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ORIGINAL ARTICLE

Spatial database applications for network analysis: Case study of bicycle accessibility of forested areas in the Poznań Metropolitan Area, Poland

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Abstract

The main aim of this paper is to introduce a solution for network analysis based on pgRouting to resolve the bicycle accessibility of forested green spaces. The proposed application uses open-source software tools such as PostgreSQL with PostGIS extension. The solution includes a complete description of how to perform network analysis using a spatial database with SQL and pgRouting. The implemented functionalities consist of solutions for finding the equidistance or isochrone area for any selected point location. The method is tested on case study data drawn from a total of 9,500 km of roads suitable for cyclists in the Poznań Metropolitan Area, located in western Poland. The results of the analysis were isochrones determining the bicycle accessibility of forested areas. The accessibility analysis was performed considering an urbanised residential area. As a result of the analysis, locations with the best and limited access to forested green areas were identified. Moreover, the described methodology is ready to be used to solve various accessibility problems.

Key words: network analysis, pgRouting, PostGIS, Dijkstra algorithm, spatial database, accessibility

1 Introduction

The development of open-source Geographic Information System (GIS) software has had a tremendous impact on computer-aided methods of analysis and the visualisation of results. The emergence of new tools such as spatial databases equipped with advanced analytical methods has offered researchers new opportunities to perform advanced spatial analyses. A spatial database is a database that contains tables with column data types designed for storing spatial objects (Obe and Hsu, 2021). These spatial objects can be represented in geometrical formats compatible with the Open Geospatial Consortium (OGC) OpenGIS specifications for geographic information; they include point locations, line networks, and administrative boundaries. The spatial database also provides functions and indexes for executing spatial queries using Structured Query Language (SQL).

Spatial queries may relate to the number of specific points located within the polygon of an administrative boundary, for example, or the number of buildings within a specific distance from a coastline or river. The problem of finding the shortest distance between objects in the spatial database can be resolved using the Euclidean distance in planar space using geometrical objects or on a spherical surface using geographical objects. However, when there is a need to find the closest distance between two objects along a road graph, network analysis algorithms are needed. The solution to this problem involves a spatial network database that combines the representation of the network topology with geospatial information. A spatial network database is based on a model that stores a network in the form of a graph, with nodes and edges. This network model enables queries about the path from a given starting node to a given destination node, as a sequence of neighbouring nodes from the first node to the last node (Brinkhoff and Kresse, 2012).

Shortest path queries are associated with routing problems, which mainly involve transportation networks such as roads. Routing depends on the correctness of the topology of the road network (Brinkhoff and Kresse, 2012). The condition for topological con-

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sistency is that each edge has nodes connected with the next edge, whereas each node should have several starting or ending edges. The topological structure of the network model is called a graph, and the network rules are set using graph theory. One of the algorithms that can be used with graph theory is the Dijkstra algorithm, which was designed to achieve greater efficiency in the problem of finding the shortest path. Another shortest path search algorithm is the A* algorithm. It is a heuristic graph search algorithm whose search is determined by the heuristic search function. Routing algorithms form the basis of several topological analysis problems, such as accessibility analysis and the travelling salesman problem. Accessibility analysis answers questions about the targets that can be reached in the network within a certain range of distance or time.

A network-dependent accessibility approach is part of a wider group of methods related to the catchment or service area problem, which can also be resolved with other methods, such as Thiessen polygons (Widaningrum, 2015) or the floating catchment method (Luo, 2004). Accessibility analyses that rely on such applications include the determination of public transport accessibility (Cyril et al., 2019; Escobar and Garcia, 2012; Ford et al., 2015; O'Sullivan et al., 2000) and the accessibility of hospitals (Merciu et al., 2013), the identification of physician shortage areas with catchment methods (Luo, 2004), catchment area analyses of convenience stores (Widaningrum, 2015), and accessibility differences for socially excluded groups of people (Achuthan et al., 2010). Another application of network analysis is the determination of the accessibility of urban green spaces using service area methods; urban green spaces include types of land that are covered with vegetation, which are used for recreational purposes in cities, and allow public access (Almohamad et al., 2018; Comber et al., 2008; Krzywnicka and Jankowska, 2021; Wei et al., 2022).

