

GATE Mobility Toolbox for QGIS: Calculation of Walking Accessibility Using Slope-Adjusted Algorithms

Teodora Koleva, Evgeny Shirinyan(✉), and Dessislava Petrova-Antonova

Sofia University, GATE Institute, 1164 Sofia, Bulgaria
{evgeny.shirinyan,dessislava.petrova}@gate-ai.eu

Abstract. Walking accessibility gains significant attention in recent years in urban planning. Various software tools provide accessibility analysis based on network graphs. However, the slope component is often overlooked. This paper introduces an open-source QGIS plugin which automates calculation of isochrones and an Accessibility Index, inspired by the 15-min city concept. The Accessibility Index evaluates access to various services within predefined distance ranges, weighted by service importance. Four computational methods are available: buffer analysis, network analysis and slope-adjusted network analysis using Tobler's hiking function and the Naismith-Langmuir rule. The QGIS plugin allows straightforward implementation and a high level of reproducibility, resulting in optimized computing time and resources. The tools Average altitude of point features, Slope calculation of network segments, Split network with points, and Accessibility Index can be used together or separately for the assessment of the urban environment. The calculations showed a significant decrease in Accessibility Index in the case of hilly terrain compared to the typical network analysis without considering the slope.

Keywords: Accessibility Index · walkability · Tobler's hiking function · Naismith-Langmuir rule · QGIS · Python

1 Introduction

The concept of walking accessibility has a key role in the scope of urban planning for the sustainable development of cities. Generally, accessibility can be defined as the ability to reach relevant activities, individuals or opportunities, which might require traveling (or walking) to the place where those opportunities are situated [1]. An urban environment can be described using 5Ds: density, diversity of land use, design, destination accessibility, and distance to transit [2]. In residential areas it is important to allocate various amenities within walking distance such as supermarkets, kindergartens, schools, parks, bus stops, restaurants, etc. In addition, walking accessibility can affect property prices [3, 4]. Terrain features such as slope can alter not only the walking speeds, but also the preferences for choosing a certain route [5].

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O. Gervasi et al. (Eds.): ICCSA 2025 Workshops, LNCS 15897, pp. 423–437, 2026.
https://doi.org/10.1007/978-3-031-97660-5_28

This study introduces an open-source QGIS plugin for the calculation of the Accessibility Index (AcsI). It is implemented with the Python API for QGIS (PyQGIS) as a part of the GATE Mobility plugin for QGIS. Pedestrian accessibility is evaluated at the building level using a slope-adjusted network analysis. Among the 5 D's the GATE Mobility plugin implements 3 of them: diversity, destination accessibility and distance to public transport are acknowledged.

The developed index of accessibility aggregates services available around a residential building and the distance calculated to them based on the pedestrian network. In order to distinguish the importance of different services a weighting system of points of interest was established. The plugin allows the use of four methods for the calculation: simple buffer analysis, network analysis, and the slope-adjusted network analysis (based on Tobler's hiking function and the Naismith-Langmuir rule). In addition, the study quantitatively compares these methods using the case of a hilly terrain.

The rest of the paper is organised as follows. Section 2 reviews the related work. Section 3 describes data and the methodology utilised. Section 4 presents the implementation of the plugin in QGIS. Section 5 features the outcome of the implementation, a quantative comparison of all the methods, and visualisation of the outputs. Section 6 provides an overview of the study and potential developments for the future.

2 Related Work

In general, the evaluation of Accessibility index is a calculation related to the concept of walkability. Numerous methods for assessing walkability have been developed with diverse variables considered for the final result [3, 6–8]. Some studies include such factors as pedestrian comfort, condition of the pedestrian network and target groups for index calculations [9, 10]. In terms of the evaluation of accessibility, network analyses, often conducted in GIS, provide a realistic dimension to the assessments. Various methods of network analyses and spatial aggregating functions were implemented as software tools [11–13].

A widely used routing application is represented by Openrouteservice and its QGIS plugin for network analysis ORS Tools. An isochrone can gather population data and avoid features and boundaries. However, it does not consider the slope as a factor for creating itineraries and isochrones [14]. Another network analysis plugin for QGIS, QNEAT3 [15], supports networks, provided by a user, and speed-adjusted analysis. Therefore, slope-adjusted calculations can be performed with some preprocessing steps.

