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Methodology for creating dynamic emergency vehicle availability maps

Abstract. One of the main priorities of emergency services is to minimize the response time to calls. In the process of proper allocation of emergency vehicles, maps of emergency vehicle accessibility are found to be helpful. These maps represent areas within which emergency services can reach the specified location within a certain time. Calculating travel times requires taking into account the rapidly changing current road conditions. This paper presents a method for dynamically generating maps of emergency vehicle accessibility, considering network models and irregular computational grids.

Keywords: accessibility; service coverage maps; ambulance-coverage-ratio; ambulance; fastest paths; GIS, big data

1. Introduction

The priority of emergency services, such as ambulance, fire department, and police, is to reach the incident location as quickly as possible. Research indicates that 10% of fatalities resulting from accidents occur within 3–5 minutes, and 60% occur within 30 minutes from the incident time. Hence, the proper location of rescue team stations is crucial in determining response time to emergency calls (Terzi et al., 2013). One way to reduce this time is by developing an early map of time coverage, which helps plan the locations of emergency vehicles effectively. Coverage maps are commonly used in analyzing the coverage of areas by telecommunication networks, but they can also be utilized in other fields to present various spatial information (Piórkowski, 2018).

With information about travel times between the vehicle's stationing location and other points, an accessibility map can be created, also known as a service map or time coverage map. Each area consists of an infinite number of points, and finding optimal routes is a time-consuming problem; hence, appropriate sampling of the area becomes necessary by selecting its representative points (Płokita et al., 2016). These points, when plotted on the map, determine the zones within which the rescue team can reach within the designated time. The available literature on the subject illustrates the evolution of GIS (Geographic Information Systems) used to reduce response times to emergency calls by creating accessibility maps. The work by Branas et al. (2000) is often recognized as one of the first systematic approaches to modeling the deployment of ambulances and hospitals based on geographical accessibility and time coverage. The application of GIS models allowed for optimizing resource allocation, resulting in a reduction of the emergency medical team's response time. Research on the optimal placement of ambulances has also been the subject of investigation described in the work by Andersson and Värbrand (2007). This article presents possibilities and decision support tools for ambulance dispatch centers, focusing on the dynamic relocation of ambulances and its impact on response times to emergency calls. Similar studies were outlined in the work by Schmid (2012), where the authors proposed a new approach to ambulance placement and management using ADP (Approximate Dynamic Programming), leading to an average reduction of 12.89% in ambulance response times.

In the study by Wajid et al. (2020), an optimization of the service area for emergency medical services (EMS) was proposed using the Double Standard Model (DSM) and Google Maps API, enabling the computation of travel times between ambulance locations and accident scenes.

The issue of service area coverage also has legal implications. In Poland, there is a legal requirement known as the “statutory response time” for ambulances to reach the incident location, which is set at 15 minutes in cities and 20 minutes outside of cities. Therefore, the aim of this study was to create a tool that dynamically and in real-time responds to changes in the transportation network or other unforeseen circumstances, in order to model ambulance service areas within the statutory response time (15/20 minutes). The significance of this issue is evident in extensive literature research on accessibility maps created in various countries.

For instance, the work by Peleg and Pliskin (2004) presents an analysis of accessibility for the city of Haifa, where the authors presented zones with travel times set at 8 and 15 minutes. The placement of ambulances and coverage of demand for the Odunpazari District in Turkey was shown in the work by Swalehe and Aktas (2016), with the aim of creating a map representing areas that ambulances can reach within 5 minutes. Similar issues were also addressed in the work by Terzi et al. (2013), where accessibility maps presented service areas achievable by EMS within 10 minutes. Ambulance accessibility zones based on travel times were also presented in the work by Shuib and Zaharudin (2010), while the articles by Budge et al. (2010) and Ingolfsson (2013) show coverage maps based on the probability of the nearest available ambulance responding to a call. In the case of ambulance accessibility in rural areas, it’s worth mentioning the work by Vanderschuren and McKune (2015), where analyses were conducted for the Western Cape region in South Africa. The article by Westgate et al. (2016) presents an analysis of the probability that the nearest ambulance in Toronto will arrive at the incident location within 4 minutes, based on a city road grid as a reference map. It is essential to emphasize that analyses and accessibility maps for emergency vehicles should assume that these vehicles move differently than civilian vehicles. This means that calculations carried out for ambulance accessibility maps should consider the speed characteristics specific to emergency vehicles. Therefore, this study was conducted as a continuation of the authors’ previous research, which demonstrated that ambulances in the Małopolska voivodeship (Poland) maintain a relatively constant average speed regardless of the time of day, weather, or season (Lupa et al., 2021). The obtained speed characteristics served as reference data for developing the solution in this study.