A network analysis package is available with the spatial database PostGIS/PostgreSQL in the form of the pgRouting extension, a library that is helpful in resolving routing problems. The library was developed by the Georepublic company and a broad user community as part of the OSGeo Labs initiative. It provides methods for developing network routing applications and graph analysis (Obe et al., 2017). The many algorithms provided by this library include a solution to the shortest path problem based on the Dijkstra algorithm. Some of the functions of this extension can be used within SQL queries for isochrone or equidistance designation. An isochrone is defined as the area that can be travelled from a selected point via the road network within a constant time. Isochrones generated in this way could be used to resolve problems of accessibility, for example, in regard to public transport or catchment areas. The pgRouting library has been used for network analysis in many applications; for example, it has been used to determine the optimal route for firefighters (Widyantoro and Santosa, 2021), to find the optimal routes for services in emergency scenarios, such as medical services or emergency evacuation during flood disasters (Choosumrong et al., 2019), and to determine suitable hiking routes in a protected area (Vías et al., 2018).

The commercial counterpart of the pgRouting library is the ArcGIS Network Analyst extension. This extension provides solutions such as network dataset preparation, route determination, finding the closest facility, solving the vehicle routing problem, and finding a serviceable area. Examples of the use of this extension include accessibility analysis for firefighting teams in forest terrain (Akay and Tas, 2020), routing analyses for the improvement of public transport (Amaguaya and Hernández, 2020), and a vehicle routing model for an urban solid waste management system (Sarmah et al., 2019).

The versatility of PostGIS as the spatial extension of a database system is demonstrated by the many different solutions for geoprocessing applications, such as the determination of shoreline changes (Kostecki, 2018) and a geodatabase for the retrieval of geochemical data from oil wells (Kabolizadeh et al., 2023). The availability of open-source tools and the simplicity of the programming

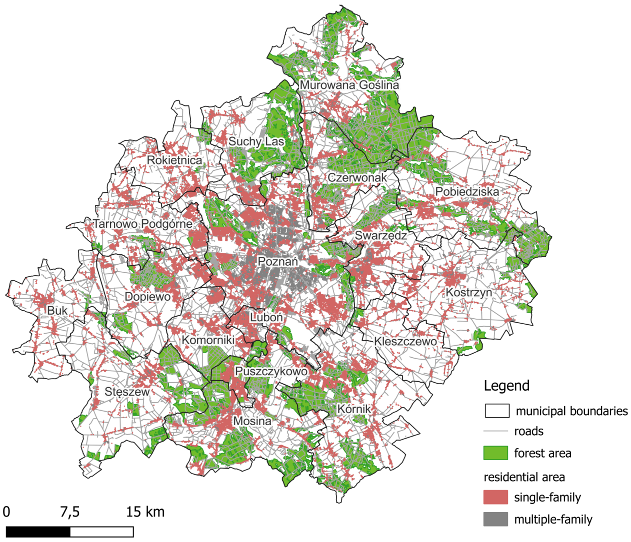

Figure 1. Map of the Poznań Metropolitan Area

languages involved enable users to implement their own programming ideas using real-time spatial analysis methods through the use of Web-GIS systems. Web-GIS provides a web-based platform for analytical methods, and it is available for GIS applications via an internet connection. The spatial data stored in a database such as PostgreSQL can be visualised and analysed on internet maps using Web-GIS methods. Examples of such applications include web applications that integrate tourism data (Afnarius et al., 2023), interactive maps for monitoring the quality of water resources (Botha et al., 2023), and spatial assessments of the quality of health care (Duarte et al., 2021).