There are other QGIS plugins related to walking accessibility, such as OS-WALK-EU [16]. The software utilises data from OpenStreetMap for services and calculates a walkability index for neighbourhood areas with population represented as a variable. The tool uses a grid of 500 × 500-m cells conforming to the European INSPIRE Grid. To measure residential walkability, OS-WALK-EU incorporates the concept of the 5 D's.

More specialised tools such as PST or Space Syntax explore connectivity and networks rather than calculation of indices. Another toolbox performing diverse spatial analyses developed for Rhino Grasshopper software is the DeCodingSpaces toolbox [17]. 15 min City Score Toolkit, a plugin for calculating urban metrics in QGIS such

as pedestrian accessibility and walkability, also leverages the service area of various categories of points of interest (POIs) [18].

A web-based service Aino.World applies the 15-min city concept for any location in the world and enriches the result with recommendations generated by large language models [19]. The calculation of isochrones is conducted using Mapbox services. Several studies consider Sofia, where the terrain is hilly in the southern part of the city, but the slope is not integrated into calculations [20–24].

In general, prior research implies the impact of slope in urban environments and how it affects walking [5, 25]. Şahin Körmeçli [26] integrates Space Syntax metrics with slope values and shows that the longest and main roads with low slope values have higher rates of accessibility. For steep slope regions, a coverage area is lower than for flat regions [27]. In Barcelona, a sidewalk network model realistically captures the pedestrian environment: an undirected graph of the city, whose edges are enriched with sidewalk width, length, slope, a level of accidents, and crosswalk locations [28]. Nevertheless, most of the tools do not consider the characteristics of slope, which is an important component of accessibility, especially in hilly regions.

The Naismith-Langmuir rule and Tobler's hiking function are commonly used approaches for considering the slope in accessibility studies and planning hiking activities. Tobler's hiking function is a more recent development and is often used in various scenarios for walking speed estimation [29, 30]. For instance, in ArcGIS Pro the Tobler's hiking function is implemented [31, 32].

The integration of slope-adjusted network analysis in the calculation of AcsI addresses the limitations of flat-surface assessments. This approach provides more accurate and realistic evaluations of heterogeneous and hilly urban landscapes.

3 Methodology

3.1 Study Area and Data

Sofia is the capital city of Bulgaria, with a population of nearly 1.27 million and 24 districts. Given its heterogeneity in geometry, infrastructure, and environment, the district Lozenets is chosen as a case study. The northern part of the district is occupied by mid-rise residential buildings with dense vegetation. On the south, the district is represented by intensive construction, where accessibility and availability of the road infrastructure, public spaces, and public services are not sufficient. The terrain of the study area varies between 549 m and 668 m above sea level.

The data needed for the calculation comprises the following datasets in the form of ready to use layers in QGIS:

- Residential buildings dataset – prepared by GATE Institute with data from the Bulgarian cadastre;
- POIs dataset (various amenities) – gathered by the researchers in GATE Institute from state and municipal registers.
- Weights of POIs – estimated by experts in GATE Institute.
- Pedestrian network dataset – provided by the municipal enterprise "Sofiaplan".

The count of the residential buildings in the dataset is 5710 features, whereas the count of POIs in the respective dataset is 5203.

POIs are divided into 8 groups and 49 subgroups. Groups are as follows – Green, School, Kids, Health, Mobility – defined as primary groups of importance and consequently with higher weights assigned; the remaining - Sport, Culture and Service are of secondary importance and with lower weights. Within each group another weighting system is used for the subgroups from 0 to 1 with a total sum equal to 1 (Fig. 1).