2. Methodology

Creating an accessibility map, even with the use of classical GIS software, always involves solving a certain computational problem. In this case, a specific computational grid is assumed, and the density of nodes in this grid determines the accuracy of the calculations. The next chapter presents a solution that reduces the number of computational nodes while increasing calculation accuracy. Furthermore, considering that the described solutions pertain to entirely dynamic accessibility maps, reducing computational complexity was necessary to shorten the time required for generating the map and, consequently, adapting it to the varying conditions on the road.

2.1. Architecture

The solution operates based on the GeoTools library and the GeoSpark system. GeoTools is a set of tools for building Geographic Information Systems in Java (GeoTools, 2023). GeoSpark is a programming platform used for processing big data spatial data (GeoSpark, 2023), built on Apache Spark, a distributed computing engine (Apache Spark, 2023). At the core of GeoSpark

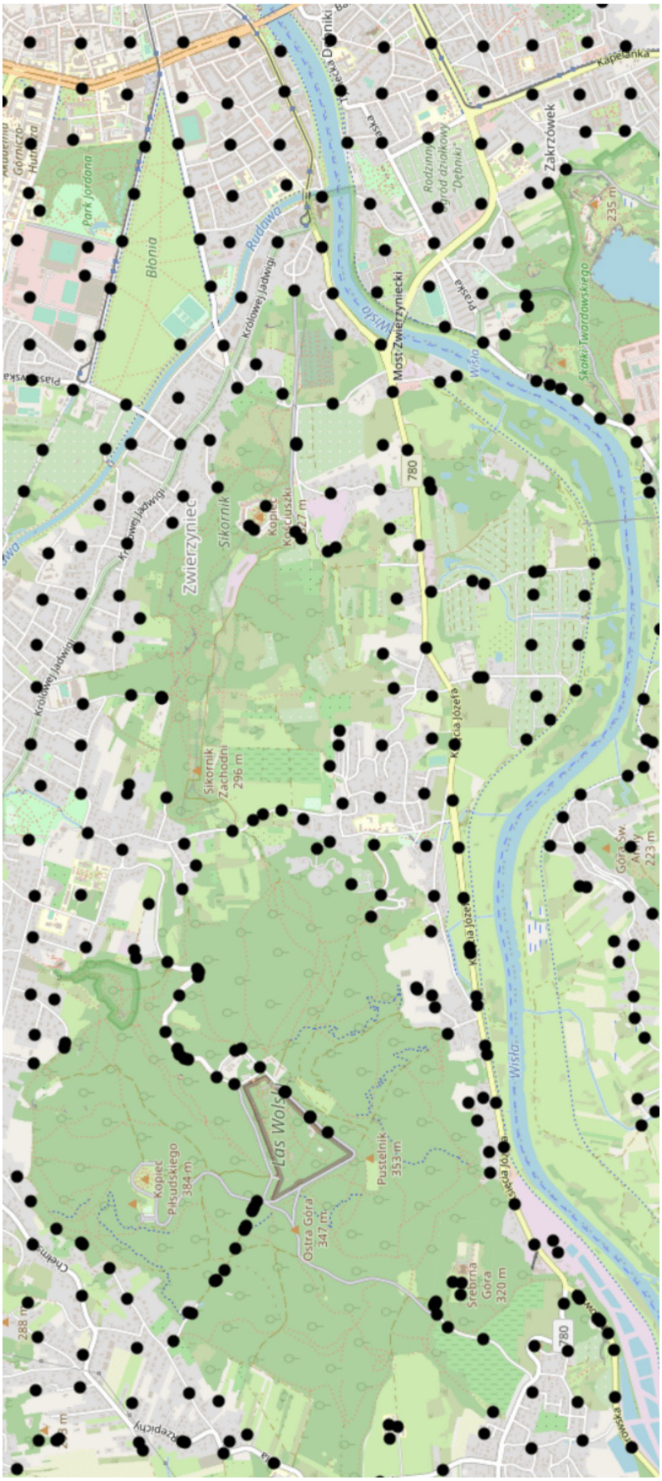

Figure 1. Fragment of the irregular computational grid (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