The potential of the PostGIS and pgRouting functions is not well known, meaning that they are not widely used, and therefore there is a need to develop new solutions and applications. The main aim of this paper is to present a network analysis application based on pgRouting for analysing bicycle accessibility of forested green areas.

The forested green spaces near residential areas play an important role in physical activity. One of the frequently chosen physical activities is cycling, either for commuting purposes or during leisure time. The previous studies found a correlation between the vicinity of green areas and the time spent on cycling daily (Campos-Sánchez et al., 2019; Kaczynski et al., 2008). The proximity of green areas to the residential environment and the overall level of physical activity are only related to a very limited extent (Maas et al., 2008). Therefore, a large number of bicycle routes in or near green areas has a positive impact on the attractiveness of physical activity such as cycling (Campos-Sánchez et al., 2019). In the light of the results of previous research, there is a need to develop analyses of the availability of forest green areas for bicycle traffic and to plan new bicycle routes.

The case study focuses on the combined area of Poznań County and the city of Poznań, which are within the Poznań Metropolitan Area in western Poland (Figure 1). This area covers around 2,181 km^2 and contains around 9,500 km of roads suitable for cyclists.

2 Materials and methods

The data used for the network analysis were drawn from the Open Street Map (OSM) repositories and downloaded in the form of a shapefile package from the Geofabrik repository. OSM is licensed under the Open Data Commons Open Database License. The location data of forests and residential areas were obtained from the Polish database of topographic objects BDOT10k (pl. *Baza Danych*

Obiektów Topograficznych), which represents a 1:10,000 scale topographic map provided by Head Office of Geodesy and Cartography (pl. *Główny Urząd Geodezji i Kartografii*, GUGiK).

The main software required was the PostgreSQL object-relational database management system (ORDMS), which was chosen from the available open-source solutions (PostgreSQL, 2024). PostgreSQL is available under a liberal open-source license, similar to the BSD or MIT licenses. PostgreSQL is a database platform that was developed in the 1970s at the University of California, and it provides enterprise-level services, unique features, and scalability (Juba et al., 2015), including methods of managing extensions. The PostGIS database system spatial extension and pgRouting were required for backend development. PostGIS is a spatial extension that supports spatial data types and the corresponding geoprocessing functions (Obe and Hsu, 2021; PostGIS, 2024). pgRouting is a library that is included with PostGIS and can be used to handle network analysis (pgRouting, 2024). The testing of the pgRouting functionality was performed using the pgRouting Layer QGIS plugin, which was designed to allow the pgRouting functions in the QGIS GUI to be used without the need to write SQL queries manually (Obe et al., 2017). QGIS is a dedicated GIS environment that can be used to analyse and visualise the data stored in the PostGIS database. PostGIS, pgRouting, and QGIS are available under the General Public License v2 license. The complete code required to perform the analysis and an example dataset are available from GitHub.

3 Development of analysis

3.1 Workflow for preparation of the routing network

The complete workflow for the network preparation process is shown in Figure 2, and the code listings are available from GitHub. The first step was to upload the data from the selected source, which in this case was an OSM shapefile package divided into subregions of the country under study. The database needed to be prepared through the installation of required extensions such as PostGIS and pgRouting. The shapefile of the road network was uploaded using a tool that was included in the spatial extension PostGIS Shapefile Import/Export Manager. The most important parameter during the upload was to keep the single geometry. The next step was the transformation of coordinates from the WGS84 spatial reference system (SRID:4326) to the local system for Poland (ETRF2000-PL/CS92, SRID: 2180). Following this, we selected a road data type that was suitable for routing purposes. The case study considered here involved a cycling network, therefore, before the preparation of the topology, all pedestrian routes, motorways, and roads that were unsuitable for cycling were deleted from the table. In the next step, a new table was created containing the geometry of the network edges that had been reduced to the selected length. The length was set to 20 m to take into account the range of the studied area. This reduction in the edge length increases the number of nodes and shortens the calculation time when searching for the shortest route. The query reducing the edge length used the PostGIS function ST_LineSubstring. The next stage of the network preparation process was topology correction using the pgRouting function pgr_nodeNetwork, which involved finding nodes where edges were crossed and resolving the problem of invalid topologies. The multi-level junctions were identified using the bool attribute brigde_tunnel and omitted during the execution of the pgr_nodeNetwork function. After this correction process, a table with the suffix 'noded' was created. Following this, the cost columns and cost calculations were added to the network table; the lengths of the edges were used as the 'cost_len' column. The value of the cost was recalculated in the form of a time, considering appropriate parameters, by moving along the edges. The 'cost_time' column was calculated using bicycle speeds estimated at 10 and 20 km per hour, taking into account the type of road surface. The