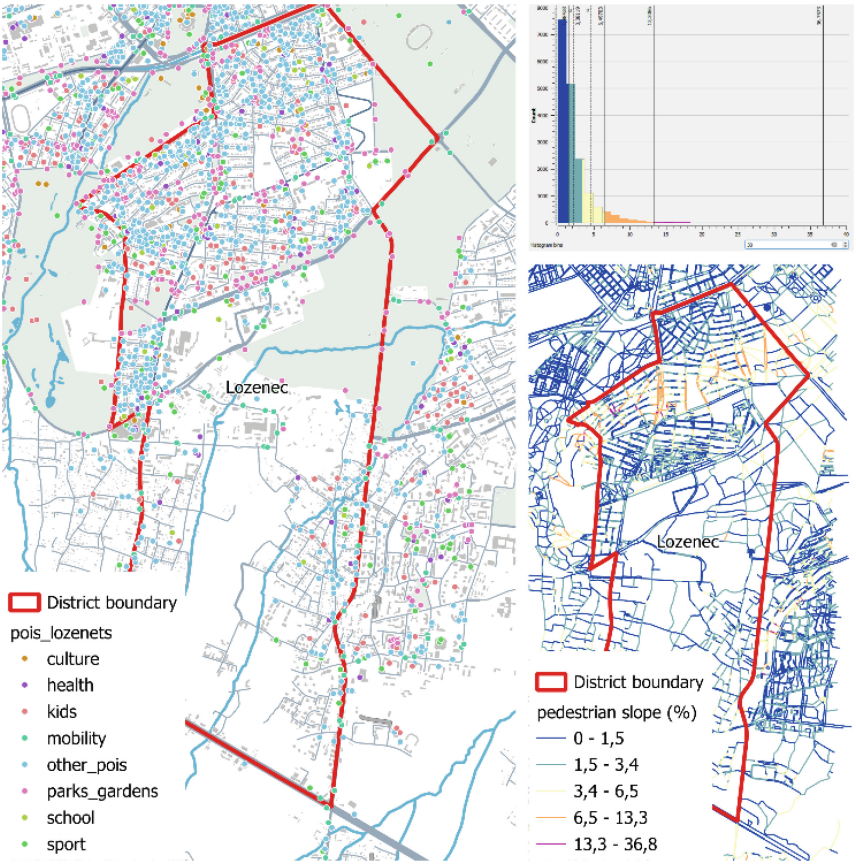

Fig. 1. Study area. Left: points of interest in the district; top right: a histogram of slope values of network segments; bottom right: a slope map of segments

3.2 General Workflow

This section describes the methodology followed for the calculation of AcsI. The main processing steps of the pipeline are shown in Fig. 2.

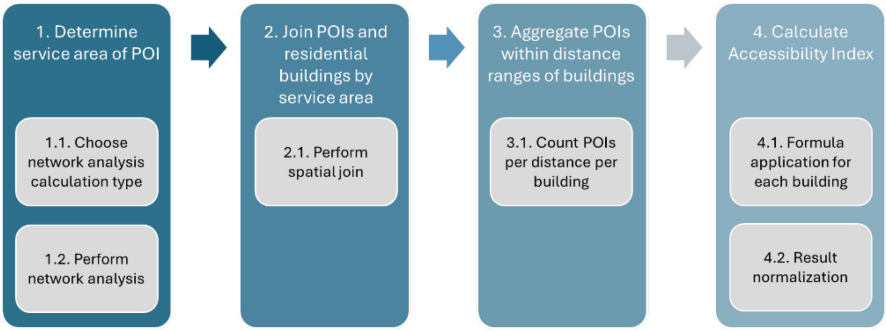

Fig. 2. General workflow

3.3 Determine a Service Area of a POI

The service area itself shows the distance extent within which a residential building would benefit from a certain POI. Four methods for determining a service area are used in the current study: buffer analysis, network analysis, and network analysis with slope in two variants. Service areas of sampled POIs were calculated with three distance steps of 500 m, 1000 m and 1500 m both for all types of analysis.

Buffer analysis is the simplest one as it does not take into consideration the pedestrian network but uses distance by air.

Network analysis uses the pedestrian network for the calculations which results in a more accurate service area. Dijkstra's algorithm calculates a shortest path over a weighted graph. Additionally, distance steps are also used as in buffer analysis with the same values.

The third and fourth methods of network analysis with slope incorporate the slope/inclination of every segment of the pedestrian network and thus impacts the distance. The estimated speed of walking is represented as a function of the slope, with two different calculation approaches applied: Tobler's hiking function and the Naismith-Langmuir rule.

Tobler's hiking function (THF) is formulated in 1993 by Waldo Tobler and has become a popular method to calculate speed in recent research. THF is defined as follows:

$$W = 6^{(-3.5|S+0.05|)} \tag{1}$$

where W is the speed and S is the slope.

According to THF, the maximum speed that can be developed is 6 km/h which is achieved at $-2.86°$ in descent, and the average speed on flat terrain is 5 km/h.

