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Development of a geoinformation method for assessing the accessibility of medical services in community infrastructure development projects

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ABSTRACT

The article develops a geoinformation method that provides a solution to the scientific and applied problem of assessing the accessibility of medical services in community infrastructure development projects. Solving this problem is the basis for planning community infrastructure development during their post-war reconstruction. The relevance of the study is determined by the need to improve the effectiveness of management decisions regarding the assessment of medical service accessibility to community populations in conditions of spatial unevenness in the distribution of medical infrastructure facilities and limited resources. The work aims to develop a geoinformation method for assessing the accessibility of medical services for the population of communities, based on the use of open geospatial data from the OpenStreetMap framework, which takes into account the topology of the road network, the spatial distribution of medical facilities, the density and distribution of the population in the communities, and the time parameters of access to medical services. The proposed method is implemented on the basis of open data using OpenStreetMap tools, OSMnx and NetworkX libraries, which ensure flexibility, scalability and transparency of calculations. A distinctive feature of the method is the automated determination of areas of community access to medical services based on the construction of isochrones around medical infrastructure facilities, taking into account the type of facility and the acceptable time of arrival of community residents to them. The developed geoinformation method was tested for adequacy. It was found that deviations are within 1 minute or 0.3 km. The results of the experimental application of the method on the example of a typical territorial community showed its ability to identify ‘grey areas’, i.e. settlements that are not sufficiently covered by the network of medical institutions, and to assess the impact of changes in the structure of the medical network on the overall accessibility of medical services to the population. The practical value of the study lies in the creation of an algorithm that forms the basis for the development of a system to support management decisions on the strategic development of communities. In particular, in terms of assessing the population's access to medical services for planning community infrastructure development projects. The proposed method can be further expanded by integrating demographic forecasts, population mobility scenarios, and data on the state of road infrastructure, which opens up prospects for its use in a wider range of community infrastructure development project planning tasks.

Keywords: Management; project; method; territorial community; medical services; geodata; infrastructure development; management decision-making.

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INTRODUCTION

In the current conditions of war, decentralisation and the need for post-war regional development, there is a scientific and practical task of ensuring equal access to medical services for the population of communities. Its solution is the basis for the effective implementation of community infrastructure development projects. This is what ensures the formation of an effective healthcare system in the communities. Spatial inequality in the location of settlements and hospitals affects the accessibility of medical services for the population, which leads to a decrease in the quality of medical care. This is especially true for rural and remote communities far from regional centres, where infrastructure is often in poor condition or completely absent [1], [2].

According to WHO research, the availability of medical services to the population directly affects mortality rates, life expectancy, and social justice in society [25]. The uneven spatial distribution of medical facilities also creates barriers to the implementation of sustainable community development projects, especially in crises such as war or a pandemic.

In recent years, there has been a growing demand for the use of geographic information systems (GIS). In particular, they can be used to plan community medical infrastructure development projects.

Spatial analysis tools make it possible to assess the current state of the population's access to medical services, identify ‘white spots’ on the access map, and model alternative scenarios for the development of the community healthcare network.

The introduction of geographic information systems into the healthcare management system allows for the combination of automated management decision-making and accuracy with simultaneous visualisation. This is an important tool for effective project management [26]. The ability to use open geospatial data, such as OpenStreetMap (OSM), is particularly valuable. It allows for up-to-date, scalable, and inexpensive spatial analysis for communities of any size [24].

Despite the widespread use of geoinformation technologies in planning, there are currently no comprehensive methods that integrate geospatial data, transport infrastructure data, and demographic data to assess the accessibility of medical services for the population. Most existing approaches either do not take into account the topology of the road network or are limited to ‘straight line’ calculations, which do not reflect the real conditions of community members' travel to medical facilities [3], [4]. Also, not much attention is paid to adapting methods to specific types of settlements (urban, rural, mountainous, or frontline), which is especially relevant for Ukraine.

Our study proposes a geoinformation method for assessing the accessibility of healthcare services for communities using OpenStreetMap open data and road network spatial analysis tools. The method is implemented as a modular system, which allows it to be adapted to the needs of specific regions and used in the planning of community infrastructure development projects. Unlike traditional approaches, the proposed method takes into account not only the distance but also the travel time of the population to medical facilities, population density, and the state of the transport network.

There is a need to create a decision-making support tool for project managers who develop community medical infrastructure. The proposed method has practical value for planning community infrastructure development projects. In particular, it can be used to optimise the location of medical centres, clinics, mobile teams or transport routes. The novelty of the research lies in the creation of a method that combines geoanalytics methods, network analysis algorithms, and open data sources to solve the scientific and applied problem of assessing the accessibility of medical services in community infrastructure development projects.

1. ANALYSIS OF LITERARY DATA

Assessing the accessibility of medical services to the population is an important planning process in community infrastructure development projects. This is particularly relevant in the context of the territorial transformation of the healthcare system. The authors of scientific works [5], [6], [7], [8] emphasise the need not only for the physical presence of medical facilities, but also for the actual accessibility of these facilities for residents, taking into account the time, type of transport used, and characteristics of the area. The main indicators for assessing accessibility are the distance to the nearest medical facility, travel time, population density in the area, average and maximum time to the start of medical services, and the spatial equality index [27], [28]. The spatial equality index is a synthetic indicator that reflects how evenly medical services are distributed across the territory of a community, showing the degree of balance between the actual accessibility of services and the normative standards. A higher value of this index indicates a more uniform distribution of access, while lower values point to significant disparities between different settlements. At the same time, traditional methods are mostly based on Euclidean or Manhattan distance, without taking into account the actual structure of the road network, which significantly reduces the accuracy of such assessments.

Over the last decade, the use of geographic information systems for healthcare infrastructure planning has become widespread. Studies [9], [10], [11] demonstrate the feasibility of using GIS. They provide the highest level of integration of spatial, demographic, and transport data for calculating accessibility indicators [29], [33]. In addition to visualisation, GIS enables multifactorial analysis, modelling of scenarios for changes in the location of medical facilities, optimisation of routes to medical facilities, and identification of the most vulnerable population groups in terms of access to medical services.

Open tools for spatial analysis have become particularly popular in recent years [12], [13]. In particular, OSM, an open and non-commercial web cartographic project, is used as a source of detailed geodata covering the road network, buildings, and types of infrastructure [14], [15], [16]. Based on OSM, a powerful tool such as OSMnx has emerged. The OSMnx library allows you to automatically build road network graphs and perform accessibility analysis, taking into account topology [24]. In combination with NetworkX, which provides the ability to calculate shortest paths, centrality, and other graph characteristics, users can obtain accurate results regarding the population's access to medical services. The free cross-platform GIS QGIS is often used for geospatial visualisation. It is a flexible environment with a large number of plugins. It allows you to combine data layers, create heatmap maps, and buffer accessibility zones [32].

There are already examples of successful application of accessibility assessment models in healthcare in global practice. In particular, the United Kingdom uses the Two-Step Floating Catchment Area (2SFCA) model, which combines data on medical resources and the load on them with spatial analysis [30]. In Canada, individual researchers have studied issues of access to rural hospitals [29], pointing to the importance of accurately accounting for road conditions and transport mobility. In Africa, where much of the territory has poor transport infrastructure, studies [31] show the need to take spatial fragmentation into account in the analysis of access to healthcare services.

Despite existing scientific achievements, most existing methods have a number of limitations. In particular, many methods are based on closed or outdated data that do not reflect the current state of the transport infrastructure of communities. Some of them ignore the differentiation of settlements by density, road types, availability of public transport, etc. Most of the known methods are quite difficult for communities to implement due to the high requirements for technical infrastructure and professional training of their users.

This necessitates the creation of a flexible, open, adaptive geoinformation method for assessing the accessibility of medical services, which is important for the practice of managing community infrastructure development projects. Such a method should use open data sources. In particular, it should include an analysis of the road network in real conditions, take into account the spatial location of settlements, and provide the possibility of interactive visualisation of the results obtained. Our research is aimed at solving this scientific and applied problem.

2. THE PURPOSE AND OBJECTIVES OF THE RESEARCH

Contemporary challenges related to spatial inequality in access to healthcare services, especially in the context of community development and decentralisation, require new approaches to the analysis and planning of healthcare infrastructure in development projects. Most existing methods for assessing the population's access to healthcare services are based on a number of assumptions. In particular, they are based on Euclidean distance to healthcare facilities or use closed or outdated data sources. This reduces their effectiveness in real community conditions, where it is particularly important to take into account the transport network, topographical constraints, settlement types, and relevant spatial data. In this regard, there is a need to create a geoinformation tool capable of adaptively reflecting the situation with access to medical services based on open, reliable and easily updatable data.

The purpose of the article is to develop a geoinformation method for assessing the accessibility of medical services for the population of communities, based on the use of open geospatial data from the OpenStreetMap framework, which takes into account the topology of the road network, the spatial location of medical facilities, the density and distribution of the population in the communities, and the time parameters of access to medical services. The resulting method improves the effectiveness of management decision-making during the implementation of community infrastructure development projects.

To achieve this goal, the following research tasks need to be solved:

– develop a geoinformation method for assessing the accessibility of medical services for the population of communities;

– based on the proposed method, develop modules for individual stages of assessing the accessibility of medical services for the population of communities using the OpenStreetMap framework, OSMnx and NetworkX libraries, and conduct experiments using a typical territorial community as an example.

