PEDESTRIAN ACCESSIBILITY ASSESSMENT USING SPATIAL AND NETWORK ANALYSIS: A CASE OF SOFIA CITY

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ABSTRACT:

Walking is the most accessible form of mobility, delivering different benefits to the cities and their residents such as improved public health, community liveability, efficient land use and cost savings in terms of needed space to allow movement. Walkable neighbourhoods provide a high-quality urban environment with public spaces and a variety of activities and services. To increase walkability, a focus should be placed on the pedestrian network which integrates all transportation modes, making it a subject of network-based analyses related to pedestrian accessibility, connectivity, and walkability. This paper aims to assess pedestrian accessibility in Sofia, Bulgaria by applying network and spatial analysis. It analyses the macro scale of the integration and availability of the street network. It also investigates the access to selected urban facilities, which help to increase the quality of life, such as public transport stops and parks. The results prove that such analyses could support the assessment of the feasibility of infrastructure projects and their efficiency. The analyses show that Sofia has a very good distribution of public transport stops and the parks and smaller gardens are also relatively evenly spread across the urban area. Despite this, the results discover some areas where specific measures need to be taken to provide pedestrian access to these amenities, especially in neighbourhoods where investments are high, and the need for such access is increasing.

1. INTRODUCTION

In recent years, a significant turn toward sustainable mobility and an active lifestyle has been undertaken in most European cities. In Sofia, the rising motorization rate and the continuous air quality issues raised serious public concerns about the mobility policy of the city. The encouragement of the EU funds in this direction provided another incentive for the city to take actions and decisions were made for Sofia to follow suit and transform its car-oriented mobility towards one with increased use of public transport, walking and cycling. One of the major focuses was the extension of the subway system. In the span of 13 years, 39 subway stations were built. The funds for these extensions were approved by the European Commission only after analysis and prediction of reduced emissions and increased users had been prepared.

In 2011, 2017 and 2021 studies of the modal split of Sofia were made, exploring the share of the different transport modes in the overall movement in the city. The results showed that, although the subway users increased, they are not as high as firstly estimated. The modal split revealed that the share of public transport, in general, is decreasing, in spite of the rise of the subway, and the motorization rate is still growing.

Diving into the estimations of the expected users showed a lack of significant transport modelling or spatial demographic analysis that could present relatively accurate predictions.

Building any infrastructure such as public buildings, streets or subway system, takes a considerable amount of funds from the city budget. Moreover, this process takes time and disrupts the everyday life of the people living or working nearby. A sign of good governance is if such projects are efficient and meet the initial estimations of increased users, reduced emissions and change in the modal split. If not, then the efforts are not well justified.

Geographic Information Systems (GISs) support cities in the analyses, planning and estimations of the outcome of development project ideas. They are widely used for decades in developed countries. Sofia is stating a digitalization and innovation focused planning, following the trends in urban planning, so it was only natural to receive attention from researchers. In this paper, motivated by the difference between the estimated and the real subway users, various GIS analyses are conducted aiming at properly assessing pedestrian accessibility to different urban amenities.

The entry and exit points of public transport are the stops or stations, so the first necessity is their availability and accessibility to the surrounding areas. Pedestrian accessibility is the first condition for these entry points to be used. Therefore, this research is focused on how it could be assessed, what tools are available, what data is needed along with its preparation for analysis and how the analysis can be performed. The research is extended towards access to other public amenities such as parks and gardens.

In a broader view, the access to a variety of services within walking distance is considered extremely vital for creating liveable cities and communities. The concept of a 10-minute city (Moreno, Allam and Chabaud, 2021) is a variation of a 15-minute or 5-minute city, depending on its size and is based on the idea that every citizen should find most of its daily necessities such as access to parks, sports, restaurants, food shops, kindergartens, schools in a 10 minutes walking distance from their household. GIS tools are used to estimate where Sofia is standing in this 10-

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minute city concept for some of these amenities and to access their accessibility for pedestrians.

The rest of the paper is organized as follows. Section 2 presents the related work. Section 3 outlines the preparation of data used in the analysis. Section 4 describes the research methods applied, while Section 5 discusses the obtained results. Finally, Section 6 concludes the paper and gives directions for future work.

2. RELATED WORK

A 2015 survey in the USA (National Association of Realtors) found that respondents who prefer walking are leading with 12 points ahead of those who prefer driving. Even though most of the participants in the study still showed a preference for the low-density neighbourhood, the study found that there was a significant increase in the respondents who would like their area to be more walkable with a variety of amenities at a walking distance without the need of driving. From an environmental point of view, walkable neighbourhoods are denser and need much fewer resources per single unit for infrastructure and energy (Norman, J., Maclean, H., Kennedy, C., 2006). The reinvention of the walkability that occurred at the turn of the century was further amplified by the Covid-19 pandemic.

