordinates), hour, estimated travel time. In order to evaluate the daily traffic dynamics, the average values for 24 hours have been calculated using the month data.



	Address sampling (demand model)	Collection of Information on routes	Optimal route selection	Model of hospital dynamics	EMS Model
Method I	All addresses in the city *~116k addresses from FMS database, OpenStreetMap*	Time evaluation by distance without any traffic data *OpenStreetMap*	Minimal time	Two working modes: day (19 hospitals), night (10 hospitals). Hospital failures.	No EMS specifics is considered
Method II	Addresses sampling according to population density statistics *143 addresses*	Real-time information collection on routes time with Yandex-Maps *Monthly monitoring*	Minimal time and stable route criterias	Two working modes: day (19 hospitals), night (10 hospitals). Hospital failures.	No EMS specifics is considered
Method III (future)	All addresses	Data on traffic dynamics for the whole road graph. Historical data.	Hospital service quality, hospital load	Daily population density dynamics and historical data	Specific model for ambulances with consideration of sirens, violations of traffic rules

Figure 3: Methods of analysis (method III corresponds to the future work and is described in section 6)

Methods of analysis. The collected and processed data was analyzed with use of several perspectives in order to evaluate the quality of EMS in different part of the city. This perspectives can be used for user-optimal and system-optimal solution construction. *Transportation time* characterizes the time to the nearest hospital. *Hospital service area* is a spatial area of the city for which the certain hospital is evaluated as optimal. Defined areas give a tool to assess the *load* on each hospital. Particular interest lies in area of EMS quality dynamics analysis. For this purpose evaluation of decisions changes in time within the dynamic environment have been performed. Decision changes depends on the criterion which is used in order to determine the optimal hospital. Two *closest hospital criteria* were used. The first one is the simplest and based on minimal transportation time (C1). But if we have the dynamic hospital assignment in real situation, choosing of the closest hospital may not always be a good solution. In some conditions there are several routes with the same transportation time equal to minimal or with time close to minimal. In this case it may be not justified to change the route. Also, the route changes during a day can occur simply because of error of route time evaluation. In order to neglect the influence of this factors the following intuitive criterion based on the term of stable hospital has been proposed (C2). Firstly the stable hospitalization direction for addresses is assessed. For this purpose we evaluate the minimal time route with C1 for each of the 24 hours, and then take the most frequent direction from a set of 24 routes as the *stable* one. After the hospital change necessity is evaluated for each hour with giving preference to the stable route by the following steps. If stable route is in set of allowable routes, which are included into p-percent deviation of minimal time, than the route does not change.

5 Results of Analysis

In the figure 4a the transportation time for each address for the case of empty roads is shown with colors (method I, C1). Travel time was computed for the case of empty roads (no traffic) assuming a mean ambulance velocity of 40 km/h. It is shown that the majority of the city center is served within a time interval of 10 minutes. Only suburbs suffer from high travel times.

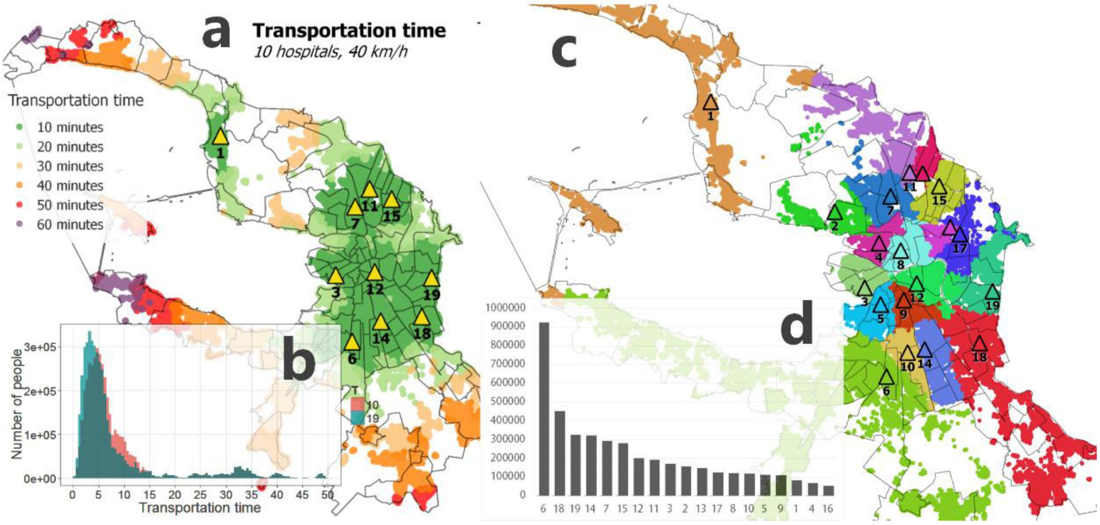


Figure 4: Ambulance service quality for Method I: (a) transportation time; (b) distribution of transportation time (with population data); (c) hospitals' service area; (d) estimated hospitals load (with population data).