The Naismith-Langmuir rule (NLR) is a combination of the work of two persons – William Naismith and Eric Langmuir. The first input was made by Naismith in 1892 for ascent and states:

> *"an hour for every 3 miles forward, with an additional hour for every 2,000 feet of ascent".*

This means that on flat terrain, the approximate base speed is 5 km/h, with travel time increasing by 0.1 min per 1 m of ascent. In 1984, Langmuir extended the rule with terms for descent that state:

> *"0.03 min should be added per 1 m of descent for slope angle greater than 12° and 0.03 min should be subtracted per 1 m of descent for slope angles between 5° and 12°".*

A limitation of the NLR is its prediction of the maximum walking speed of 12 km/h on shallow slope and at the threshold of a 12° slope an abrupt change from 12 km/h down to 3 km/h takes place which seems to be unrealistic.

This third method also uses Dijkstra's algorithm for the network analysis where the edges are weighted with the travel times according to the speeds. Table 1 reveals a sample of the pedestrian network with calculated speeds following THF and the NLR.

Table 1. Street segments with speeds calculated using THF and the NLR

fid	id	type	slope_percent	length	THF	NLR
13677	114806	road	-5.380042414	38.727	5.917	5
13678	114807	road	-2.960065746	19.587	5.594	5
13679	114807	road	0.347647693	0.847	4.983	4.859
13680	114807	road	0.071644611	23.744	5.018	4.97
13681	114807	road	0.409492245	1.974	4.966	4.835
13682	114807	road	3.711535743	0.058	4.422	3.819
13683	114807	road	0.638499088	53.916	4.931	4.747
13684	114808	sidewalk	3.057700387	3.467	4.516	3.985
13685	114808	sidewalk	3.607642024	44.308	4.437	3.844
13686	114808	sidewalk	2.949741138	51.989	4.548	4.013
13687	114813	sidewalk	0.747040771	36.879	4.914	4.707
13688	114813	sidewalk	0.688988874	5.182	4.914	4.729
13689	114813	sidewalk	2.239638063	2.55	4.661	4.214
13690	114813	sidewalk	1.53703794	7.814	4.778	4.432

Figure 3 shows a slope map of the area, service areas calculated as simple buffers, isochrones calculated without slope and isochrones calculated with the slope according to THF and the NLR respectively.

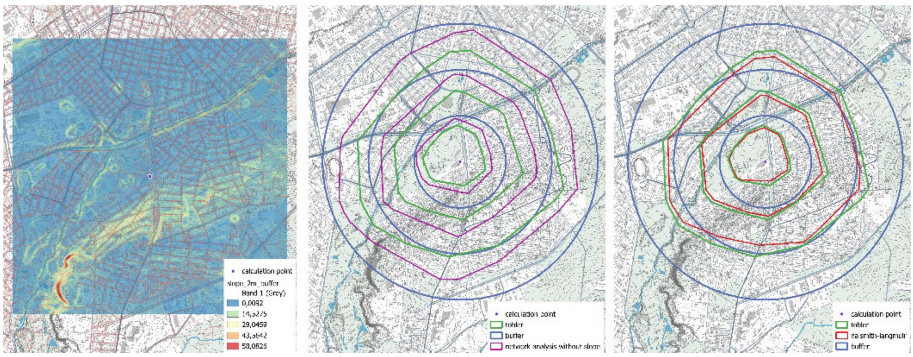

Fig. 3. From left to right: slope map of the area; network analysis compared to THF; the NLR compared to THF

3.4 Join POIs and Residential Buildings by Service Areas

Once the service area has been evaluated for each POI, the residential buildings that fall within every service area should be detected with the corresponding distance range. The spatial join is performed that examines the relations between the geometries of join features (residential buildings) and target features (service areas). It is a one-to-many operation that joins all the features from the join features into the target features by producing several overlapping records. In this case the algorithm seeks for all residential buildings that are within a considered service area. The type of POIs, the distance range, and the count of POIs are also integrated with a building.

3.5 Aggregate POIs within Distance Ranges of Buildings

Having the data from step 3.4 it needs to be summarised so that counts of POIs per building per distance range can be obtained. An aggregate function for counting is utilised. Aggregate functions execute a calculation on a dataset and return a single summary value as a final result. The dataset can be divided into groups on a specific basis and thus the aggregate functions return a single value for each group of the dataset.