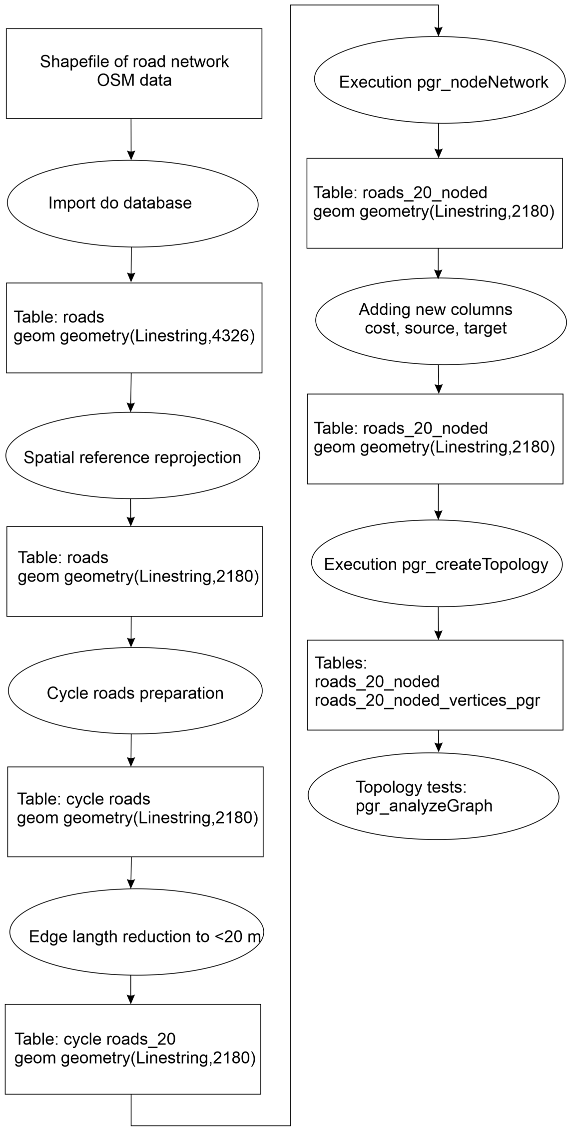

Figure 2. Flowchart of the preparation process for the routable road network

table of edges also needed two integer columns, labelled source and target, to store the IDs of nodes at the ends of road edges.

After the preparatory work described above, the topology of the routing network was created using the pgRouting function pgr_createTopology. The execution of this function resulted in a node table with the suffix 'vertices_pgr' and node IDs in the columns labelled source and target. Following the creation of the topology, the function pgr_analyzeGraph was executed to perform topology checks, which included detecting the number of isolated segments, dead ends, potential gaps near dead ends, intersections, and ring geometries. The low values of these parameters confirmed the high quality of the topology of this network. The network was now ready to perform analyses using the functions pgr_Dijkstra (to search for the shortest route) and pgr_drivingDistance (to determine ranges of equidistance). To use other functions such as pgr_aStar, columns containing the coordinates x1, y1, x2, and y2 for all nodes needed to be added to the edge table. pgr_aStar is a function for searching for the shortest path using the A* algorithm. In contrast to the pgr_Dijkstra function, pgr_aStar, during path searching, requires additional arguments in the form of a list of columns with the vertex coordinates x1, y1, x2, and y2, which were used during heuristic calculations. An example showing part of the processed road network is presented in Figure 3.