Also, it is shown that at night, when only 10 hospitals operate, the transportation time increases in the city center. Mean transportation time for 19 hospitals is equal to 7.94 minutes. In case of 10 hospitals working all day long this parameter shifts to 8.76 minutes (fig. 4b). For each hospital its service area is shown with colors in the figure 4c. Relying on this separation, the hospital load was calculated as the number of people living in a certain area (figure 4d). Using this information, it can be concluded that the load for different hospitals is unbalanced: hospitals that are situated on the periphery (e.g. #6, #18, #19) take more patients than others. This fact is consistent with statistics (fig. 1b). But at the same time, real numbers are more balanced. Here hospital #6 has an area twice as large as hospital #18 at the second position.

These results do not reflect the traffic dynamics and can be used only for case of roads with little traffic, e.g. at night. The similar results for data reflecting traffic dynamics were got with the use of method II. In the figure 5, the sample of transportation time map (a) and service area map (b) for the time 2pm are presented. Traffic influences transportation time dramatically: even in central parts of the city there are zones where transportation takes more than 30 minutes. Calculated mean transportation time (see fig. 5c) reflects the daily rhythm of population mobility: the two peaks correspond to rush hours.

An analysis of hospital changes provides a picture of what addresses do not change linked hospital during a day and what addresses do require changes. Detailed information on changing statistics is presented in the figure 6. The concrete numbers depend on the chosen hospital selection criterion. About 40% of addresses belong to the first class and can be linked to one hospital (see fig. 6c). Peaks on even numbers in the case of criterion 1 (C1) leads to the assumption that the hospital is changed temporally in conditions of high traffic load. Using stable route criterion allows to decrease the number of changes.

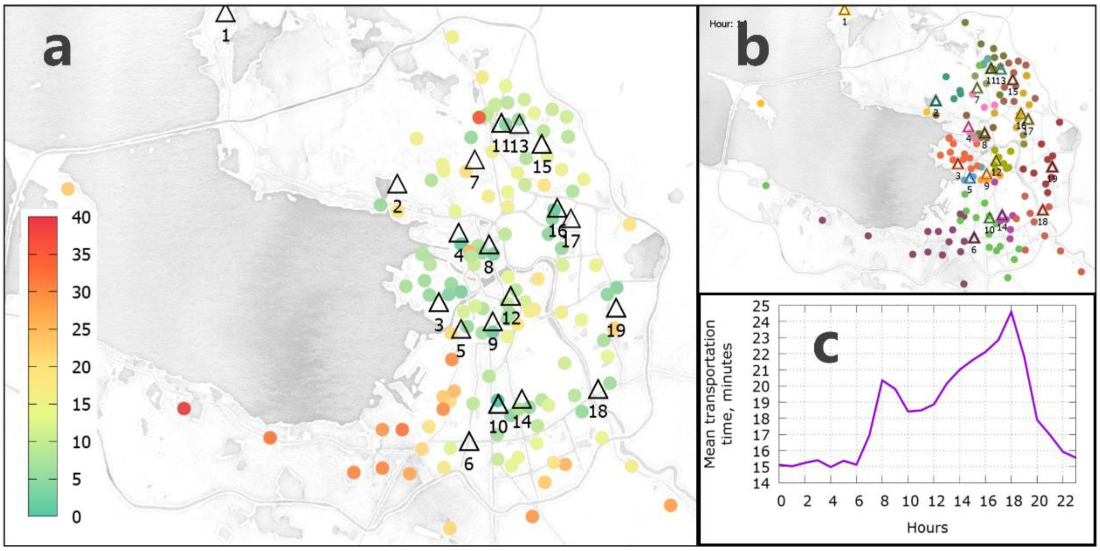


Figure 5: Ambulance service quality estimated by Method II: (a) transportation time for 2pm; (b) hospital service area for 2pm; (c) change of mean transportation time for day time

In order to get closer to answering the question of whether or not we can use static separation on hospital areas, we consider cases of stable hospital changes separately (fig. 6b). For all of the 240 cases occurred during a day the mean time overhead of stable route is 7.88 minutes (standard deviation 7.44).