Table 2 presents a sample list of buildings (id 278, 387, 2233) with aggregated counts of POIs. For example, a building with id 278 has one pharmacy in 500 m, 1000 m, and 1500 m; 4, 13, and 2 bus stops in 500 m, 1000 m, and 1500 m, respectively.

Table 2. Buildings with POI count

id	phrm_500	phrm_1000	phrm_1500	b_stp_500	b_stp_1000	b_stp_1500
278	1	1	1	4	13	2
387	1	1	1	6	7	4
2233	0	4	1	0	5	2

3.6 Calculate Accessibility Index

AcsI uses the following formula for the calculation:

$$AcsI = \frac{\Sigma(\Sigma(Subgroup\,Weight \times Step\,Weight\,) \times Group\,Weight)}{\Sigma(Subgroup\,Weight) \times Group\,Count} \quad (2)$$

where *AcsI* is the Accessibility index, Subgroup Weight is the weight assigned to the subgroup, Step Weight is the weight of the distance range, Group Weight is the weight of the group and Group Count is the count of the groups present. For instance, a residential building has access to a playground in 500 m, a health centre in 1000 m and a pharmacy in 1500 m. The playground is a part of the subgroup "playgrounds" with a weight of 0.15 within the group "Kids" with a weight of 15. The distance step weight for 500 m is 1, for 1000 m is 0.75 and for 1500 m is 0.5. The result for this group will be $(0.15 \times 1) \times 15 = 2.25$. The health centre and the pharmacy are part of group "Health" with a weight of 15 in subgroups "health centres" with a weight of 0.30 and "pharmacies" with a weight of 0.20 respectively. The calculation for the group is $((0.30 \times 0.75) + (0.20 \times 0.50)) \times 15 = 4.875$. The final equation will be $(2.25 + 4.875) / ((0.15 + 0.30 + 0.20) \times 2)$ which will result in Accessibility Index of 5.48. The formula does not consider the number of POIs from a specific subgroup type available within a distance range, but whether there is a POI (from a specific subgroup type) available in the certain distance range.

After the calculation of AcsI for all the residential buildings the values are normalised from 0 to 100 through the subsequent equation:

$$Value_{normalised} = \frac{Value}{Value_{max}} \times 100 \quad (3)$$

where *Value* is the result of the AcsI calculation and $Value_{max}$ is the maximum possible value of the index for the current dataset.

4 Implementation

The AcsI calculation is entirely executed in the scope of QGIS using the GATE Mobility plugin, which contains a collection of automated geospatial analyses. Currently, there are four algorithms developed within the plugin that perform diverse spatial tasks: Average altitude of point features, Slope calculation of network segments, Split network with points, Calculation of Accessibility Index.

The calculation of Accessibility Index algorithm is facilitated by the Python libraries *math* and *pandas* together with PyQGIS short for the QGIS Python API (Fig. 4).

According to the methodology, the algorithms applied through QGIS and PyQGIS for the automated calculation of AcsI are described below.

For **determining service area of POIs** with buffer analysis the algorithm "Multi-ring buffer (constant distance)" is implemented from Processing Toolbox.

If network analysis is applied instead of buffer analysis, the Service area (from layer) algorithm is executed. This calculation implements the "shortest path" method. The resulting service area is generated as a Multiline geometry and converted to a polygon