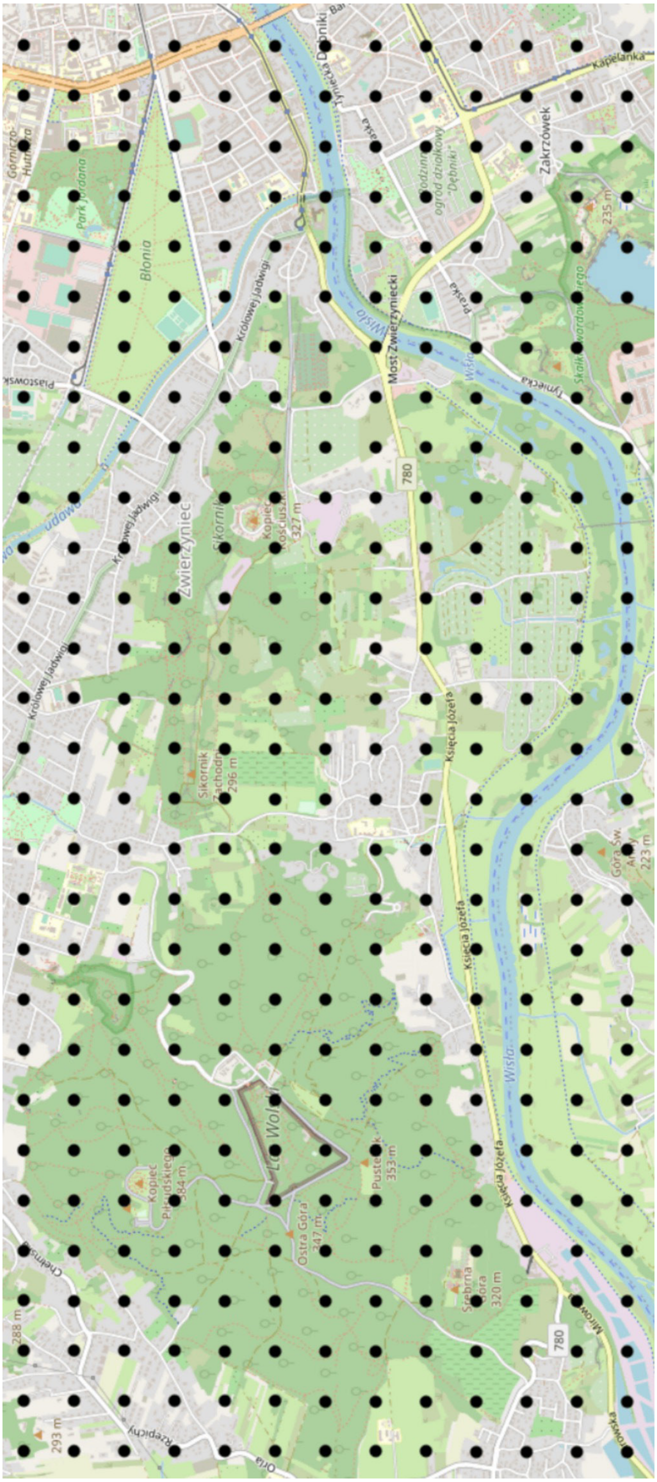

Figure 2. Example of a regular computational grid (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

lies the Spatial Resilient Distributed Dataset (SRDD), which stores spatial data across multiple computer units' disks or memory and enables parallel manipulation (Karau et al., 2016). Such a dataset can be stored in the distributed Hadoop Distributed File System, managed by the Apache Hadoop programming platform (Apache Hadoop, 2023).

The user interface was developed using the OpenLayers library, which presents the data on an OpenStreetMap basemap with an overlaid irregular grid of computational points. An illustrative fragment of this grid is depicted in Figure 1. The grid nodes are strategically positioned in areas accessible to motor vehicles while excluding points within buildings, fields, or forests. The grid creation is facilitated by employing the Open Source Routing Machine (OSRM) routing engine, elaborated in the subsequent subsection. The OSRM engine is based on OpenStreetMap data, where the road network is represented by nodes (OSRM, 2023).

2.2. Irregular grid point

Ensuring appropriate sampling of the area is crucial for the application's functionality. The grid points can be distributed with equal distances and density (Figure 2) or irregularly, as shown in the image above (Figure 1). The nodes of a regular grid rarely correspond to locations accessible to motor vehicles. This fact can significantly hinder the usability of the accessibility map, leading to inaccurately determined routes and difficulties in calculating travel times. Additionally, it can greatly extend the time required for computation. As a result, the optimal solution was to create a grid tailored to the road infrastructure layout.

Among the various possibilities, the OSRM engine offers the ability to determine the nearest point on the road network for any given pair of geographic coordinates. OSRM is based on OpenStreetMap data in the WGS84 coordinate system (EPSG 4326). Communication with the OSRM server occurs through web APIs (HTTP), which return responses in JSON format, similar to the one presented in Figure 3.

The algorithm for constructing an irregular computational grid based on the OSRM routing engine proceeds as follows:

1. Calculate the coordinates of a regular grid with nodes spaced at 250-meter intervals.

```
http://osrm2-4199.cloud.plgrid.pl/nearest/v1/driving/19.956389,50.051952

code:            "Ok"
▼ waypoints:
  ▼ 0:
    ▼ nodes:
        0:       243362171
        1:       243362183
    ▼ hint:      "sgwAgP___38FAAAAEgAAAFkAAAAOAAAA-
                 xW2QE0WbkFUM8NC7vRxQQUAAAASAAAAWQAAAA4AAAB1AAAA3oEwAWm8-
                 wKlgjABcLv7AgQA7wMHy0w3"
      distance:  31.145364
    ▼ location:
        0:       19.95619
        1:       50.052201
```

Figure 3. The difference (property "distance" [m]) between the location of the nearest point on the road network and the coordinates of a grid node

2. For each node in the regular grid, send an HTTP request to the OSRM server to obtain the coordinates of the nearest point on the road network.