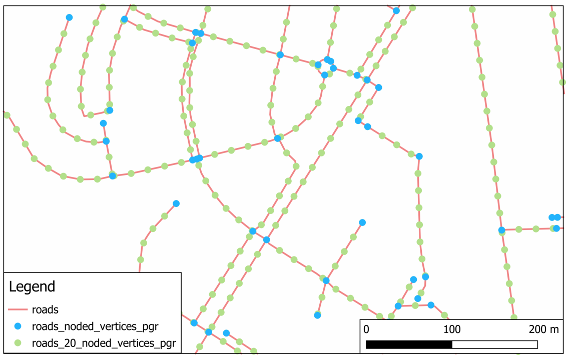

Figure 3. Part of the processed road network with vertices

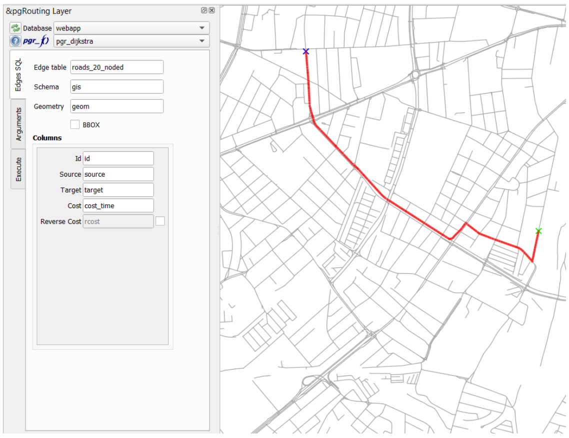

Figure 4. Example showing a search for the shortest route between selected vertices using the function pgr_Dijkstra in pgRoutng Layer QGIS plugin

3.2 Route testing with the road network and routing wrapper

The fastest way to carry out the quality testing of the routing with the prepared network was to use the pgRouting Layer QGIS plugin. After establishing a connection with the database and the recognition of the uploaded extension, the tool required the parameters of the network as input, as shown in Figures 4 and 5. This plugin implements several pgRouting options from the Dijkstra and aStar family of routing algorithms. Executing the plugin resulted in a route along the tested road network based on the selected vertices, movement cost, and algorithm type. The resulting route could also be saved as a separate layer.

A more flexible testing tool is QGIS DB Manager, as the user can run any pgRouting algorithm using SQL queries (Figure 6). The subsequent queries were therefore executed in DB Manager with the pgr_Dijksta and pgr_aStar functions that can be executed in DB Manager, and the geometrical results were visualised using the QGIS map canvas. The arguments needed to perform the analysis with the functions described above were the numbers of starting and ending vertices, with a selected column containing the cost value. After the successful testing of the routing algorithms with the created network, we began writing wrapper functions. Native pgRouting functions were constructed in a generic form to enable them to be applied to many solutions. The wrapper functions tailor code to a specific problem based on selected algorithms to provide a simple application of a function without the need for a bulky SQL code (Obe et al., 2017).

The custom alphashape wrapper function was used to find isochrones. The starting point coordinates and the alphashape range are required in the units of the spatial reference system of

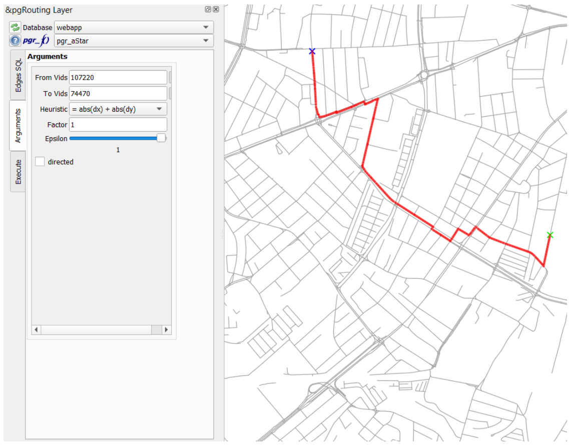

Figure 5. Example showing a search for the shortest route between selected vertices using the function pgr_aStar with selected heuristic in the pgRoutng Layer QGIS plugin