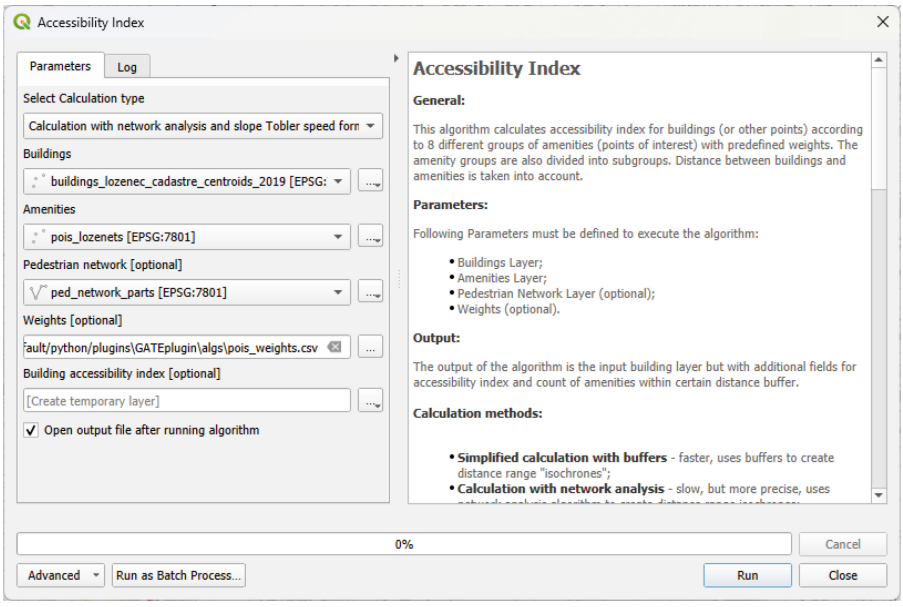

Fig. 4. An interface of the plugin – Accessibility Index

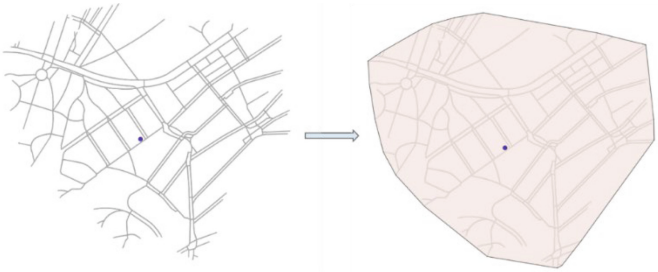

Fig. 5. Lines from Service area and the resulted convex hull polygon

using the Convex Hull algorithm. Figure 5 presents the conversion of the service area from lines to a polygon.

The service area assessment with network analysis and slope calculations also deploys Service area (from layer) algorithm followed by the Convex Hull algorithm. However, it implements the "fastest path" method so that speed and therefore slope can affect the service area. Once the speed is calculated using either THF or the NLR, it is saved as an additional attribute field for each section of the pedestrian network. Slope details are obtained with the Slope calculation algorithm in the GATE Mobility plugin.

For the step "**Join POIs and residential buildings by service area**" the algorithm used is known as "Join attributes by location" from the Processing Toolbox in QGIS.

The step **"Aggregate POIs within distance ranges of buildings"** does not use the Aggregate algorithm, which requires significant time and resources to execute. Therefore, a complete Python solution is adopted without QGIS involved for aggregating the counts of POIs.

The calculation of **Accessibility Index** is automated through a Python function. The weights of the POIs are defined in a .csv file with a specific structure and imported in the function. Figure 6 demonstrates a fragment of a Python code of the AcsI calculating function. In addition, calculations can be executed as "qgis_process" commands without a graphical user interface.

```
result_numerator += group_amenity_weights_sum * group_weight
result_numerator_max += group_amenity_weights_sum_max * group_weight
result_denominator = amenity_weights_sum * len(amenity_groups_to_count)
accessibility = result_numerator / result_denominator
accessibility_max = result_numerator_max / result_denominator
feature["accessibility_index"] = accessibility
feature["accessibility_normalized"] = accessibility / accessibility _max * 100
```

Fig. 6. Python code of the AcsI calculating function

5 Results

This section presents the results of calculating of the AcsI for the whole district of Lozenets using four methods: buffer analysis, network analysis, THF, and NRL, as shown on Fig. 7.

Buffer analysis shows a clear differentiation between the northern part and the southern part of the district can be noticed. The northern part is older and closer to the city center, consequently residential buildings situated there have greater access to services which results to higher AcsI scores. On the other hand, the southern part is still developing and is known for its problems with pedestrian network which explains the lower results of AcsI. As for buffer analysis, calculations took approximately 5 min for the whole district of Lozenets.

In the case of the network analysis method, AcsI scores are generally higher in the northern part of Lozenets compared to the southern part. The resulting values vary between 30 and 91.50. The high scores of buildings indicate an access to almost all types of services in every distance range. The calculation of the index for the southern part results in minimum value of 3.1 and a maximum value of 59.6. It can be observed a similar distribution of the values as for the whole district – northern parts with higher scores and southern parts with lower scores. Calculation of the whole district took approximately 30 min.