The results obtained will allow comparing the effectiveness of the proposed method with traditional approaches, identifying weaknesses in existing practices for assessing the accessibility of medical services for the population of communities, and proving the feasibility of introducing a geoinformation method into the field of community infrastructure development project management. This approach not only increases the accuracy of management decisions, but also ensures that real spatial and temporal indicators of accessibility to basic medical services for the community population are taken into account.

3. RESEARCH METHODS

The methodological basis of the study is based on the use of geoinformation analysis and network modelling methods of spatial accessibility to medical facilities for the population of communities. This provides an accurate and adaptive assessment of accessibility to medical facilities based on the actual configuration of the road network, the location of settlements, and the characteristics of the transport infrastructure. Geoinformation analysis is the basis for processing and visualising spatial data. This allows quantitative and spatial characteristics to be combined within a single model [34]. The use of geoinformation analysis makes it possible to accurately identify medical facilities and the coverage areas of individual communities and to compare alternative scenarios for the development of medical infrastructure.

The basic tool for spatial data analysis is network modelling of the population's access to medical services. For this purpose, graphs of the community road network are constructed, taking into account street geometry, traffic restrictions and road types. To determine the shortest routes from settlements to medical facilities, Dijkstra's algorithm and its modifications are used, which allow calculating the shortest travel time, taking into account the actual length of the routes [35], [36], [37], [38]. Isochronous analysis is also used to form zones of accessibility to medical services within a given time threshold, which is especially useful for the visual representation of areas of access to medical services for the population. The use of such methods makes it possible to obtain an accurate picture of the accessibility of medical services for the population of communities compared to traditional Euclidean metrics.

One of the important stages of the study is the classification of territories into urban, rural, or mixed zones. This classification is used when modelling the acceptable travel time for community residents to medical facilities in accordance with health care standards, as well as for constructing differentiated scenarios for community infrastructure development. Such stratification of territories is an important condition for spatial equality and allows for targeted planning adapted to the needs of each type of settlement [33].

To calculate the travel time of the population to medical facilities, the topological properties of the road network are used, as well as the average speeds of vehicles on different types of roads, which are set in accordance with the OpenStreetMap classification. In particular, for the initial assessment of the method, an average speed of 50 km/h is used for inter-settlement roads and 30 km/h for urban areas. This approach allows the method to be quickly adapted to specific conditions without the need for complex transport simulators. If necessary, the method can be expanded in the future to include real data on traffic, weather conditions or transport restrictions.

To automate the calculations, all stages of the method are performed in the Python environment using modern open-source tools. The OSMnx library is used to download and process geodata from OpenStreetMap, which allows you to form a road network graph for a given territory [24]. Graph construction and shortest path calculation are performed using the NetworkX library, which provides extensive capabilities for analysing network topology and dynamics. GeoPandas and Pandas are used to work with spatial data and attribute tables, allowing for the efficient processing of both vector layers and tabular data [17], [18], [19]. The results are visualised on interactive maps using the Folium library, which integrates with Leaflet.js and provides users with a clear picture of the areas of access to medical services for the community.

The combination of these methods and tools ensures the flexibility, accuracy, and scalability of the method. This makes it suitable for practical application in the management of infrastructure projects at the community, district, or regional level.

4. METHOD FOR ASSESSING THE AVAILABILITY OF MEDICAL SERVICES TO THE POPULATION OF COMMUNITIES

The scientific and applied task of assessing the accessibility of medical services for the population of communities remains one of the foundations of the public health system. It is particularly relevant in the context of decentralisation, demographic imbalance and the post-war implementation of community infrastructure development projects. The proposed geoinformation method allows for a systematic assessment of how evenly and effectively access to medical care is provided to residents of different communities. Its main feature is the integration of spatial, demographic, infrastructure and topological data into a single analytical system using open sources such as OpenStreetMap and spatial modelling tools [24], [26].

The geoinformation method for assessing the accessibility of medical services in community infrastructure development projects involves 13 stages. The algorithm of the proposed method is presented in Fig. 1.

Step 1. The first stage of the proposed geoinformation method for assessing the accessibility of medical services for the population of communities is to enter the name and characteristics of the target administrative-territorial unit. That is, it only applies to the community for which the accessibility of medical services is being assessed. At this stage, the user enters the official name of the community in the format accepted in the database of the administrative-territorial structure of Ukraine. The name of the community is used as an input query for the automated import of its geometric contours from open sources, in particular from the OpenStreetMap service. In parallel with the geographical delineation, basic attributes are entered – the type of community (rural, settlement, urban), the number of settlements, the total area of the territory, the permanent population, the population density, and the availability of medical facilities. These characteristics are imported from state statistical sources (e.g., data from the State Statistics Service or the Ministry of Health) or entered manually based on previous research.

The formalisation of the community as a spatial unit is carried out in the form of a polygon that sets the boundaries of the analysed territory. This polygon serves as a framework for further loading the road network, determining the locations of settlements, and constructing an accessibility matrix. Thus, the first stage not only initialises the method, but also defines the boundaries of spatial coverage, the framework for sampling and filtering OSM data, and forms the initial demographic context for management decisions.

Step 2. The next stage of method implementation is the loading of geospatial data from the open cartographic source OpenStreetMap. This stage is fundamental for the formation of a spatial representation of road infrastructure, medical

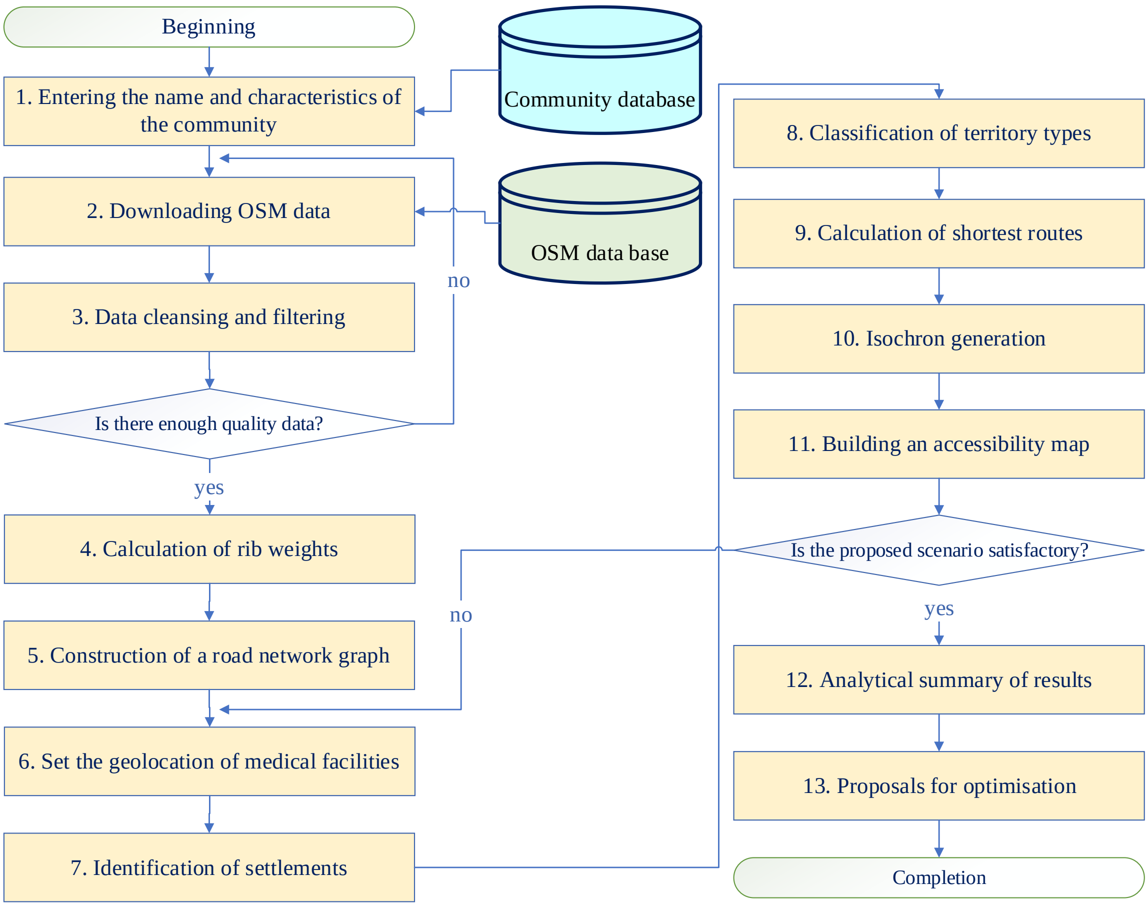

Fig.1. **Flowchart of the algorithm of the proposed geoinformation method for assessing the accessibility of medical services for the population in community infrastructure development projects**
***Source*: compiled by the authors**

facilities, and settlement boundaries. Based on this, a transport network graph is constructed and the location of medical facilities is displayed. OSM data is free, up-to-date, multi-layered and has a detailed topological structure, which makes it accurate and suitable for solving geo-analytical modelling tasks in the public sector [24].