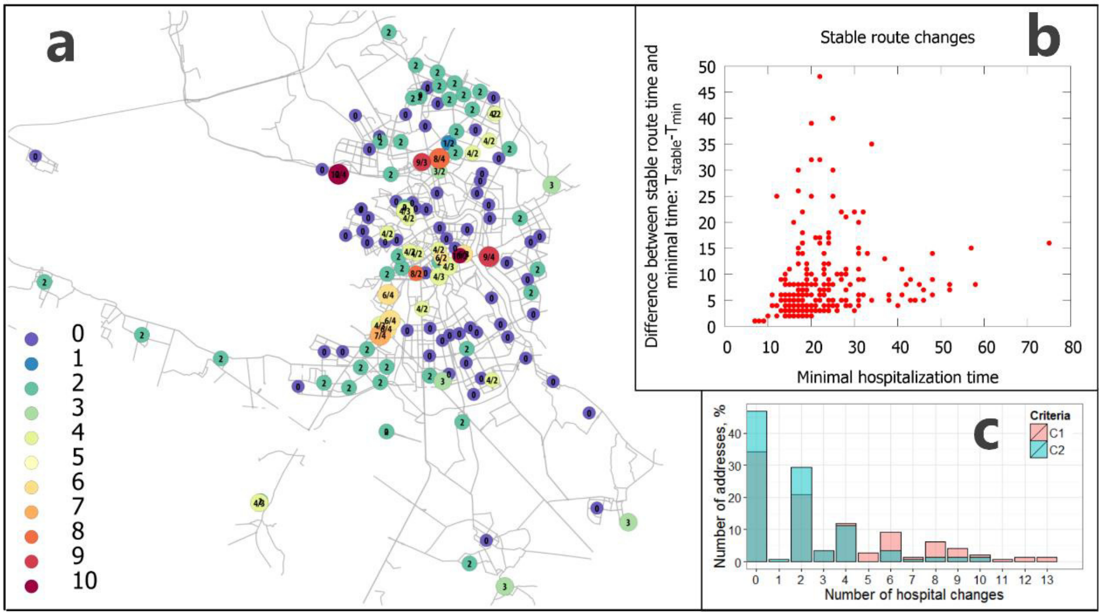


Figure 6: (a) hospital change data, circles color – number of changes per day, size – number of unique serving hospitals (labels carries information in form "number-of-changes/number-of-unique-hospitals"); (b) stable route change cases, C2, p=10%; (c) distribution of number of hospital changes for two criteria

Assessment of hospital load during the day for different hospital selection criteria is presented in the figure 7. The difference between C1 (a) and C2 (b) is essential: load distribution between different hospitals changes dramatically (e.g. #11 and #10). Change of parameter *p* of C2 from 10% (b) to 20% (c) leads to insignificant changes of mean values, and hospital ranks remain the same. But it decreases the dispersion.

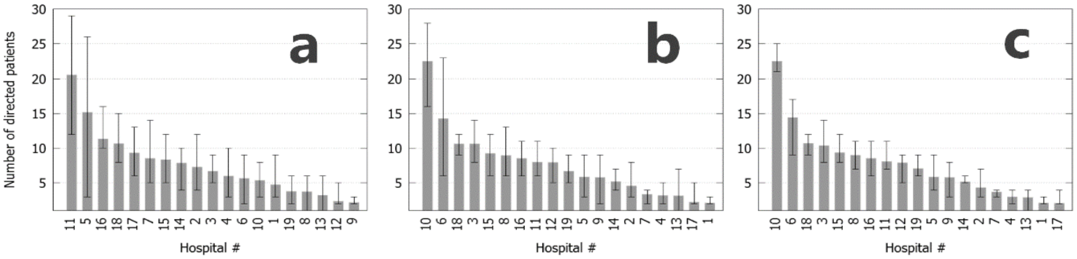


Figure 7: (a) distribution of addresses over hospitals for C1 criterion; (b) distribution of addresses over hospitals for C2 criterion (10%); (c) distribution of addresses over hospitals for C2 criterion (20%)

The analysis shows that the estimated load in most cases does not correspond to the real load (see figure 1b). The reason could be that the shortest path criterion is too simple and does not take into account system's dynamics: hospital load, quality of service.

6 Future Work

Future research can be pursued in several directions (see figure 3, method III). The first one is enhancing data acquisition: getting wider address sample will provide us with more precise statistics on hospital change dynamics. The obtained results require clarification by taking into account historical data of EMS operation: database of hospitalized patients, medical information systems, registers, and geo-tracks of ambulances. Traffic dynamics data on full road graph load will allow investigation of the hospital network and EMS quality in detail. Publicly available service providing data on travel time relies on the statistics for ordinary vehicles without special capabilities like lights and siren. That's why it is important to develop the correction model, which will take into account traffic conditions on the way and assess the time with the use of lights and siren. Such model can be created with the use of agent-based simulation applied to different road conditions.

Integration of traffic model will enable forecasting traffic load which will lead to a more precise travel time estimation. It also provides the capabilities to evaluate the system behavior in different scenarios (what-if experiments). Incorporation of the model of population mobility dynamics will take into consideration the daily activity of people who influence the distribution of possible places EMS calls, thus forming EMS demand.

7 Conclusion

The service quality of STEMI hospitals network has been analyzed using several types of data sources. Supply was modeled with the use of publicly available GIS OpenStreetMap providing data on road map, and the real structure of the hospital network. EMS demand was assessed using population statistics and public statistics on ACS treatment. As a general source of data on travel times, based on observations of traffic conditions, the Yandex.Maps service have been utilized. The result of the analysis gives possibility to formulate the following conclusions. It is important to take into account traffic conditions during selection of an optimal hospital and hospitalization route in Saint-Petersburg. The city cannot be statically separated into zones linked to the pre-defined hospitals. Only 40% of addresses from the sample set did not change optimal hospital in time. It should be also mentioned, that this assessment refers to mean values of travel time computed for monthly data. And highly dynamic factors like accidents and spontaneous traffic jams are not considered.

Future research will include design and development of a model-based decision support system for EMS. As the first step a navigation service prototype has been developed. It enables the selection of an optimal hospitalization route with the use of Yandex.Maps service providing optimal routes in current traffic conditions.

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