THF and the NRL demonstrate the same distribution pattern. The calculation time took 40 min to be completed. Overall, calculation with the NLR predicts more residential buildings with AcsI score in the lower ranges compared to THF.

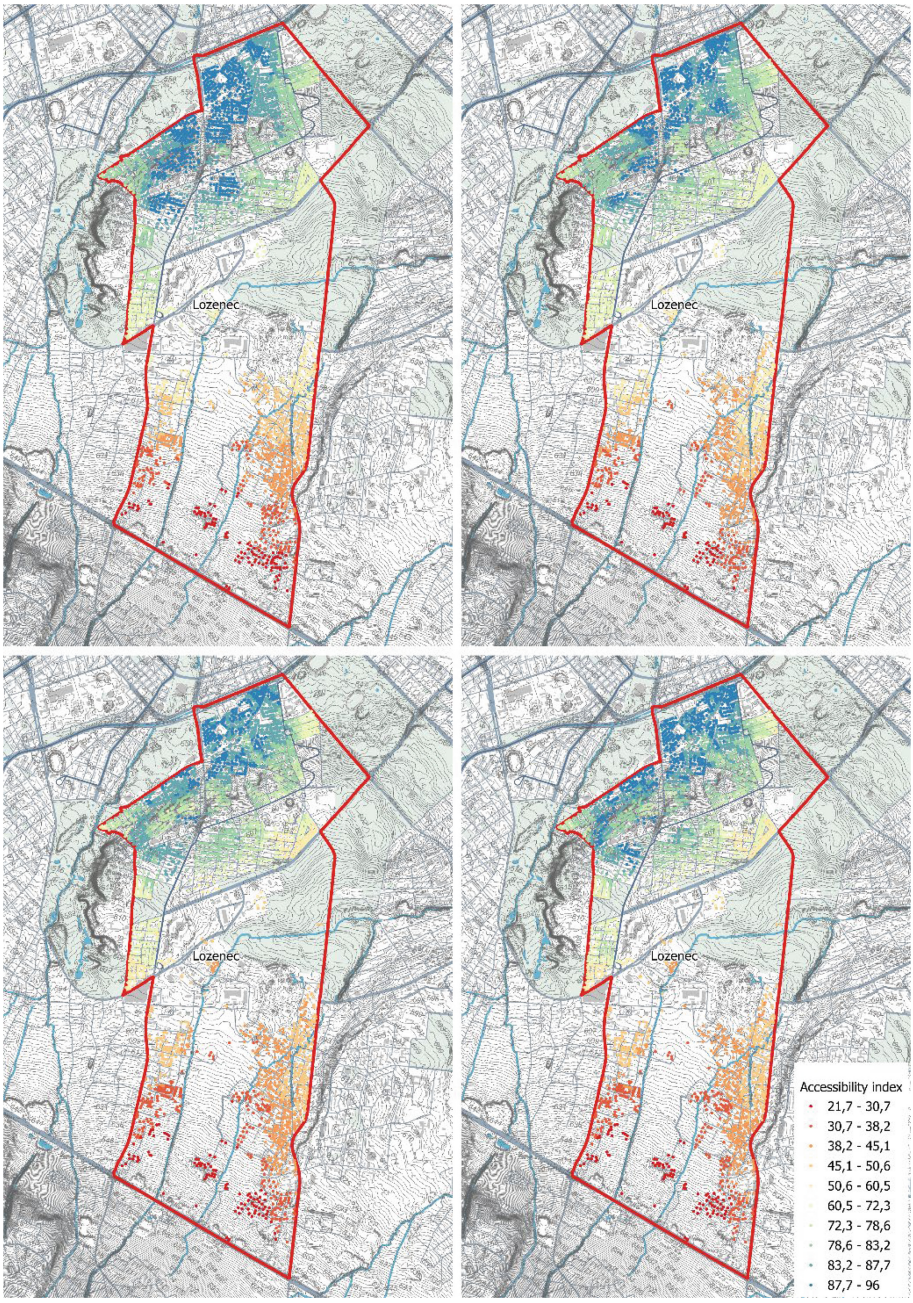

Fig. 7. AcsI scores of the Lozenets district: buffer analysis (top left), network analysis (top right), THF (bottom left), NRL (bottom right)

Figure 8 demonstrates the distribution of scores across all the types of the analysis. Buffer analysis yields too optimistic results, with values reaching up to 96 points, with mean value of 76.3. Similar results can be observed in the network analysis without slope. The lowest maximum belongs to the NLR with 80.4, followed by the THF-based method with 85. The largest group of values in the case of the NLR clusters around 76. Buildings with high AcsI values are distributed in the northern part of the district including sloped areas. In the case of THF the northern flat part with high values is more articulated, which shows higher sensitivity to terrain variations. Finally, the ratio between network analysis and THF shows up to 2.5 times decrease of AcsI in the southern parts of the district.