The OSMnx library is used to download data, which allows OSM objects within a specified community polygon to be obtained via the Overpass API interface. The query is formed as a filtered query to the database, specifying the types of objects (tags) that are necessary for analysis. The main types of data extracted at this stage are:

– roads (tags highway=*), which include residential, main, secondary, rural, and dirt roads;

– medical facilities (amenity=hospital, clinic, doctors);

– populated areas (place=village, town, city);

– buildings and structures, if necessary (building=*).

The result of the download is two main geo-objects – an oriented graph of the road network and a set of point or polygonal objects of medical infrastructure. To perform this process, a module in Python was created, the diagram of which is shown in Fig. 2.

The module diagram (Fig. 2) is designed to ensure sequential loading, processing and visualization of spatial data for the selected community. First, coordinates defining the boundaries of the community territory are entered. Next, a geometric polygon is formed on their basis, which represents the community as a polygon. After that, the road network graph is loaded using OpenStreetMap tools, which allows obtaining an oriented graph of the transport infrastructure.

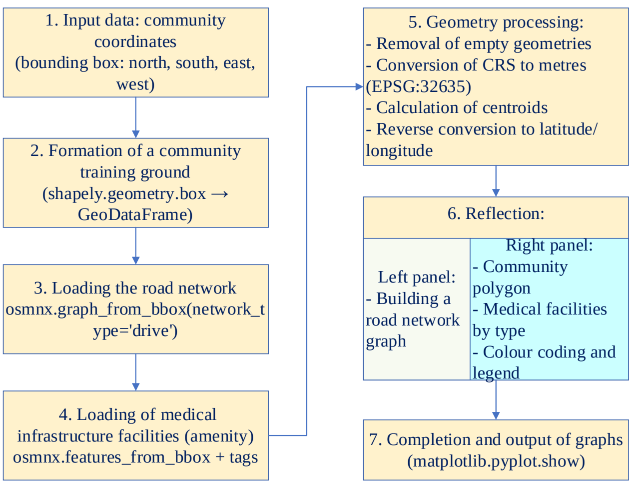

Fig.2. **Module diagram for downloading geospatial data from the OpenStreetMap open mapping service**

***Source*: compiled by the authors**

After that, a request is made to obtain point objects of medical infrastructure, such as hospitals, clinics and outpatient clinics. In order to improve the accuracy of the visual representation, the coordinates of the objects are converted into a metric system. Geometric centres are calculated, and the data is returned to the geographic coordinate system. The final stage is the construction of two graphic panels. They display the road network graph and medical facilities, broken down by type, using a colour legend placed outside the map for ease of perception.

Table 1 shows the relationship between OSM tags and the corresponding attributes used in the proposed method.

Table 1. **The relationship between OSM tags and the corresponding attributes used in the method**

OSM tag	Attribute	Purpose in the model
highway=primary	road type	Determines the speed of traffic and route priority
amenity=hospital	coordinates of the medical facility	Center of accessibility zone
place=village	Settlement point	Source of population traffic
maxspeed=*	Speed limit	Affects the weight of the graph edge
access=no	Road inaccessibility	Removed from the graph or assigned a weight

***Source*: compiled by the authors**

One of the features of this stage is the ability to dynamically update data, which is quite important for analyzing the state of communities that need infrastructure development projects.

The result of this stage is the following set D:

$$D = \{R,\ H,\ S\}, \qquad (1)$$

where R is the set of road network edges with attributes (length, type, speed); H are the coordinates of medical facilities; S are the points of settlements.

The resulting set (1) is transferred to the next stage of the method – data cleansing and filtering, followed by a quality assessment of the obtained dataset.

Step 3. After loading the initial layers from OpenStreetMap, the next mandatory stage of the geoinformation method is data cleaning and filtering. Raw data contains incorrect geometries, duplicates, empty values, or does not correspond to the specified spatial coverage. For example, in set $features\_from\_bbox$, there are objects that go beyond the specified *bounding box* due to polygonal shapes or topology errors. Therefore, there is a need to bring all geometric objects to the same coordinate system, most often EPSG:32635. It is used for further metric calculations of the time it takes for patients to reach medical facilities and the distance.

Next, a topological correctness check is performed, which is implemented, in particular, by filtering out objects with $geometry == None$ and using geometry type filtering. The following logic is used for this:

$$\begin{aligned} df \; = \; & df.geometry.notnull() \; \& \\ & df.geometry.is\_valid() \; \& \\ & df.geom\_type.isin\left(\begin{bmatrix} "Point", \\ "Polygon", \\ "MultiPolygon" \end{bmatrix}\right) \end{aligned} \quad (2)$$

where df is a data frame (table in the Python environment) containing spatial objects that have been cleaned of empty and incorrect geometries and prepared for further accessibility analysis.

This leaves only those objects that are suitable for further analysis of the population's access to medical services. In the case of polygonal medical infrastructure objects, it is advisable to calculate their centers using the centroid formula:

$$c = \frac{1}{A}\iint_S r\,dA . \quad (3)$$

where c is center (centroid) of a polygonal object; A is the area of the object; r is the position vector of the point on the surface S.

This allows all types of objects to be unified to point coordinates for routing. Table 2 shows examples of typical anomalies and corresponding data cleaning actions.

After the data cleansing and filtering stage (Step 3), the system performs a quality assessment of the obtained dataset. This verification is carried out by calculating the completeness of the data (coverage of road segments, medical facilities and settlement centroids), checking topological correctness (absence of disconnected fragments and duplicate geometries), and comparing the number of objects with the baseline statistical registers of the community. If the share of missing or invalid objects exceeds the threshold of 5%, the dataset is considered insufficient and the workflow is redirected to an additional data update from the OpenStreetMap source. Otherwise, the process continues to the calculation of edge weights.

Table 2. **Typical anomalies and corresponding data cleaning actions**

Error Type	Example	Handling Method
Empty geometry	geometry = None	Remove the row
Invalid topology	Self-intersecting polygons	df.geometry = df.buffer(0)
Unnecessary geometry types	LineString, GeometryCollection	Filter using df.geom_type.isin()
Duplicate records	Objects with identical coordinates	df= df.drop_duplicates()

***Source*: compiled by the authors**

Step 4. At the stage of calculating rib weights, the geometric road network graph is transformed into a weighted one, which allows routing to be performed taking into account transport characteristics.

Edge weights are interpreted as the time or distance traveled by vehicles along the corresponding road segments. The basic formula for calculating edge weight is:

$$w_{ij} = \frac{l_{ij}}{v_{ij}} . \quad (4)$$

where w_{ij} is the edge weight between nodes *i* and *j*, c; l_{ij} is the road length, m; v_{ij} is the speed, m/s.

If maxspeed is not specified in the OSM data, then the speed is assigned according to the typical value for the road type. Table 3 provides examples of the correspondence of vehicle speeds during the delivery of patients to medical facilities depending on the road type.

Table 3. **Examples of vehicle speeds when transporting patients to medical facilities depending on road types**

Road Type (OSM highway)	Typical Speed, km/h	Comment
motorway	110	National highways
primary	60	Regional roads
residential	30	Streets within populated areas
service	20	Private roads, driveways

***Source*: compiled by the authors**

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Step 5. The length of each edge is calculated automatically using function $ox.add\_edge\_lengths$. Then, a weight function is applied, which stores the values in field $travel\_time$. Thus, each edge of the road network graph acquires characteristics that allow the use of shortest path algorithms (Dijkstra) in the future, taking into account not only the geometry but also the actual duration of vehicle movement during the delivery of patients to medical facilities.

Step 6. The next step is to spatially locate medical infrastructure objects on the map of the study area using OpenStreetMap tags, in particular $amenity = hospital$, $amenity = clinic$, and $amenity = doctors$. For each object found, the coordinates of the centroid of the geometry are recorded, which allows these points to be used as destination nodes in routing.

To improve the quality of the analysis, it is important to remove duplicates, objects without geometry, and establishments located outside the community polygon. These filters are performed using the Geopandas library.

If the geometry of an object is a polygon (e.g., the outline of a hospital), then the center coordinates (x_c, y_c) are calculated as:

$$(x_c, y_c) = \left(\frac{1}{A} \int_A x dA, \frac{1}{A} \int_A y dA \right), \qquad (5)$$

where A is the area of the polygon; x and y are the coordinates of the points on the boundary.

For point objects, their direct geocoordinate values are used.

The data is obtained using functions $ox.features\_from\_polygon()$ or $ox.features\_from\_bbox()$ after the community polygon has been formed. The coordinates (latitude and longitude) are given in the WGS84 system (EPSG:4326) and are used for further route calculations or determining isochronous accessibility. The formed set of geolocations of medical facilities allows them to be used as destination nodes in algorithms for finding the shortest routes and constructing isochrones.

Step 7. At the stage of identifying settlements, points are selected that represent the centers of settlements that are part of the corresponding territorial community. These points serve as sources of potential demand for medical services and are the starting nodes in the spatial analysis model. Data on settlements are obtained from OpenStreetMap by querying objects with the tag $place = *$, where $place = village$, $place = town$ or $place = city$, depending on the type of settlement.