3. Create an irregular grid using the coordinates obtained in the responses from the OSRM server (Figure 4).

4. A standard OpenStreetMap topographic map is used as the base map for analyses.

In the first step, a regular grid consisting of 5221 points was created, covering the area of Kraków city, as illustrated in the image below (Figure 5). The grid size (250 m) was dictated by a desire to compare results with the study by Piórkowski (2018). However, the grid size can be arbitrarily adopted, adjusting analyses to the desired precision. As a result of the above-described process, it was transformed into an irregular grid (Figure 6).

Some points on the road network serve as the nearest points for multiple nodes in the regular grid simultaneously. An example of such a point can be seen in Figure 7. As a result, the final irregular grid comprises only 4759 nodes. This characteristic reduces the amount of information needed for the accessibility map

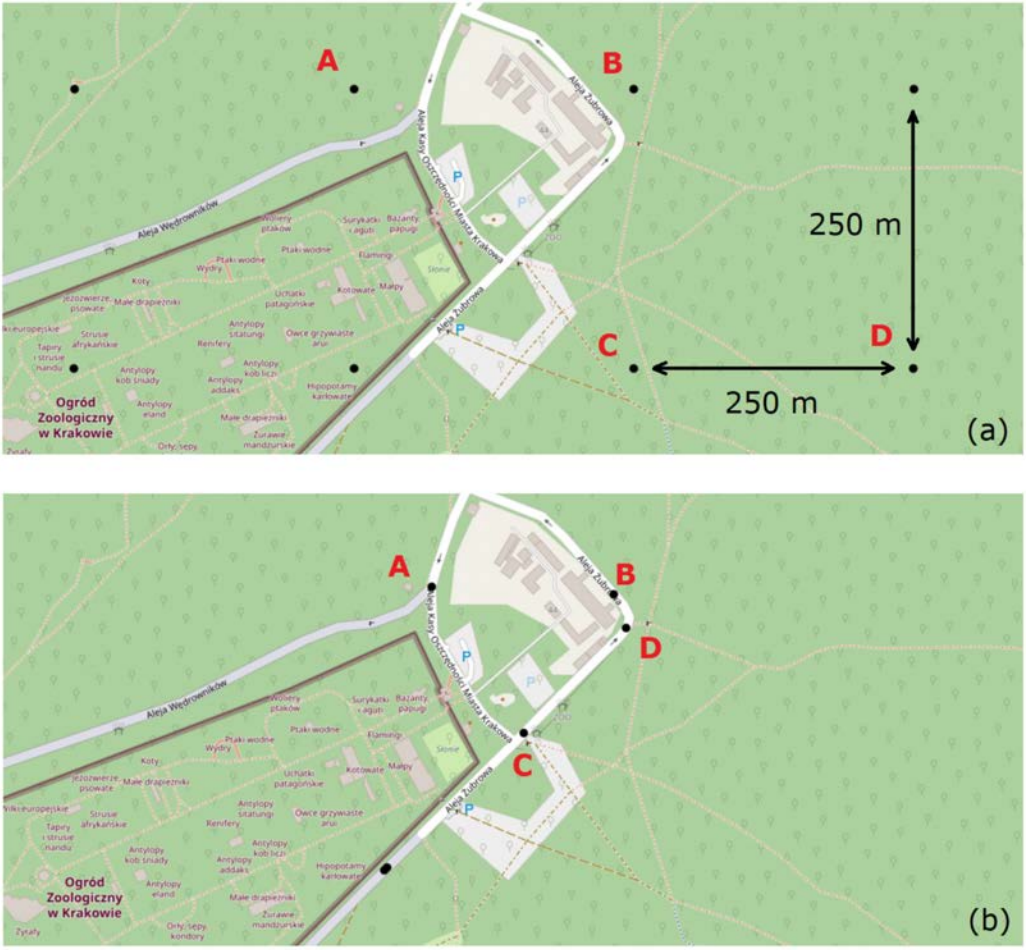

Figure 4. Points arranged regularly (a) and their corresponding nodes in the irregular computational grid (b) (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