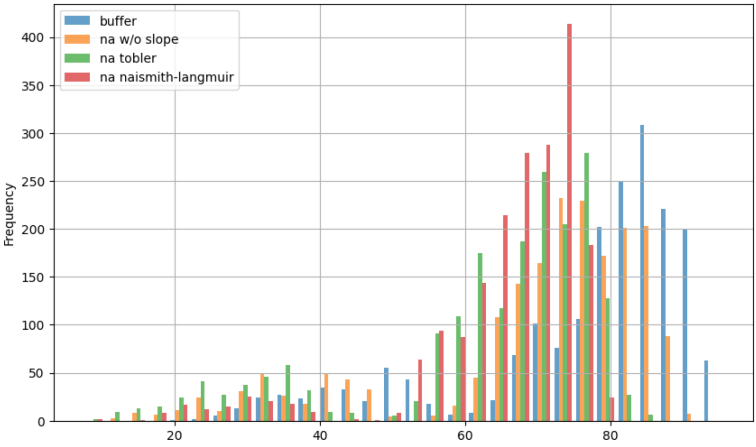

Fig. 8. Ratio of AcsI without slope and with slope considered

5.1 Limitations

The main limitation of the method is the significant computation time at the district scale. Therefore, the possibility of batch processing should be envisioned. In addition, the weights of POI are not present in the user interface, which limits ease of customisation for end-users. Currently, the plugin does not consider steps or elevators.

6 Conclusion and Future Work

This paper introduces a comprehensive approach for calculating AcsI, a key metric for assessing urban environment and development. The methodology is universal and by incorporating multiple calculation methods – buffer analysis, network analysis and network analysis with slope (Tobler's hiking function and the Naismith-Langmuir rule) – it offers a flexible framework that adapts to various urban conditions and datasets. The QGIS built-in network analysis toolbox with implementation of Dijkstra algorithm is preferred combined with several custom changes. The incorporation of the slope into

calculations decrease AcsI up to 2.5 times in hilly areas compared to a regular network analysis.

The suggested AcsI focuses on urban morphology and pedestrian networks, providing a universal methodology applicable across various urban scenarios. AcsI evaluates the ease of reaching various points of interest (POIs) within a 15-min walk along pedestrian pathways. The significance of each category of POIs is represented by the weights allocated for the accessibility evaluation.

The plugin is openly available on GitHub where the latest version can be downloaded and utilised in QGIS. Automated algorithms within GATE Mobility plugin are beneficial for both urban and rural use cases.

The case study conducted in Lozenets District proves that the AcsI calculation method is transferable and offers perspectives on conducting calculations not only for the entire city of Sofia, but also for other cities. Consequently, comparisons across distinct cities can be performed. Integration of resulting datasets can be visualised in 3D city models as well. The GATE Mobility plugin operates with user provided data for services, pedestrian network and residential buildings to calculate an index for each building in the dataset. Furthermore, the weighting system for the services can also be modified according to the users' preferences, as well as accounting for staircases or the physical quality of sidewalks.

Future work entails refinements in the calculation process of the index by combining additional factors involved in the 15-min city concept. The GATE Mobility plugin upcoming developments are focused on optimizing the calculation time for certain algorithms including the Accessibility Index calculation and automatisation of further geospatial analyses. Moreover, developments of automated computations for Shannon Diversity Index and Simpson Diversity Index will be explored.

Acknowledgments. This research is part of the GATE project funded by the Horizon 2020 WIDESPREAD-2018-2020 TEAMING Phase 2 programme under grant agreement no. 857155 and the programme "Research, Innovation and Digitalization for Smart Transformation" 2021-2027 (PRIDST) under grant agreement no. BG16RFPR002-1.014-0010-C01.

Disclosure of Interests The authors have no competing interests to declare that are relevant to the content of this article.

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