The formula for determining the geodetic distance to a medical facility (in the absence of a graph) is expressed using a spherical model of the Earth:

$$d = R \cdot arccos \begin{pmatrix} sin\phi_1 \cdot sin\phi_2 + cos\phi_1 \cdot \\ \cdot cos\phi_2 \cdot cos(\lambda_2 - \lambda_1) \end{pmatrix}, \qquad (6)$$

where ϕ_1, ϕ_2 are latitude of the settlement and medical facility; λ_1, λ_2 – longitude of the settlement and medical facility; R is radius of the Earth ($R \approx 6371$ km).

In our study, the use of a more simplified planar model is considered inappropriate because such an approach ignores the real curvature of the Earth's surface and the heterogeneity of the transport network. While planar models may be effective within the boundaries of large cities with a high density of medical facilities, where the scale is limited and distortions are minimal, their application at the community or regional level leads to significant inaccuracies in accessibility assessment. The use of a spherical model of the Earth allows for the correct calculation of geodetic distances between settlements and medical facilities, taking into account latitude and longitude, which is especially important for sparsely populated or extended territorial communities. Thus, although planar models may save computational resources in urban environments, in our case the use of geodetic calculations ensures greater accuracy and reliability of results for strategic community infrastructure development planning.

Completion of this stage is the basis for moving on to the next stage – assessing transport accessibility and constructing zones of reachability for medical services.

Step 8. The stage of classifying types of territories consists of spatially dividing the community's territory into categories. These categories characterize its functional use, building density, and accessibility of transport infrastructure. This classification is necessary for further consideration of typical scenarios for vehicle movement, traffic speeds, population density, and access restrictions when modeling the reachability of communities to medical services. This approach is based on the integration of OpenStreetMap cartographic layers with satellite imagery, cadastral data, and open statistical resources.

The method provides for the identification of at least three main types of territories: densely built-up urban areas, rural settlements, and sparsely populated or forested areas. In practice, this division is implemented by filtering by tags $landuse = *$, $place = *$, $building = *$. The types of territories within a territorial community are presented in Table 4.

Table 4. **Types of territories within the territorial community**

Category	Selection Criteria	Example OSM Tags	Acces-sibility Coefficient
Urban dense development	Presence of buildings, roads, healthcare facilities	building=*, highway=*, amenity=*	1.0
Rural development	Individual houses, agricultural lands	place=village, landuse= farmland	0.75
Forested or sparsely populated	Absence of development, dominance of natural features	landuse= forest, natural=*	0.5

***Source*: compiled by the authors**

The classification also provides for the assignment of accessibility coefficients that take into account travel conditions and vehicle speeds in different areas.

These coefficients are then used to modify the weights of the transport graph edges according to the formula:

$$w' = \frac{w}{k}. \tag{7}$$

where w is base weight of the rib, for example, inversely proportional to the speed of vehicles during the delivery of patients to medical facilities; w' is modified weight taking into account the type of territory; k is accessibility coefficient, reflecting travel conditions depending on the type of territory (densely built-up urban areas, rural settlements, forested or sparsely populated areas).

Thus, the classification of territory types serves as a bridge between geospatial data and behavioral scenarios of access to medical services for the community population, ensuring the method's adaptability to different local conditions.

Step 9. The next stage involves calculating the shortest routes. This is the main stage in the method for assessing the accessibility of healthcare services to the community population. It is this stage that allows us to determine the time or distance required to reach the nearest healthcare facility from each settlement in the community. For this purpose, an oriented road network graph is used. It is based on OpenStreetMap data. In it, nodes represent intersections or changes in direction, and edges represent individual road segments with weights that take into account length, speed limits, and type of territory.

Optimal routes are determined using shortest path search algorithms, in particular Dijkstra's algorithm. The input parameters are the coordinates of points (e.g., a village or town in a community) and the nearest hospital, projected onto the graph nodes. The calculation itself is performed using functions from the Networkx library, where the minimum weight metric is applied:

$$d(u,v) = min\sum_{i=1}^{n} w_i. \tag{8}$$

where $d(u,v)$ is the length of the shortest path between vertices u and v; w_i is the weight of each edge of the route, which takes into account the length, speed of movement, and type of terrain according to the classification performed at the previous stage.

The choice of Dijkstra’s algorithm in this study is due to the specifics of the task — the need to determine the shortest paths on a weighted, oriented road graph with non-negative edge weights. Dijkstra’s algorithm guarantees finding the optimal solution for such conditions and is widely implemented in modern geoinformation libraries (in particular, NetworkX), which ensures reproducibility and transparency of calculations. Compared to heuristic algorithms such as A (A-star), Dijkstra’s algorithm does not require the definition of an admissible heuristic function, which may be non-trivial in the context of heterogeneous transport networks of communities. At the same time, compared to algorithms for approximate search, it provides exact results, which is critical when assessing accessibility for healthcare services.

In the case of highly branched graphs with a large number of edges and nodes, the computational complexity of Dijkstra’s algorithm may increase significantly. To address this, several optimization strategies can be applied: restricting the area of analysis to a buffer zone around the community of interest; using precomputed shortest-path trees; or applying bidirectional search to halve the number of iterations. In practice, the road networks of territorial communities have a moderate density compared to metropolitan transport systems, so the use of Dijkstra’s algorithm remains computationally feasible and justified, while ensuring the required accuracy of results.

Step 10. At the isochron generation stage, reach zones are constructed around medical infrastructure facilities for visual analysis of the level of accessibility for the community population.

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Isochrones are polygons covering all points that can be reached from a given facility (e.g., a hospital) within a specified time interval or at a certain distance along the road network. This allows us to identify those settlements that fall within the standard travel time. From a mathematical point of view, an isochrone is a set of vertices v of a graph $V \subseteq G$ such that:

$$V = \{ v \in G | \ d(v,s) \leq T \}. \tag{9}$$

where $d(v,s)$ is the shortest route length from node s (medical facility) to node v (patient location); T is the time limit.

Isochrones are constructed by searching for the optimal radius of patient service by the hospital, taking into account the weights of the edges in the road network graph. Distance or time indicators stored in the graph edge attributes are used.

The generation of isochrones allows for the visual identification of gaps in coverage and the optimization of the location of new medical facilities, which is especially important in conditions of uneven spatial distribution of community settlements.

Step 11. After constructing isochrones, the next logical step is to create an integrated map of accessibility to medical infrastructure facilities for the community population. This stage provides an assessment of the population's access to health services, taking into account the transport network, travel time, and the geographical location of settlements.

To build an accessibility map, a methodology is used to aggregate the results of routing or isochronous analysis into a single geospatial model. Each point (e.g., a grid cell on the map or the center of a settlement) is assigned an accessibility value, which is defined as the minimum distance to the nearest medical facility or the time required to reach it. If we denote the coordinates of point x_i and the distance to medical facility j as d_{ij}, then the accessibility index value A_i for point x_i is determined as:

$$A_i = min_j \left(d_{ij} \right). \tag{10}$$

where $j = 1,2,...,m$ is the number of medical facilities.

If the travel time of patients to the hospital is taken into account instead of the distance, a similar formula can be used, replacing d_{ij} with t_{ij} – the duration of the trip.

When building models of accessibility to medical facilities, standardized travel time limits (in minutes) are used, which correspond to accepted standards of accessibility in the field of healthcare [20], [21], [22]. These values may vary depending on the type of medical care, population density, and territorial conditions. However, there are general guidelines recommended by the WHO [41], the European Commission [42], and spatial medicine practitioners [43], which are presented in Table 5.

The standard values for the travel time of the population to medical facilities take into account the average speed of motor vehicles in rural and urban areas. In cities, the average speed is assumed to be 30–40 km/h, and in rural areas, up to 60 km/h.

These standards allow for the formation of coverage zones and the construction of isochrones, which visually reflect the boundaries of healthcare facility accessibility on an accessibility map. Thus, standard values are used both for operational analysis of the accessibility of medical services for the population and for strategic planning of the development of medical services at the community, district, or regional level [23].

At the branching stages of the algorithm (Fig. 1), two control checks are provided. The first decision block “Is there enough quality data?” is evaluated on the basis of completeness and

Table 5. **Accepted standards of accessibility for the population of communities to medical facilities**

Type of Medical Facility	Recommended Maximum Travel Time (min)	Purpose
Primary care outpatient clinic	15-20 minutes	Daily services, consultations, non-complicated cases
Polyclinic or medical center	up to 30 minutes	Specialist consultations, planned diagnostics
Secondary-level hospital	up to 45 minutes	Inpatient care, basic surgery, therapy
Intensive care hospital	up to 60 minutes	Emergency care, resuscitation, childbirth, serious injuries
Regional medical center / tertiary hospital	60-90 minutes	Highly specialized care, transplantations, complex interventions

***Source*: compiled by the authors**

correctness of geospatial data imported from OSM and statistical sources. If critical anomalies are detected (e.g., missing geometries, incorrect coordinates, or incomplete population statistics), the process returns to the stages of data cleansing and community database formation. The second decision block "Is the proposed scenario satisfactory?" is determined by comparing calculated accessibility indicators with regulatory standards (Table 5) and by evaluating error metrics such as MAE. If the model reveals excessive deviations or large uncovered areas, the algorithm redirects to optimisation stages, where alternative locations of medical facilities or road improvements are tested. These branching conditions ensure the adaptability of the method and allow iterative refinement until acceptable results are achieved.