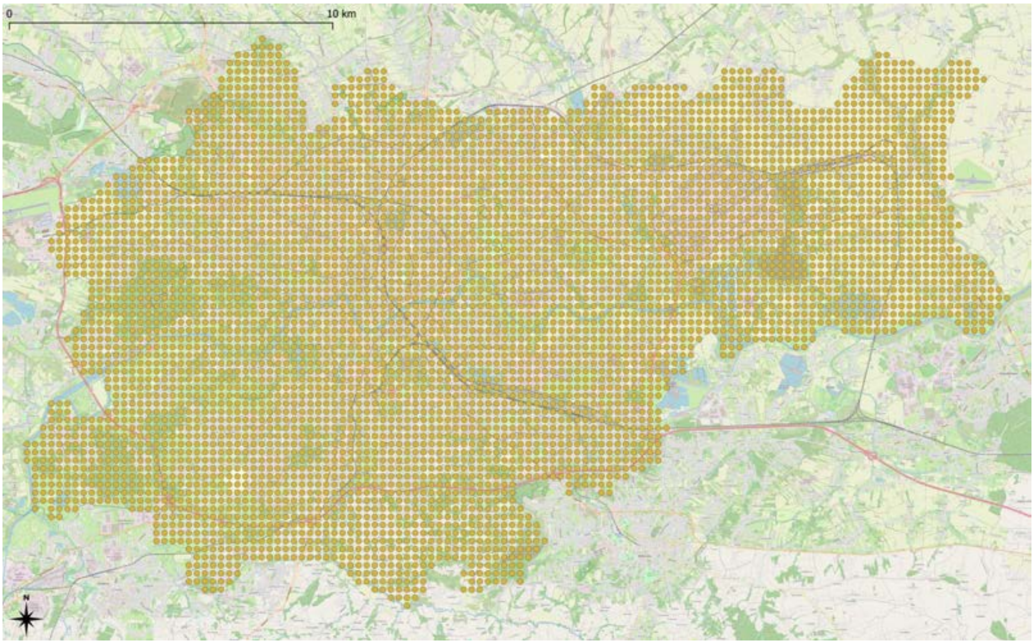

Figure 5. Regular grid of points covering the area of Kraków city (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

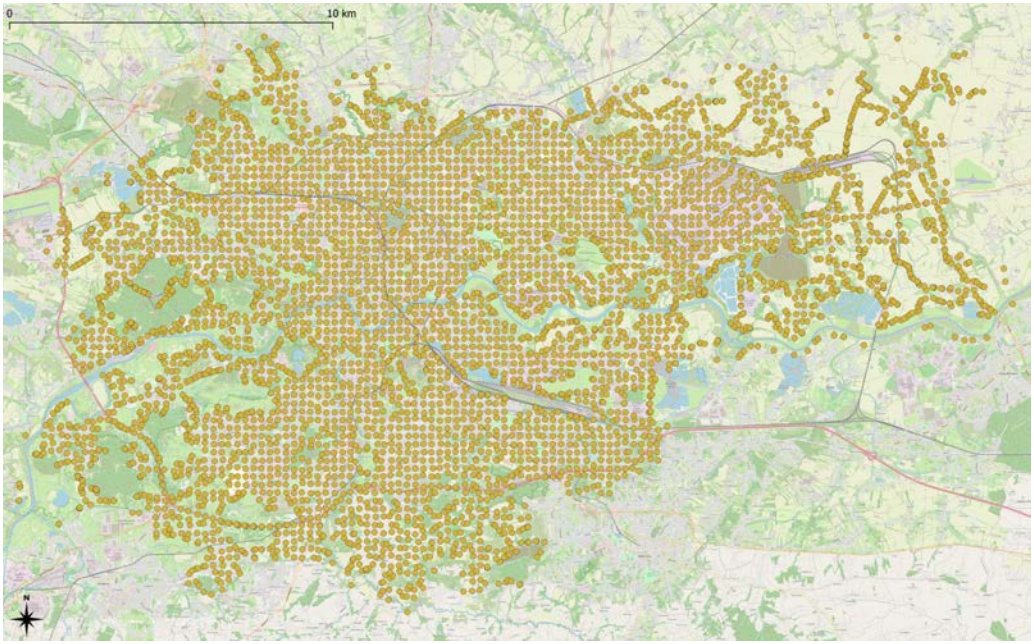

Figure 6. Irregular grid of points covering the area of Kraków city (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

Figure 7. Points in the regular grid (a) sharing the same nearest point on the road infrastructure (b) (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

creation, thereby shortening the computation time. Further reduction in computation time can be achieved by aggregating points with distances less than 100 meters (Figure 8).

2.3. Routing

To construct an ambulance accessibility map, it is essential to calculate travel times between all pairs of points in the computational grid, considering both directions (Kozieł, 2014; Lewandowicz & Flisek, 2017; Mitosz et al., 2014; Piórkowski, 2018).

$$PT = (G\ x\ G),$$

where $PT[x,y]$ represents the travel time between point Px and Py.