City policies turning towards creating more walkable communities stimulate research in the area. National Walkability Index is created in the USA. It is based on three measures of the urban environment that are assumed to affect the choice to walk as a mode of transportation. These are street intersection density, proximity to public transport stops, and diversity of land uses. The measures are estimated for a block group, which is a statistical division of the census tracts (National Walkability Index). Based on the values of the different measures, a score is assigned. The developed index summarizes the measures to allow a quantitative comparison of the spatial areas. Although this method was considered proven to assess the walkability of different spaces, in Sofia, the spatial structure and the street network of the city were not analysed in detail. The POI data for Sofia was not in such great detail and it was used in the current study for additional analyses. In the current study, the main focus was decided to be on the research of the network of the city, rather than a comparison index, thus finding the level of integration of the different segments through various GIS tools. Creating knowledge about the values of the street segment would serve as a base for further additional analyses.

One of the research methods, the Space syntax, is a tool that analyses the spatial structure and could identify regeneration opportunities. It could assess whether new proposal ideas would fit into the spatial potential of the existing urban environment (Akkelies, N., Claudia, Y., 2021). It was considered vital to start with the network in order to gain more understanding of the movement in the city. This understanding could be further developed in a comparison between not just neighbourhoods but cities (Zaleckis, K., Chmielewski, S., Kamicaityt, J., Grazuleviciute-Vileniske, I., Lipinska, H., 2022).

3. DATA PREPARATION

The data used in the study is presented in Table 1. The street network of the city is a prerequisite for accessibility analysis. Since data for the pedestrian network was not available at the time of the study, pre-processing of the street network was performed. Every street, with very few exceptions in the outskirts, has an adjacent sidewalk, which is why it was considered sufficient to be used in the accessibility analyses. Pedestrian park alleys were integrated into the street network to ensure they were calculated in the analyses. Informal pedestrian networks are not to be omitted if such data is available (Zhang and Zhang, 2019).

Dataset	Format	Source
Street network	Shp	OpenStreetMap
Park alleys	Shp	OpenStreetMap
Parks	Shp	OpenStreetMap
Buildings	Shp	OpenStreetMap
Transport stops	Shp	OpenStreetMap
POI	Shp	OpenStreetMap

Table 1. Used datasets.

The data preparation process includes running an integration feature tool to look for and close gaps, below a certain length value, between the vertices of different edges of the street network (ESRI Technical Paper, 2005). The edges are split at every intersection with another street segment to ensure the network’s connectivity through a common vertex. Special attention is given to the overpass/underpass street segments where the connectivity between them must be disabled at the exact intersection, so the use of the corresponding ramp or staircase is ensured (Figure 1).

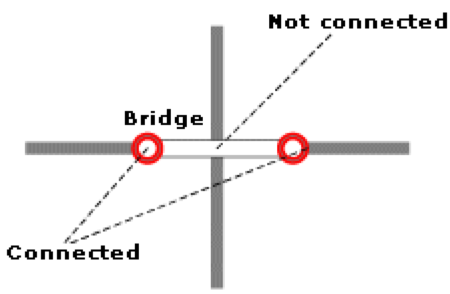

Figure 1. Network connectivity (Understanding connectivity, ArcMap).

The travel time attribute is calculated for every edge of the network, accepting a speed of 4.8 km/h. This speed covers 400 meters of distance in 5 minutes of walking and is considered as typical. (Transport for London, 2010). Other datasets used in the analyses were public transport stops – bus, tram, trolley and subway, which were used to assess the pedestrian service area around them. Parks and city gardens were also used to assess the access to recreational areas. Buildings were included to show more clearly the accuracy of various GIS tools in calculating the spatial service. The points of interest (POI) dataset was obtained from OpenStreetMap and was used to create a map of the various activities in the city and to look for the relation between good integration of the pedestrian network and the concentration of such activities.

4. RESEARCH METHODS

Suppose a city is working on increasing its share of pedestrian mobility. One area of focus is to improve the urban environment in a way that encourages people to walk more. That includes widening sidewalks, creating pedestrian crossings more often and connecting major centres of activities such as parks, public buildings, schools, and shopping centres in an attractive pedestrian route. Increasing safety is another key principle that should be followed which includes reducing the speed limit of the adjacent streets, improving the visibility on the routes and generally making physical changes to the street design that prioritize pedestrians over car traffic. Besides these redesign efforts, if a city aims for more pedestrians, it should also improve

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public transport. Walking 10 minutes is considered an acceptable time for pedestrians to have a walk to reach their point of interest. For destinations beyond this limit, another mode of transport is typically chosen. So in order for a city to encourage more walking, a reliable public transport service needs to be developed, including the distribution of transportation stops around the territory and physical access to them (Crawford, 2002). The stops need to be located at no more than 10 minutes of walking for the potential users (Federal Highway Administration, 2013). In order to assess the 10 minutes of walking requirement, a spatial analysis needs to be performed.