Step 12. An analytical summary of the results of the study of the accessibility of medical facilities for the population of the Chervonohrad city territorial community makes it possible to determine whether all settlements have a normative level of accessibility to healthcare facilities. To this end, the minimum travel time to the nearest medical facility is calculated based on the OpenStreetMap road network graph, taking into account the lengths of the sections and the average speeds of vehicles. For each settlement in the community, the shortest route to the nearest medical facility is determined. The duration of the trip is calculated using the weighted shortest path method:

$$T_i = min_j \left\{ \sum_{(u,v)\in P_{ij}} \frac{L_{uv}}{v_{uv}} \right\}. \quad (10)$$

where T_i is the minimum travel time for patients from the *i*-th settlement to the medical facility; P_{ij} is a set of edges on the shortest path to the *j*-th medical facility; L_{uv} is the length of the section between nodes u and v; v_{uv} is the average speed of movement on a given section.

Step 13. At the final stage of the implementation of the geoinformation method, a comprehensive assessment of its effectiveness is carried out from the point of view of its practical applicability in the planning and implementation of community infrastructure development projects. Such an assessment is necessary to determine the extent to which the developed method allows for the accurate and timely identification of spatial disparities in the population's access to medical infrastructure, as well as to make informed management decisions regarding the optimal location of medical facilities.

In addition to tabular analysis, an integrated indicator of the accessibility of medical services for the community is used, which takes into account the ratio between the normative and calculated travel time to medical facilities. It is determined by the formula:

$$E_m = \frac{1}{n} \sum_{i=1}^{n} \frac{T_n(i)}{T_f(i)}. \quad (11)$$

where $T_n(i)$ is standard travel time for the population to reach the *i*-th medical facility; $T_f(i)$ is actual travel time for the population to reach the *i*-th medical facility, calculated using the proposed method; n is number of settlements in the community.

An average value of $E_m \approx 1$ indicates that the community's access to medical services is fully compliant with current standards. Exceeding this indicator indicates excess infrastructure capacity. If the value is $E_m < 1$, this is a basis for implementing community infrastructure development projects [39], [40].

Thus, two groups of evaluation criteria are distinguished: 1) coverage-oriented indicators that measure the effectiveness of healthcare accessibility for the population (e.g., the integral index E_m); 2) accuracy-oriented indicators that assess the adequacy of the geoinformation model itself (e.g., MAE). Their combined application provides a comprehensive assessment of both the quality of the model and the sufficiency of healthcare services in the community.

The proposed geoinformation method allows for a more accurate assessment of the accessibility of medical services for the population of communities. Compared to existing methods, accuracy is improved by taking into account the actual configuration of roads, the spatial location of medical facilities, and the characteristics of polygonal boundaries of settlements. As a result of using the proposed method, the accuracy of calculations is increased through the use of modern flexible open tools. This allows for the identification of critical areas where there is a discrepancy with current standards for public access to medical facilities. The recommendations developed for project managers form the basis for planning community infrastructure development projects.

5. EXPERIMENT RESULTS

Based on the use of the developed geoinformation method, the accessibility of medical services for residents of the Chervonohrad urban community (Lviv region) was assessed. To determine the adequacy of the proposed method for assessing the accessibility of medical services, the modeling results were compared with the actual values for the conditions of the given community, obtained through the analysis of cartographic services. This allows us to establish how accurate the method is and whether it can be used as a reliable tool for making management decisions when planning community infrastructure development projects.

The main criterion for assessing the accuracy of the method is the mean absolute error (MAE), which is determined by the formula:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| . \qquad (12)$$

where y_i is actual (real) value for the i-th settlement; $\hat{y}_i$ is value obtained based on the method; n is total number of observations.

The assessment was carried out for two indicators: distance in kilometers and travel time in minutes. Actual values were collected for each settlement by determining the shortest route to the nearest medical facility using Google Maps. In turn, the modeling results were obtained using a geoinformation method created based on data from the OpenStreetMap service.

Table 6 shows the results of a comparison of indicators of population access to medical services for several settlements in the Chervonohrad urban community. It should be noted that the Chervonohrad urban territorial community consists of 14 settlements in total (including cities, towns, and villages). In this study, the assessment was carried out for 5 settlements (36 % of the total number), which makes it possible to verify the adequacy of the proposed method on a representative sample. At the same time, this limitation highlights the need for future research to expand the analysis to all settlements of the community and to perform a statistical power analysis to formally justify the sufficiency of the sample size.

The above formula (12) was used to calculate the error:

$$MAE_{dist} = \frac{1}{5}\left(0.3+0.2+0.2+0.2+0.5\right) = 0.28\ km.$$

Similarly, the average absolute error for the time it takes the population to reach medical facilities:

$$MAE_{time} = \frac{1}{5}\left(1+1+0+1+1\right) = 0.8\ min.$$

Table 6. **Results of comparing actual indicators and indicators obtained using the method for assessing the accessibility of medical services**

Settlement	Distance (method), km	Distance (actual), km	Time (method), min	Time (actual), min
Silets	4.5	4.2	7	6
Dobryachyn	8.2	8.4	12	13
Hirnyk	3.5	3.3	5	5
Volsvyn	6.3	6.5	9	10
Boryatyn	11.6	11.1	18	17

***Source*: compiled by the authors**

The MAE values obtained indicate the high accuracy of the proposed method. The deviations are within 1 minute or 0.3 km. This is acceptable for the task of assessing the population's access to medical services. Thus, the proposed geoinformation method is adequate. That is, it is capable of accurately reflecting the real accessibility of the population to medical facilities within the community.

Within the Chervonohrad municipal community, 14 settlements were automatically selected, including the city of Sheptytskyi, the town of Hirnyk, and the villages of Silets, Benduga, Hirnyk, and others (Table 7). Their coordinates are converted to the GeoDataFrame format, which allows these objects to be integrated into spatial calculations using the Geopandas and Osmnx libraries.

Table 7. **Geographic coordinates of settlements in the Chervonohrad urban community**

Settlement Name	Type	Latitude (lat)	Longitude (lon)
Sheptytskyi	city	50.39176	24.23402
Sosnivka	city	50.39102	24.26265
Hirnyk	urban-type settlement	50.37583	24.24475
Silets	village	50.42095	24.19853
Bendyuga	village	50.40116	24.22261
Berezhne	village	50.34771	24.24380
Boryatyn	village	50.33896	24.25170
Volsvyn	village	50.41687	24.26417
Horodyshche	village	50.31425	24.25311
Dobryachyn	village	50.34596	24.20703
Mezhyrichchia	village	50.35483	24.22945
Ostriv	village	50.33047	24.21289
Pozdymyr	village	50.32278	24.27654
Rudka	village	50.31066	24.23128

***Source*: compiled by the authors**

Fig.3. **Results of downloading road network layers (left) and medical facilities (right) from the OSM service**

***Source*: compiled by the authors**

Using the developed software modules, geospatial data was downloaded from the open cartographic source OpenStreetMap. This made it possible to obtain basic types of data (roads, medical facilities, settlements, buildings and structures, etc.). The results of downloading layers of the road network (left) and medical facilities (right) from the OSM service for the Chervonohrad community in the Lviv region are shown in Fig. 3.

Table 8 shows the coordinates of medical facilities obtained from OpenStreetMap within the Chervonohrad city territorial community. They were selected by the tags $amenity = hospital$, $amenity = clinic$ та $amenity = doctors$. All objects underwent an initial check for the presence of coordinates and inclusion within the community boundaries.

Fig. 4 shows the results of data filtering. Red indicates objects that were left, and gray indicates those that were removed as a result of filtering by spatial and semantic criteria.

Thus, data cleaning is a very important step that ensures the reliability and accuracy of the subsequent stages of analyzing the accessibility of medical services for the population of communities.

Fig. 5 shows road segments colored according to the calculated duration of vehicle travel when transporting patients to medical facilities.

Table 8. **Geographical coordinates of medical facilities obtained from OpenStreetMap within the Chervonohrad city territorial community**

Facility Name	Type (amenity)	Longitude (lon)	Latitude (lat)
Municipal Non-Profit Enterprise "Chervonohrad City Hospital"	hospital	24.23402	50.39176
Chervonohrad Children’s Hospital	hospital	24.22957	50.39241
Outpatient Clinic of Chervonohrad City Hospital	clinic	24.23385	50.39308
Medical Center “Dobrobut”	clinic	24.23811	50.38612
Private Family Doctor’s Office	doctors	24.23544	50.38803
General Practice Outpatient Clinic, Silets	clinic	24.19853	50.42095
Feldsher-Obstetric Station (FAP), Bendyuga	clinic	24.22261	50.40116
Pharmacy Point with Medical Consultation	doctors	24.24007	50.38902

***Source*: compiled by the authors**

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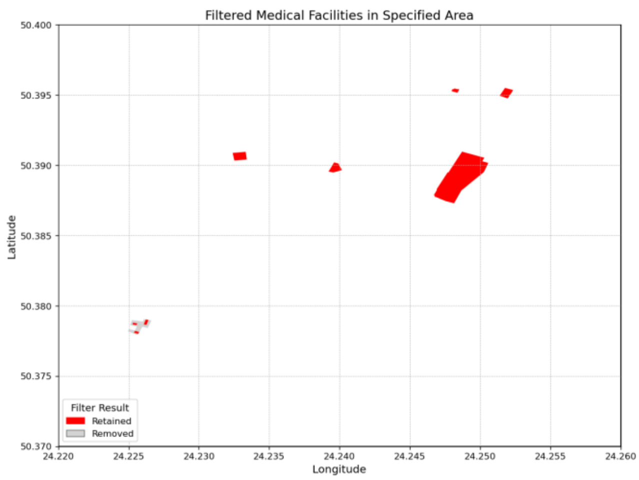

Fig.4. **Visualization of the results of filtering community medical infrastructure objects**

***Source*: compiled by the authors**

Thus, the construction of a weighted graph creates the basis for further modeling the accessibility of medical facilities for the population of communities, as well as identifying critical areas with excessive travel times for patients to medical facilities.