For this purpose, we utilized the aforementioned OSRM routing engine and the Contrac-

Figure 8. Closely located points in the irregular grid that can be merged into one point (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

tion Hierarchies algorithm (Geisberger et al., 2008) to determine the route and travel time between each pair of locations. Gathering this information, the solution stores it in a distributed spatial data set (RDD), allowing for various fast computational operations (GeoSpark). By employing this approach, the calculations can be executed in parallel across computational clusters, leading to a substantial acceleration in data generation. The process of adding a new object to the collection, and thus, performing the calculations for all grid points, proceeds as follows:

1. Sending an HTTP request for the route and travel time between specific points.
2. Creating an instance of the LineString class representing the route's geometry.
3. Adding travel time information to the UserData field of the created object.
4. Adding the object to the distributed data set.

These calculations are schematically presented in the following figure (Figure 9).

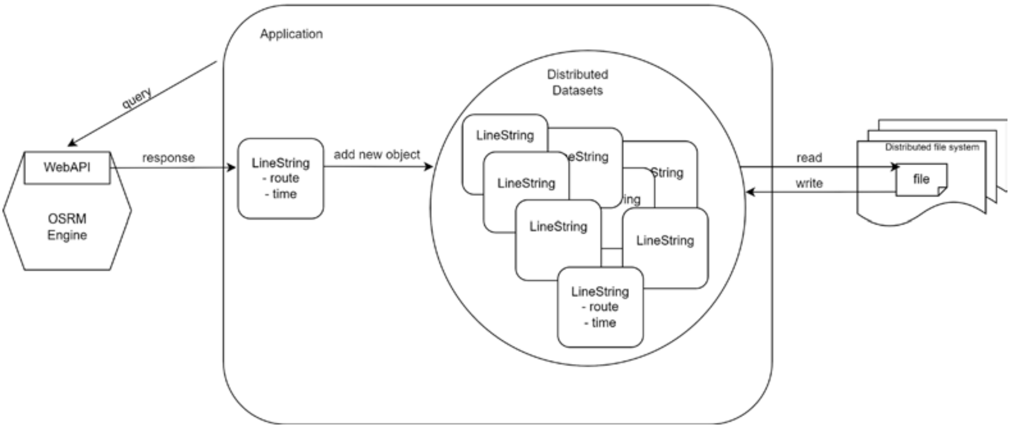

Figure 9. Scheme of distributed computations

After gathering the information, the application saves the dataset in a text file. Each line of this file corresponds to a single route saved in the Well-Known Text format for LineString, along with additional travel time information. Next, this information is stored in a distributed file system (DBFS), enabling rapid data reloading without the need to retrieve them again from external sources.

3. Dynamic coverage map

The creation of a dynamic accessibility map begins with a trigger action – indicating a point for which polygons representing travel times will be returned. Each point indication triggers the following sequence of actions:

1. Sending a POST request with a list of coordinates for the selected positions to the application controller.
2. Filtering the SRDD (containing all possible routes) to identify routes originating from the points in the list.
3. Remapping the obtained set of routes into a collection of pairs containing the following values:
    a. Endpoint of the route (also a node in the irregular computational grid).
    b. Travel time to that endpoint.
4. Determining the shortest travel time for each node.
5. Sending the information obtained in the previous step to the view layer.
6. Displaying the coverage grid, where points are colored based on travel times:
    a. 0 minutes (vehicle parking location) – pink color.
    b. Between 0 and 7 minutes – green color.
    c. Between 8 and 15 minutes – yellow color.
    d. Between 16 and 20 minutes – red color.
    e. Above 20 minutes – black color.

The effects of the user's actions can be observed in the image below (Figure 10). The selected intervals correspond to the EMS statutory travel times in Poland (15/20 minutes). Furthermore, the accessibility map can be generated for a single point (case (b) – Figure 10) or for two or more points (case (c) – Figure 10).