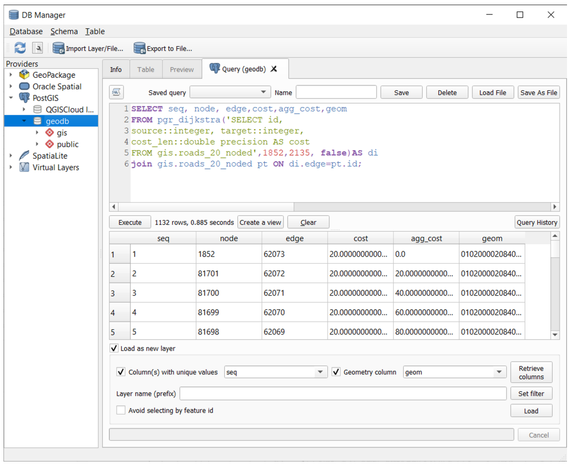

Figure 6. Example showing pgr_Dijksta query testing in the QGIS DB Manager with edge geometry

the road network. The location of the starting point, uploaded in the form of WGS84 coordinates, is used to find the nearest vertex using the KNN (k-nearest neighbor) method. pgr_drivingDistance and ST_ConcaveHull are the main functions used to find the range of the alphashape. In this case, the function pgr_drivingDistance was used to search for network vertices in the selected range from the starting point, and the alphashape polygon was then created from the selected vertices using the ST_ConcaveHull function. This function creates a polygon that encloses the vertices of the input geometry with the parameter param_pctconvex, which controls the concavity of the computed hull, where values between 0.3 and 0.1 produce reasonable results. A value of 0.3 for param_pctconvex was used for the solution presented here. The older version of the pgRouting library (version 2) provided a pgr_alphaShape function that was dedicated to creating an alphashape polygon from the supplied vertices; since version 3, however, pgr_alphaShape has been available only with the spoon_radius parameter as a proposed function. The newest version of PostGIS (included in versions 3.3 and above) also provides a function called ST_AlphaShape with an alpha parameter that controls the concave results. This function computes a concave hull geometry in a similar way to ST_ConcaveHull but using a different algorithm.

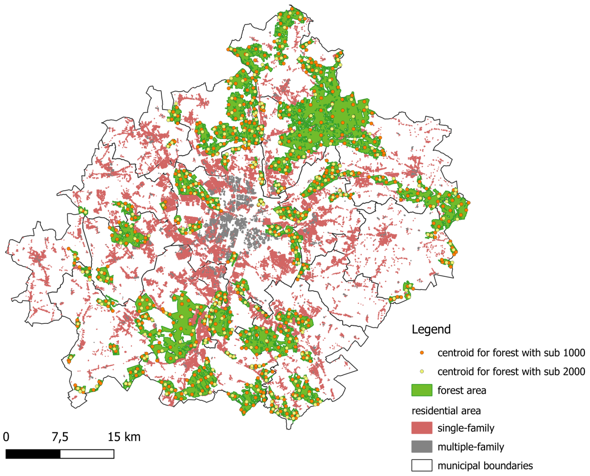

Figure 7. Map of analysed area with generated centroids using two methods of subdivision