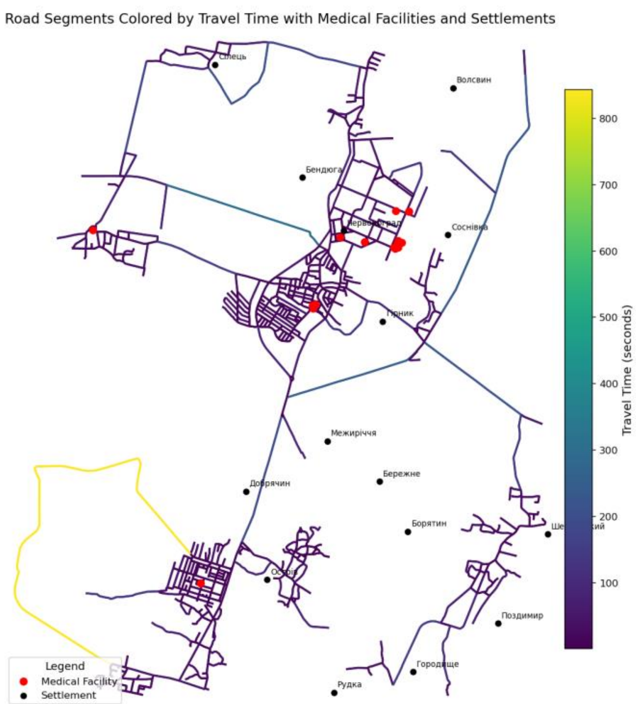

Fig.5. **Visualization of rib weights based on the criterion of patient arrival time at medical facilities**

***Source*: compiled by the authors**

Fig. 6 visually depicts the main types of territories based on layers from OSM.

The general healthcare facility in the Chervonohrad urban community, which is the Chervonohrad City Hospital, must serve the community population within a 45 km radius, and the time of arrival at the medical facility must not exceed 45 minutes.

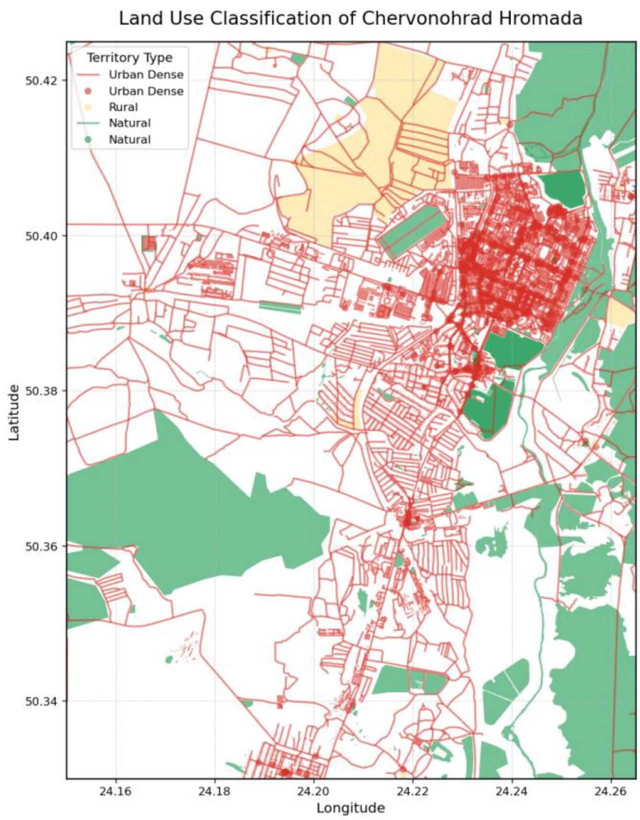

Fig.6. **Visualization of territory types based on layers from OpenStreetMap**

***Source*: compiled by the authors**

Fig. 7 shows the spatial reach zones (isochrones) of three key medical facilities within the Chervonohrad urban community. Isochrones represent conditional territories from which community residents can reach the relevant medical facility within 45 minutes by car. To construct the isochrones, a road network generated based on OpenStreetMap data was used, and the boundaries of the zones were determined taking into account the accessibility graph based on the shortest route length.

On the graph, each medical facility is represented by a colored star, the color of which corresponds to the shade of the isochronous zone and the legend at the bottom of the image. In particular, yellow indicates the zone of accessibility to the Chervonohrad City Hospital, blue indicates the Chervonohrad Children's Hospital, and green indicates the Chervonohrad Hospital Polyclinic. The semi-transparent fill of each isochronous zone visualizes the territories that do not fall within the coverage radius, calculated based on the Euclidean distance on the road graph.

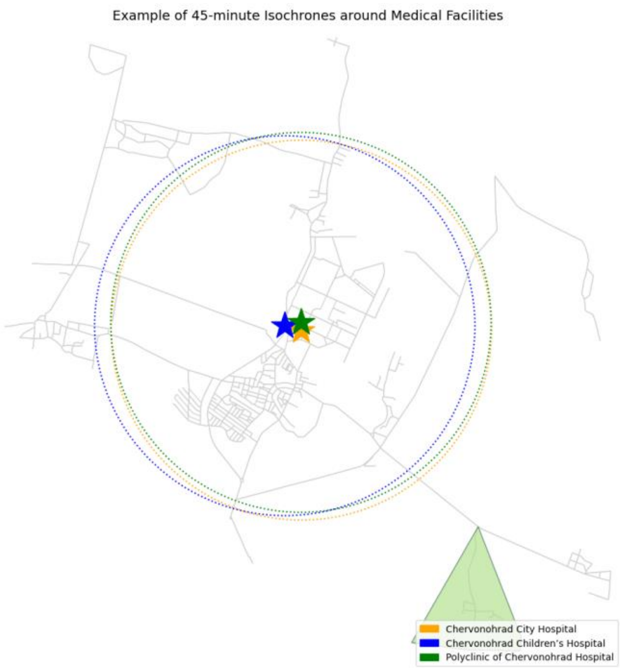

Fig.7. **Visualization of the 45-minute isochron of accessibility to medical facilities**
***Source*: compiled by the authors**

It should be noted that the isochrones in Fig. 7 were constructed only for the key medical facilities providing secondary healthcare (the City Hospital, the Children’s Hospital, and the Polyclinic). Other facilities listed in Table 8 (such as outpatient clinics, feldsher stations, private practices, and pharmacy consultation points) represent local providers of primary care and therefore were not included in this stage of visualization. Their integration into the accessibility model will be the subject of further research.

The boundary radius is marked to visually distinguish the areas of influence of each medical center. As can be seen from the image, the isochronous zones partially overlap, which indicates the possible duplication of medical services in some parts of the city and also allows identifying areas with insufficient accessibility. The constructed figure allows assessing the effectiveness of the spatial location of medical facilities and can be used for further management decisions regarding the development of the community's medical infrastructure.

Graphical visualization of settlement points is presented on the road network map to control the spatial correctness of their location (Fig. 8). In the geoinformation method, these points play the role of route starting points when calculating the time and distance to the nearest medical facilities.

An accessibility map was created using the example of the Chervonohrad urban community (Fig. 8). It shows the extent to which the community's territory is covered by medically accessible facilities. It is presented as a thematic map with the boundaries of settlements and roads superimposed and the accessibility of medical services classified according to the maximum travel time to the nearest medical facilities.

The map of accessibility of medical facilities for the population is a valuable tool in planning community infrastructure development projects. It allows for informed management decisions to be made regarding the creation of new facilities or the modernization of transport links to remote settlements.