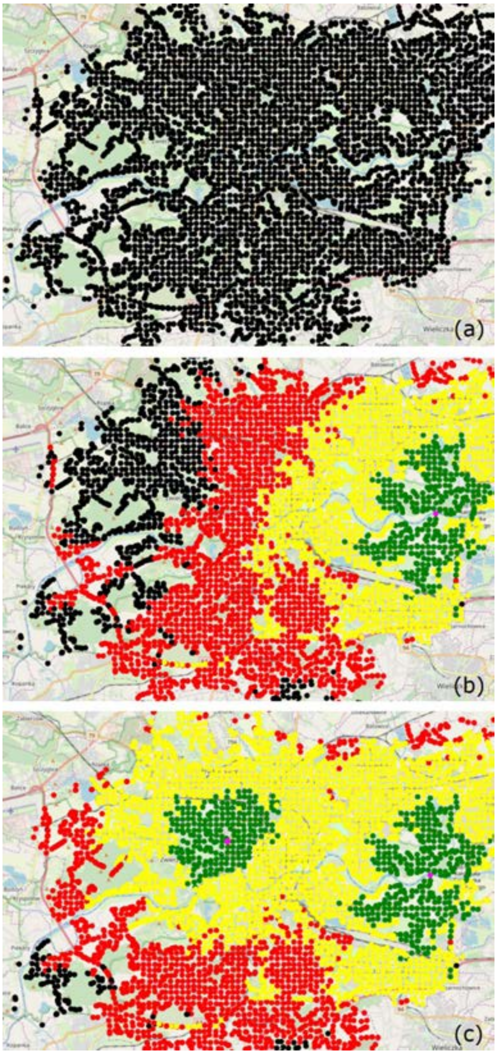

Figure 10. Time coverage maps – before marking the vehicle location (a), after marking one location (b), and after marking two locations (c) (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

3.1. Exclusion of a road section from traffic

The authors' research focused on developing a solution for dynamically creating an accessibility map. This entails the map's responsiveness to unforeseen events, such as road incidents, construction work, accidents, mass events, and other factors that may affect ambulance accessibility in urban areas. To achieve this, an algorithm was devised that allows for the exclusion of selected segments of the road network, adapting the accessibility map to the current situation prevailing in the analyzed area.

The closure of roads necessitates the need to establish new routes, as the current ones, previously considered the fastest, become impassable. Detours can significantly extend travel times. In such cases, a recalculation of the accessibility map is required. Additionally, acquiring new travel time information between all grid nodes would involve sending n^2 HTTP requests to the OSRM server (where n is the number of nodes), significantly reducing the solution's efficiency. As a result, regenerating the accessibility map for the entire area would introduce time overhead, affecting EMS response time, and ultimately, the arrival time at the incident location.

To address this, the authors developed an algorithm for generating dynamic accessibility maps that updates travel times solely for routes overlapping or intersecting with the closed road segments. This way, the EMS dispatcher, upon receiving information about changes in traffic organization, can identify the specific road segment that will be excluded from the accessibility map (Figure 11).

The closure of a road segment triggers the generation of a new accessibility map according to the following scheme:

1. Identifying road segments corresponding to the user-defined polyline (the line marked by the user may differ from the actual road segments, as shown in Figure 12).

2. Creating an update file that contains information about the exclusion of specific road segments.

3. Restarting local instances of the OSRM engine, incorporating the additional update file.

From now on, the engine should calculate new routes and travel times, taking into account the exclusion of the road segment.

A sample comparison of ambulance accessibility maps for Krakow before and after the closure of several roads is shown in the image below (Figure 13).

4. Discussion

Vehicle accessibility maps can be a very valuable tool when managing a fleet of emergency vehicles, such as ambulances. Moreover, these maps can play an even larger role in public safety if the times on the accessibility zones are validated. Therefore, developing appropriate tools for assessing accessibility maps is one of the key research aspects facing the authors of this work. The authors believe that this assessment can be conducted through the analysis of historical data, in which the ambulance route will be reconstructed based on GPS logs. This could involve, for example, determining the starting and ending points of the ambulance route along with the total transit time. These points and times can then be overlaid on the availability map, and the difference between the transit time and the estimated time can be

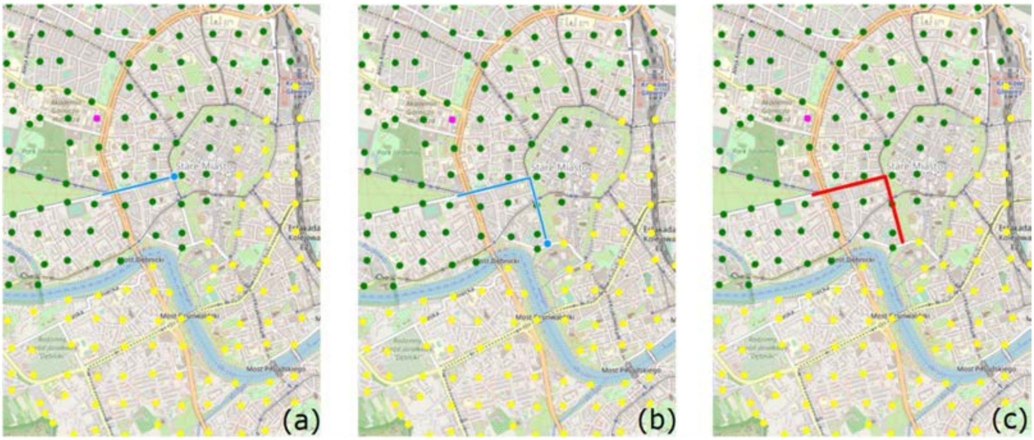

Figure 11. Marking successive road segments closed for use (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