In this research, Network Analysis is used to assess the pedestrian accessibility of the transportation stops and their respective service areas. Such analysis considers the existing available infrastructure and runs along it. It is important to mention that this analysis is on a macro scale and doesn't consider the condition of the walking pavement or other indicators such as safety, comfort, and attractiveness of the urban environment which have an impact on pedestrians when choosing a walking route. If population data for each building is present, the number of residents that are served by public transport could be calculated.

As it is mentioned in the introduction section, Sofia had made wrong estimates about the potential users of the subway. The lack of detailed transport modelling may be a reason, but another one could be that around each stop a circle was used by the Metropoliten (subway management municipal company) to measure the serviced residents, which was inaccurate. That is why a comparison is performed between the typical buffer service area (circles) and the Network Analysis service area. An isochrone impedance is set, using values of 400 m and 800 m corresponding to 5 and 10 minutes of walking. This is considered as an acceptable walking time to a stop (El-Geneidy and Tetreault, 2009). Larger distances would cause a different choice of transportation to be preferred, usually personal vehicles. The buffer uses a radius of the impedances in a straight line whereas the network analysis uses the existing network to traverse the distances (Figure 2). The results show that the Network Analysis is substantially more accurate and gives a realistic insight into the number of buildings, and respectively people, located in the service area.

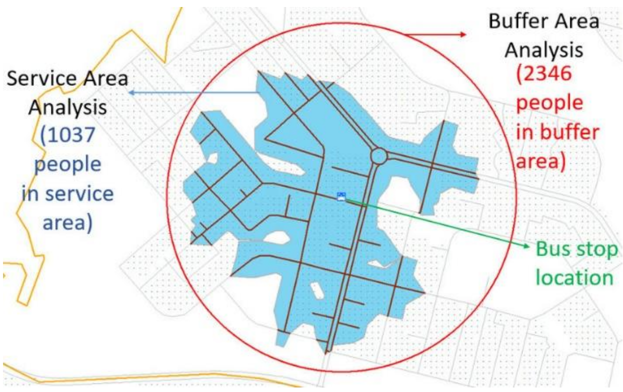

Figure 2. Comparison of Buffer and Service Area Analysis (Aslan, H., Kocaman, H., 2018).

The Network Analysis is performed on all public transport stops to analyse the coverage of the preferred service area of under 10 minutes of walking. Then the same analysis is applied only to the subway stations to estimate the access to the fastest way of public transport.

The previously mentioned concept of 10-minute city is tested here, extending the analysis with the public parks and gardens. Thus, the vertices of the polygons of the parks dataset are taken as initial entry points for which the Network service area is generated.

Next, an Urban Network Analysis (UNA) is performed using an open-source toolbox for ArcGIS by the Massachusetts Institute of Technology (Sevtsuk and Mekonnen, 2012). It utilises the buildings as a third element of the network dataset, including edges and intersections. The buildings are considered main destination points, and their assessment is based not only on the value of the nearest street segment but also on the location of a building along a segment. Additional weighted parameters could be set for every building, such as function, volume, jobs, occupants, or cultural significance. Such parameters could be essential for route choice. For example, the position of a certain significant building like the national theatre or trade centre could deviate the pedestrians to pass by it, instead of taking the shortest path to their destination. (Sevtsuk and Mekonnen, 2012). UNA provides 5 measures – Reach, Gravity, Betweenness, Closeness and Straightness. Additionally, a search radius could be set. It represents the maximum distance between any arbitrary building and its surrounding buildings along the street network. Then values are assigned to the buildings based on the type of selected measure as well as weighted parameters if such are present (Figure 3).

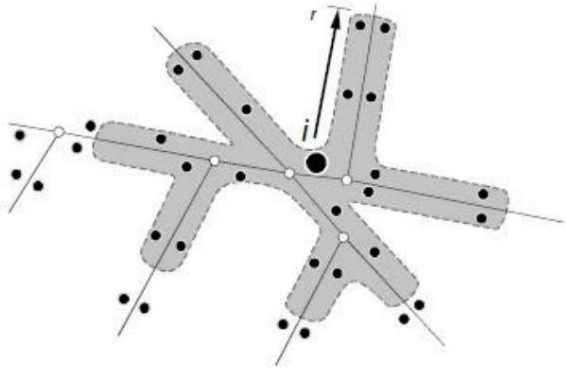

Figure 3. Reach index illustration (Sevtsuk and Mekonnen, 2012)

The spatial relations of the network are analysed by applying a Spatial Syntax, developed by the University College of London (Hiller, B., 1989). The Spatial Syntax provides a set of techniques, which are combined to analyse the spatial layout and human activity. It is applicable to an open urban environment, as well as in indoor areas. Two key propositions are defined (Hiller, B., 2014). The first one is that the space is not a background to the human activity, where behaviour adapts to the space as usually accepted. Rather, space is intrinsic to the activity, which has its own geometry represented in space. The second proposition is that space is foremost configurational, which means that the human activity in a specific space is fundamentally determined by the relationships between that space and the network of spaces to which it is connected.