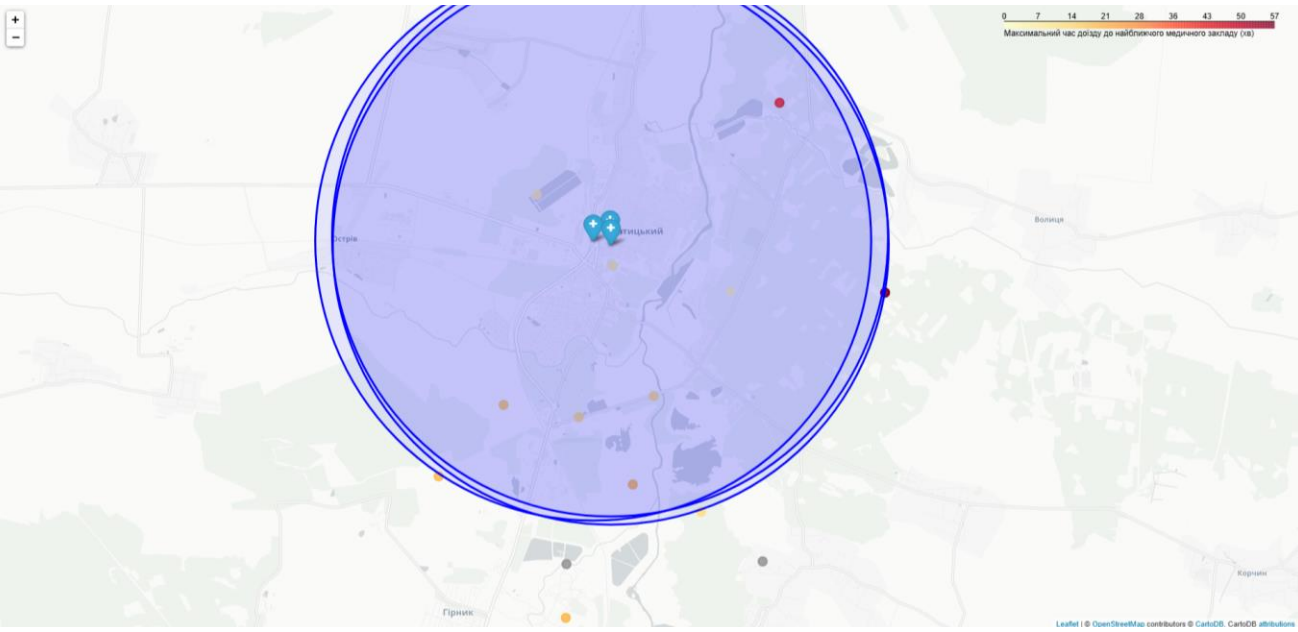

Fig.8. **Results of creating a map of the accessibility of the population of the Chervonohrad urban territorial community to medical facilities**
***Source*: compiled by the authors**

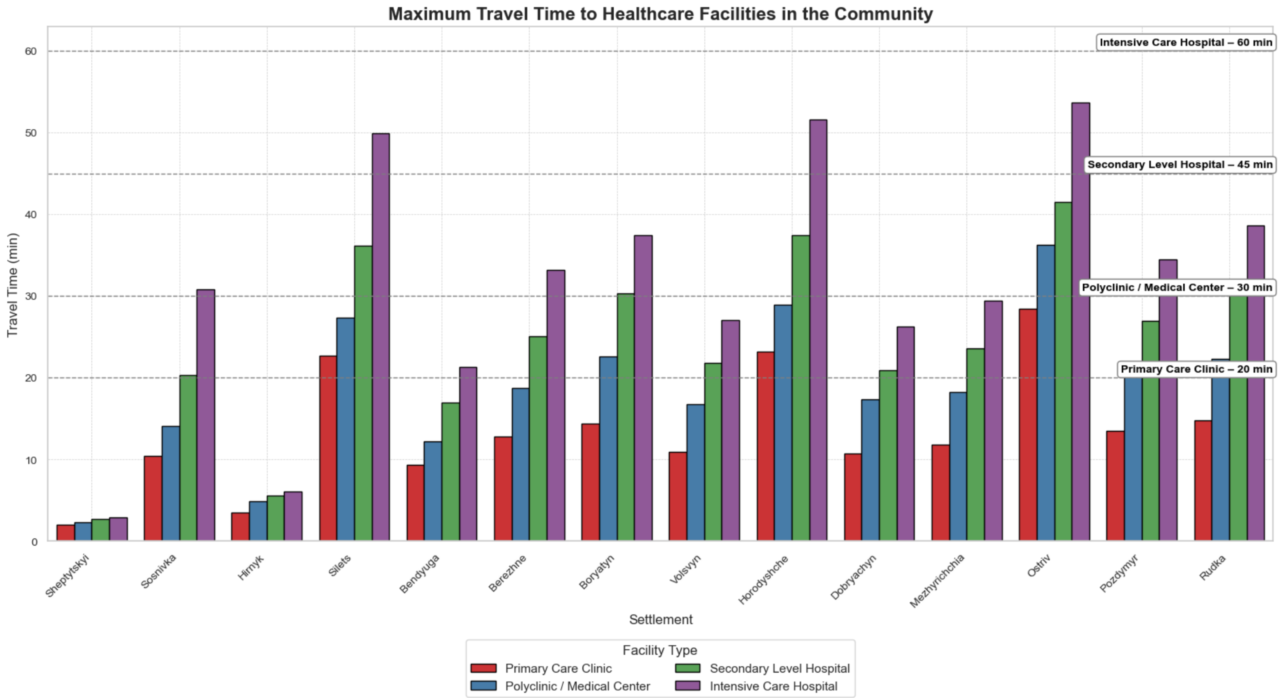

Fig.9. **Histogram of maximum travel time for residents of individual settlements in the Chervonohrad urban community to the nearest medical facility**
***Source*: compiled by the authors**

An analytical summary of the results of a spatial analysis of the accessibility of medical facilities in the Chervonohrad municipal community showed varying levels of access to medical services among the population.

The visualization obtained on the basis of geoinformation modeling (Fig. 8) shows the areas covered by medical facilities in the city of Sheptytskyi. This city has the largest number of medical institutions of various levels – outpatient clinics, polyclinics, and secondary hospitals. Accordingly, settlements such as Sheptytskyi, Hirnyk, and Benduga are within easy reach of both primary care medical facilities and secondary and intensive care hospitals.

As a result of the modeling, the maximum travel time for the population from individual settlements of the community to the nearest medical facility was determined (Fig. 9).

An analysis of Fig. 9 shows significant spatial inequality in the level of access to medical services within the community under study. The best indicators are observed for the population of Sheptytskyi, where the travel time to any type of medical facility does not exceed 3 minutes. This is logical given the presence of medical facilities directly within this settlement.

For villages such as Hirnyk, Benduga, Volsvyn, and Dobryachyn, the situation is relatively favorable, as access to all types of medical facilities is provided within 6 to 27 minutes. This fully complies with the regulatory limits of accessibility for outpatient, polyclinic, and secondary medical care.

At the same time, some settlements, in particular Silets, Gorodishche, and Ostrov, show significant time spent by the population on traveling to medical facilities, ranging from 49 to 54 minutes in the case of needing to get to secondary level hospitals. Such indicators exceed the permissible standards and indicate potential risks for the timely provision of emergency care.

In particular, for the village of Ostrov, the travel time to the clinic is 28.4 minutes, which exceeds the recommended threshold (15–20 minutes). A similar situation is observed in the village of Gorodishche. This poses a challenge for the healthcare system, especially given the need for rapid response in urgent situations.

Based on the use of the proposed geoinformation method for assessing the accessibility of medical services for the project environment of the Chervonohrad urban territorial community, recommendations for the implementation of community infrastructure development projects have been formulated (Table 9). These recommendations are not generated automatically by the system but are developed by experts, taking into account the results of spatial analysis, the assessment of the population's travel time to various types of medical facilities, and the identification of areas with critical access to medical services.

It has been established that in the villages of Ostrov and Gorodishche, the travel time of the population to outpatient clinics is more than 30 minutes, which significantly exceeds the norm of 15–20 minutes. This indicates the need to create new primary health care centers in their territory or to introduce mobile medical services.

A similar situation exists in the village of Silets, where the maximum travel time for the population to reach a secondary hospital exceeds 49 minutes. This confirms the feasibility of strengthening the community's infrastructure hubs. In particular, the creation of a stabilization medical center in Sosnivka, which is geographically close to the eastern villages and can become a point of concentrated medical care.

The introduction of a dynamic geoinformation model for monitoring the population's access to medical services in real time will make it possible to identify local overloads and emergency areas and quickly change available resources. This is especially relevant in conditions of war or post-war, when the project environment is changing dynamically.

Given that most violations of the standard travel time for the population to medical facilities are related to poor road quality, it is necessary to invest in the overhaul and asphalting of rural roads. Based on the results obtained, roads should be reconstructed (Silech – Chervonohrad, Dobryachyn – Sosnivka), which will reduce the average travel time to medical facilities by 8–12 minutes.

Integrating indicators of population access to medical services into the strategic management system of the Chervonohrad city territorial community makes it possible not only to respond to changes in the project environment, but also to proactively plan community infrastructure development projects, taking into account the level of access to basic services for its population.

In contrast, the proposed geoinformation method focuses on the integration of open geospatial data (OpenStreetMap, OSMnx, NetworkX) and network analysis to calculate travel times and generate isochrones. This ensures higher accuracy in conditions where transport infrastructure is heterogeneous and rapidly changing. Unlike gravity models, our method explicitly accounts for road

Table 9. **Recommendations for project managers for the implementation of infrastructure development projects in the Chervonohrad urban community**

No.	Recommendation	Type of Intervention	Justification
1	Establish an outpatient clinic or Feldsher-Obstetric Station (FAP) in the villages of Ostriv and Horodyshche	Expansion of primary care network	Travel time to medical facilities exceeds 30 minutes, which is above the norm for outpatient care
2	Optimize transportation routes to community hospitals	Transport and logistics reconfiguration	In most villages (Silets, Mezhyrichchia, Rudka), access to hospitals exceeds 45 minutes
3	Build a stabilization medical center in Sosnivka	Establishment of a subregional medical center	This is the largest city in the community and can serve the eastern periphery
4	Implement GIS-based monitoring of population access to healthcare services	Digitalization of the community healthcare system	The geoinformation method showed uneven distribution of access-dynamic control is required
5	Perform spatial optimization of emergency medical service locations	Reorganization of ambulance service points	Some villages (Pozdymyr, Dobryachyn, Berezhne) exceed the standard travel time to medical facilities
6	Develop an infrastructure program to restore rural roads	Capital investment in road infrastructure	The current road network does not support normative travel times under existing speed limits
7	Integrate healthcare accessibility indicators into the community’s strategic planning system	Strategic management of community infrastructure projects	The GIS model formalizes healthcare accessibility and should be considered in master planning

***Source*: compiled by the authors**

topology and travel time standards, and compared to 2SFCA, it requires less statistical input while still identifying underserved areas (‘grey zones’). Therefore, the method is particularly effective for operational planning in communities with limited resources and urgent needs for healthcare system restoration.