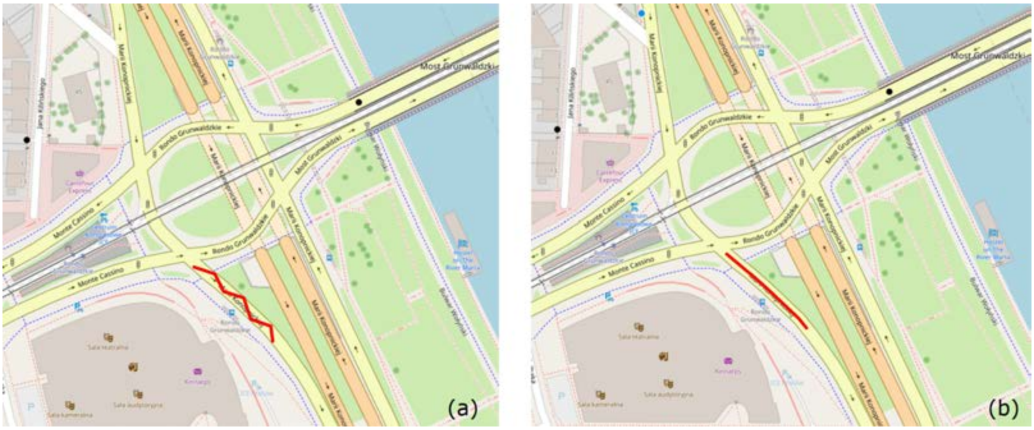

Figure 12. User-defined line (a) and its matching to actual road segments (b) (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

calculated as an RMSE (Root Mean Square Error) measure. These measures should be determined for computational grids of varying density, as well as different hours and days of the week when ambulances are operating.

In the case of grids with varying densities, a choice must be made between the expected level of spatial accuracy, the available computing cluster, and the maximum computational time that the dispatcher operates with to generate a new, dynamic accessibility map. All these issues were also the subject of consideration by the authors of this work, who decided to move away from raster/polygon (Azizan et al., 2013; Diller et al., 2014; Lee, 2014) data in favor of points, which take on different colors depending on the travel time to a given area. Compared to the solutions described in the literature (Fisher & Lassa, 2017), our solution is characterized by much lower complexity and reduced calculation time while still leaving an appropriate amount of information on the map for the dispatcher.

The new accessibility maps have been designed keeping user-centricity in mind. Our new approach makes use of intuitive and universally-recognized symbols, aimed at ensuring users from diverse backgrounds can understand the map without extensive prior knowledge. Color differentiation and map perception (Lupa et al., 2017) is a key aspect of accessibility maps, which is why we avoid maps presented in grayscale (Myers et al., 2015). The proposed solution is based on classic colors that are easily associated with a specific phenomenon, such as green – easily accessible and red – difficult to access (Piórkowski, 2018). The usa-

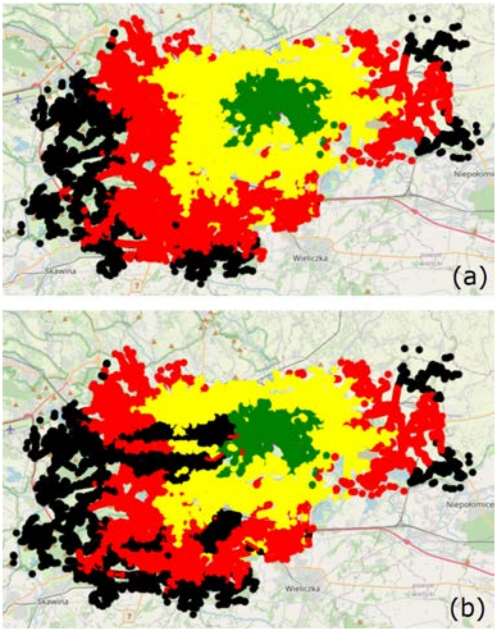

Figure 13. Time coverage map before (a) and after (b) the closure of several roads (base map: map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org)

bility of a map directly affects decision-making. A map that is easy to read, understand, and interpret allows decision-makers to quickly grasp the situation and act accordingly.

5. Conclusions

This work presents a method for generating dynamic accessibility maps that can be used by medical dispatchers managing EMS fleets. Temporal availability of an ambulance, i.e., the area that can be reached within a feasible response time, significantly impacts the safety of city and rural residents during emergency situations. As demonstrated by the literature on Geographic Information Systems (GIS) and decision support systems, the topic of accessibility maps has been a subject of interest for over 20 years. So far, both commercial and open-source GIS tools have only offered static solutions for generating accessibility maps, which implies the need to regenerate the entire map in the event of an unforeseen occurrence. This puts dispatchers in a difficult position – either regenerate the map using static GIS tools or rely on an outdated accessibility map, hoping that a closed road will not hinder EMS response to the incident. This work presents an approach that minimizes the challenges of generating accessibility maps by adapting them to the current road conditions, thus contributing to the enhancement of public safety.

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