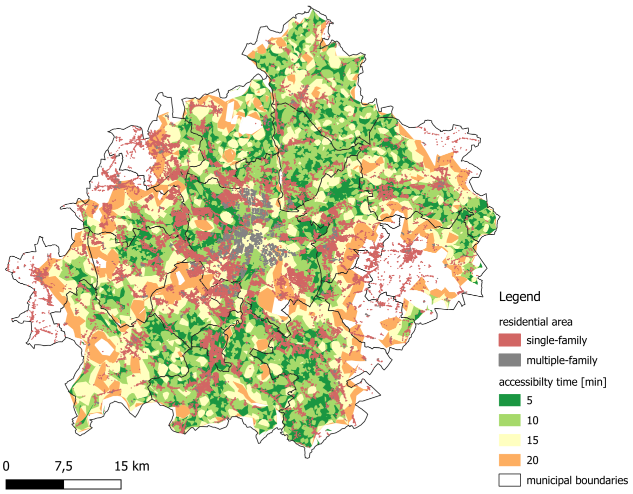

Figure 8. Bicycle accessibility map to forest areas in the Poznań Metropolitan Area with centroids from subdivision with 1000 m hexagonal grid

3.3 Workflow of isochrone preparation

The forested area polygons were used to determine centroids for isochrone analysis. The first step was the selection of forest polygons with an area of over 500,000 m^2, eliminating small areas of trees. As a result, 100 polygons remained. Due to large forest areas, the location of one centroid deep in the forest was insufficient for accessibility analysis. Therefore, the next step was to divide the forest polygons into smaller parts using two variants: 1000 m and 2000 m hexagonal grids. The divided polygons were used to determine the locations of centroids for accessibility analysis. This process resulted in 597 points of centroid locations for subdivision using a 1000 m hexagonal grid and 310 points for the 2000 m grid (Figure 7). The next step was to create isochrones by query using the alphashape function described in the previous subsection, the two sets of centroids of forest locations, and time intervals of 5, 10, 15, and 20 minutes. The query resulted in a materialised view consisting of polygons describing accessibility within the proposed time intervals (Figure 8). The summary of contributions of the residential area within the range of individual isochrones was calculated by query and stored in the materialised views.

4 Case study results

A method that consists of the subdivision of polygons of forested areas into smaller parcels using a hexagonal grid and the determination of centroids for accessibility analysis was proposed in this study. There are also other solutions for accessibility analysis that have been proposed in previous studies, such as the use of the centroids of park polygons and determination accessibility with network analysis (Połom et al., 2017), the use of Euclidean distances to evaluated sites using buffers (Krzywnicka and Jankowska, 2021), and the use of the intersections of the main road and pavement inside the park as the starting point for the network analysis (Almohamad et al., 2018). The large and complicated forested polygons in the presented study excluded solutions with only one centroid, the location of which would not be representative. However, road intersections with the border of evaluated polygons create a large number of points on the external and internal borders, and the network analysis would not include cycling within a forested area. A more appropriate solution seems to be dividing the polygons into smaller parts. The method of subdivision using a hexagonal grid was tested using two hexagon edge sizes, 1000 m and 2000 m. The denser spread of centroids in the case of the subdivision of the 1000 m hexagonal grid revealed larger areas in the range of isochrones from 0 to 20 minutes (Figure 8) and are more representative for an accessibility analysis for cycling in a short amount of time.

The resulting isochrones were compared to a residential area in a particular commune and the contribution of this area was calculated for the cycling time intervals (Table 1). By analysing the spatial structure of forest accessibility in the studied area, it can be concluded that most of the inhabited areas are located relatively close to the evaluated areas. This is particularly important when compared to previous research in Polish cities, where residents often have difficulty accessing larger public green areas (Wysmułek et al., 2020). Previous research has also shown that the number of green areas in the vicinity of residential estates promotes greater physical activity (Neuvonen et al., 2007). Some studies particularly emphasize the role of forests in the vicinity of large urban agglomerations, which are places for physical activities such as running and cycling (Janeczko et al., 2019).