CONCLUSIONS AND PROSPECTS OF FURTHER RESEARCH

A geoinformation method has been developed to assess the accessibility of medical services in community infrastructure development projects. It involves 13 stages based on a network representation of road infrastructure, topological analysis of routes, and the construction of isochrones. The method allows for the automated calculation of the minimum distance and approximate travel time for residents from each community settlement to the nearest medical facility, taking into account standards and the type of facility. This is achieved through a combination of geanalytics methods, network analysis algorithms, and open data sources such as OSM. As a result of using the proposed method, areas of the community with insufficient access to medical services are systematically identified. This ensures accurate management decisions regarding the assessment of access to medical services in community infrastructure development projects.

Based on a well-founded geoinformation method, software modules have been developed for each stage of assessing the accessibility of medical services, including the construction of a road network graph based on OpenStreetMap data, the identification of the nearest nodes between community settlements and medical facilities, the calculation of the shortest route matrix, generating isochrones of reachability, and visualizing the results of community residents' access to medical services on a map. All modules are implemented using the OSMnx, NetworkX, GeoPandas, and Matplotlib libraries, which ensures their scalability and adaptability to other territorial communities.

We verified the adequacy of the proposed method for assessing the accessibility of medical services using the MAE criterion. To do this, we compared the modeling results with the actual values for the given community, obtained by analyzing cartographic services. The obtained quantitative MAE values indicate the high accuracy of the proposed method. The deviations are within 1 minute or 0.3 km. This is acceptable for the task of assessing the accessibility of medical services in community infrastructure development projects, given possible GPS errors, inaccuracies in the road network, and changing road conditions.

It should be emphasized that the choice of Dijkstra’s algorithm and the geodetic model was determined by the need to balance accuracy and computational feasibility. While the use of Euclidean or Manhattan distances and a planar model would reduce the computational load, they would introduce systematic distortions by ignoring the actual road network structure and the Earth’s curvature. In the case of community-level studies, the deviations caused by such simplifications may exceed the permissible error thresholds for management decisions. At the same time, Dijkstra’s algorithm, although more resource-demanding, remains computationally feasible for the scale of a territorial community and provides exact solutions on the weighted road graph. Future research will include a comparative analysis of the computational efficiency of these approaches to further justify the choice of the method.

The method was tested experimentally using the example of the Chervonohrad urban community. It was found that over 85% of the community's population has access to medical facilities. However, in the villages of Ostrov and Gorodishche, the travel time to outpatient clinics is more than 30 minutes, which significantly exceeds the norm. This indicates the need to create new primary health care centers in their territory or to introduce mobile medical services. In the village of Silets, the maximum travel time for the population to reach a secondary hospital exceeds 49 minutes. This confirms the feasibility of strengthening the community's infrastructure hubs. In particular, the creation of a stabilization medical center in Sosnivka, which is geographically close to the eastern villages and can become a point of concentrated medical care.

Recommendations have been formulated based on the use of the proposed geoinformation method for assessing the accessibility of medical services for the project environment of the Chervonohrad city territorial community. These recommendations enable project managers to improve the efficiency of planning the implementation of community infrastructure development projects.

The developed geoinformation method for assessing the accessibility of medical services for community residents is the basis for planning the implementation of community infrastructure development projects. One of the priority areas for future research is the integration of demographic and socio-economic characteristics of the population into the method. This will allow for the consideration of not only the geographical but also the social accessibility of medical services for community residents. This is particularly relevant for rural regions with uneven population density, high levels of aging residents, or limited transport links.

Another promising area is the expansion of the method to include data on traffic intensity, road surface quality, and seasonal changes in access to medical services. Taking these factors into account will make it possible to more accurately assess the actual time spent by residents traveling to medical facilities and will facilitate management decisions on the prioritization of investments in community infrastructure development projects.

Despite its advantages, the proposed geoinformation method has certain limitations. It was primarily designed for medium-sized communities where the distances to medical facilities range from 10 to 20 km. In large urban settlements, where the average distance to healthcare facilities is below 5–10 km, the method may be less sensitive to micro-level variations in street density and traffic distribution. Furthermore, the model does not yet incorporate factors such as seasonal variability, real-time congestion, road accidents, or the demographic and social characteristics of the population, which may significantly affect accessibility in metropolitan areas. These aspects will be addressed in future research to expand the applicability of the method to different territorial contexts.

The study only provided a geoinformation method for assessing the accessibility of medical services, which is the basis for deeper integration into community management practices. In the future, this method needs to be supplemented with a full-fledged decision support system that not only visualizes accessibility but also allows analyzing infrastructure development scenarios, taking into account resource constraints, demographic situation, and changes in the road network.

Particular attention should be paid to developing an interface that is convenient for local administrators who are not specialists in GIS or modeling. It should be an easy-to-use tool that allows you to see the picture of residents' access to medical services in real time and quickly check how the creation of a new medical facility or the closure of an existing one will affect coverage of the entire community. This approach is particularly relevant for communities undergoing post-war reconstruction, where every management decision carries high risk and weight.

In practical terms, the developed geoinformation method can be applied differently depending on the type of community. For urban communities, it helps to optimise the spatial distribution of clinics and hospitals, identifying overlaps in coverage and reducing bottlenecks caused by traffic congestion. For rural communities, the method is particularly valuable in detecting underserved areas and justifying the creation of mobile medical units, feldsher-midwife stations or small outpatient clinics to achieve compliance with accessibility standards. For frontline or post-war affected communities, the model supports scenario-based planning for emergency medical evacuation, the establishment of stabilisation centres, and the prioritisation of transport corridors under high-risk conditions. Such differentiation of use cases demonstrates the adaptability of the method to diverse project environments and confirms its practical value for supporting evidence-based decision-making in community healthcare infrastructure development.

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Розробка геоінформаційного методу оцінки доступності медичних послуг у проектах розвитку інфраструктури громад

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АНОТАЦІЯ

У статті розроблено геоінформаційний метод, яка забезпечує вирішення науково-прикладної задачі оцінювання доступності медичних послуг у проєктах інфраструктурного розвитку громад. Вирішення цієї задачі є основою планування інфраструктурного розвитку громад під час повоєнного їх відновлення. Актуальність дослідження зумовлена потребою підвищення ефективності прийняття управлінських рішень щодо оцінювання доступності населення громад до медичних послуг в умовах просторової нерівномірності розміщення об'єктів медичної інфраструктури та обмежених ресурсів. Метою роботи є розробка геоінформаційного методу оцінювання доступності медичних послуг для населення громад, який базується на використанні відкритих геопросторових даних із відкритого некомерційного веб-картографічного проєкту OpenStreetMap, що враховує топологію дорожньої мережі, просторове розміщення медичних закладів, щільність і розподіл населення на території громад, а також часові параметри доступності до медичних послуг. Запропонований метод реалізовано на основі відкритих даних із використанням інструментарію OpenStreetMap, бібліотек OSMnx і NetworkX, що забезпечує гнучкість, масштабованість та прозорість обчислень. Особливістю методу є автоматизоване визначення зон доступності населення громад до медичних послуг на основі побудови ізохрон довкола об’єктів медичної інфраструктури з урахуванням типу закладу та допустимого часу прибуття мешканців громад до них. Виконано перевірку розробленого геоінформаційного методу на адекватність. Встановлено, що відхилення знаходяться в межах до 1 хвилини або до 0,3 км. Результати експериментального застосування методу на прикладі типової територіальної громади показали її здатність виявляти «сірі зони», тобто населені пункти, недостатньо охоплені мережею медичних закладів, та оцінювати вплив змін у структурі медичної мережі на загальну доступність населення до медичних послуг. Практична цінність дослідження полягає у створенні алгоритму, який є основою для розробки системи підтримки управлінських рішень стратегічного розвитку громад. Зокрема, в частині оцінювання доступності населення громад до медичних послуг для планування проєктів інфраструктурного розвитку громад. Запропонований метод у подальшому може бути розширений шляхом інтеграції з демографічними прогнозами, сценаріями мобільності населення та даними про стан дорожньої інфраструктури, що відкриває перспективи для його використання в ширшому спектрі задач планування проєктів інфраструктурного розвитку громад.

Ключові слова: управління; проект; метод; територіальна громада; медичні послуги; геодані; інфраструктурний розвиток; прийняття управлінських рішень

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