Analysing the results presented in Table 1 and the map (Figure 8), we could conclude that the largest part of the residential area is located in the range of the 0- to 20-minute isochrones. Generally, the highest accessibility in the range of 20 minutes of bicycle travel was revealed in communes, such as the city of Poznań and surroundings, where 100% of the residential area is located within this range. Meanwhile, generally the worst forest accessibility was found for communes located in the western part of the metropolitan area. From analysing time intervals, the best accessibility of forested areas was revealed in communities located in the southern part of the studied area and in the northern part where the largest residential area is located within the 0-to-5-minute isochrone. This is due to the proximity of larger forest complexes in these parts of the metropolitan area: Puszcza Zielonka Landscape Park is located in the northern part, and Wielkopolski National Park is located in the southern part. The largest residential area within an isochrone of 5 to 10 minutes consisted of the communes with a well-developed road network that is located not too far from forested parcels. The isochrone of 10 to 15 minutes dominated in the residential area only in the case of two administrative units, where only small forested areas exist. The forest accessibility at a range of 15 to 20 minutes dominated in the residential areas of the communes, where the distance to the nearest forested area is significantly higher than in the case of other communes in the studied area.

Taking into account the distribution of availability described above, it can be concluded that the temporary availability of forests is determined primarily by their location. You should also be aware that some inhabited areas are too far from forested areas (over 20

Table 1. The contribution of residential area of the individual communes in the range of bicycle travel time to 20 minutes

Commune	Contribution of residential area in isochrones [%]				
	5 min	10 min	15 min	20 min	Sum
Buk	1.3	3.0	17.1	28.4	49.8
Czerwonak	54.2	44.4	1.2	0.0	99.8
Dopiewo	22.7	50.5	25.3	1.1	99.6
Kleszczewo	15.6	12.3	11.0	29.7	68.5
Komorniki	10.3	23.5	54.9	11.4	100.0
Kostrzyn	1.7	4.0	5.9	8.4	19.9
Kórnik	44.0	41.7	9.0	1.7	96.5
Luboń	11.9	47.9	37.6	2.6	100.0
Mosina	57.2	41.3	0.9	0.2	99.7
Murowana Goślina	13.1	61.9	22.6	1.3	98.7
Pobiedziska	32.7	42.6	12.6	5.0	92.9
Poznań	22.8	48.3	25.8	3.1	100.0
Puszczykowo	84.4	15.3	0.1	0.2	100.0
Rokietnica	0.7	16.2	31.9	30.1	78.9
Stęszew	9.9	55.7	27.7	5.4	98.7
Suchy Las	26.4	59.6	13.4	0.3	99.8
Swarzędz	16.1	52.2	16.8	7.1	92.2
Tarnowo Podgórne	24.0	21.2	19.5	19.3	84.0

minutes) and it will be important to organize local parks and small green areas.

The expansion of the network of bicycle paths, especially in suburban areas, where unpaved trails often cut through forest and agricultural areas, will improve the availability of green areas. It should be taken into account that the development of bicycle routes improves the availability of green areas, especially since previous research (Campos-Sánchez et al., 2019) has shown that green areas do not only affect cyclists, but also the bicycle infrastructure in addition to environmentally comfortable spaces and routes with attractive destinations.

5 Conclusions

The PostgreSQL spatial extension PostGIS, together with the pgRouting library, is a complete system that is ready to perform fast and flexible network analysis. The approach discussed here has great potential as a flexible and powerful tool for the network analysis of transport routes. The most important solutions in the proposed methodology are the reduction of the edge length in the network, which increases the number of nodes and enhances the accuracy of the analysis, and the proposal of a wrapper function that creates an alphashape. The presented methodology was tested on the Poznań Metropolitan Area road network, considering the bicycle accessibility of forested areas. The most important advantage of the presented solution is the complete control of the road network during the analysis, including the correction of the topology, cost calculations, and the selection of the appropriate network algorithm. The cost of cycling was calculated by taking into account different types of road surfaces that affect the moving speed. The presented approach identified areas where the accessibility of green spaces such as forests is limited, which may affect the quality of life of the residents and should be considered during urban planning. The described methodology can be applied to perform analyses and evaluate various accessibility problems. The research should be continued on the planning of cycling routes and the difficulty of routes that take into account slope in calculating cycling times as well as in relation to other types of green spaces.

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