To analyse the space as a network of choices, three basics concepts are considered as follows:

- Isovist – sets of all points visible from a given vantage point in space (Space Syntax Glossary).
- Axial - defined as the longest straight line representing the maximum extension of a point of space (Space Syntax Glossary).

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- Convex - one in which no straight line drawn between any two points goes outside the space (Space Syntax Glossary)

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One of the most popular measures is the Integration measure. It represents a normalized measure of the distance of any space or line to all others in a system (Vaughan, L., 2015). It shows how space is integrated into all other spaces in a system. The measure is applied with or without a set search radius. This radius could limit the extent to which a measure, such as Integration, would be calculated. When no radius is set, the Integration measure takes into account the whole system without restriction. It is used for city or region scale analysis. Setting a search radius reduces the scale and is used to discover well-integrated local centres.

For Sofia, an axial map is created and the level of integration of the segments in the network is analysed. The measure is calculated without a Search radius to discover the city-scale arterials. Another analysis is performed within a 400 m radius to unveil the integrated segments on a local community level, which have the potential to be public centres.

Finally, a Spatial cluster analysis is performed to evaluate the concentration of services using data for POIs (food and beverage stores, fast food places, hotels and other accommodations) from OpenStreetMap. Although the POI dataset is not complete, OpenStreetMap provides sufficient data for the purpose of the analysis. Three clusters are formed, which shows the territorial intensity of the different services. These categories are strongly related to pedestrian activity and are another basepoint for investment initiatives in the urban environment.

The results of the Spatial analysis are overlaid with the Network Analysis in order to discover relationships between hot spots of activity with the street network. That is vital for the city if it aims to become a 10-minute city with a vast quantity and diversity of activities on a human scale, and pedestrian distances.

5. RESULTS

The Network Analysis of the stops of the whole public transport system shows a very good distribution among the urban area. Most of the residential buildings are covered in the 5-minute (400 m) impedance. The 10-minute (800 m) impedance covers almost everything in the compact area of the city (Figure 4). Few major gaps are emerging clearly. They are all located in the southern part of Sofia (Figure 5). This area used to play a buffer area between the compact city and the low-density neighbourhoods south of the ring road, along with Vitosha mountain. In the last 30 years, the area got under the focus of investors.

The city did not cope with the intensity of the private development and the infrastructure such as public buildings or even the street network fails behind. Large arterial streets were not created, so public transport vehicles are not able to pass through the small former outskirts alleys and gravel roads. The closeness of the mountain and the well-connected to the city centre radial boulevards help the area to attract more residents. The investments in the area continue, which makes the problems, illustrated by this analysis, more relevant. The lack of pedestrian-friendly streets and wide enough boulevards in the neighbourhoods to allow public transport helps with the increasing use of private cars in the area. Residents don't have a really fast and reliable alternative to private vehicles. The infrastructure is the primer condition for the mobility choice of the residents. It is impossible to expect a rise in active mobility and public transport if there are no conditions for them. Another key factor for attracting users besides the urban environment is the quality of the public transport service. Further analysis of the frequency of the public transport vehicles of the nearby lines should be conducted to plan proper optimization.

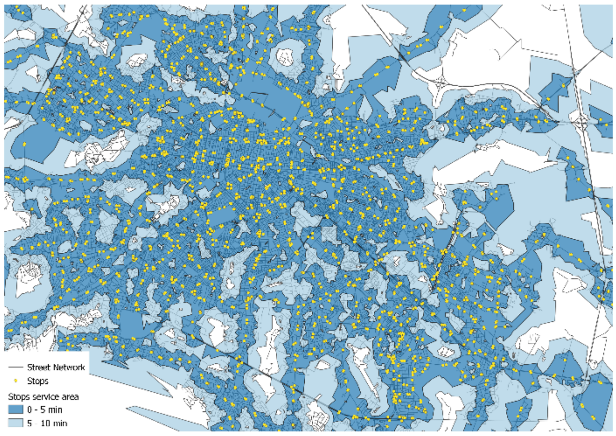

Figure 4. Service area of every public transport stop.

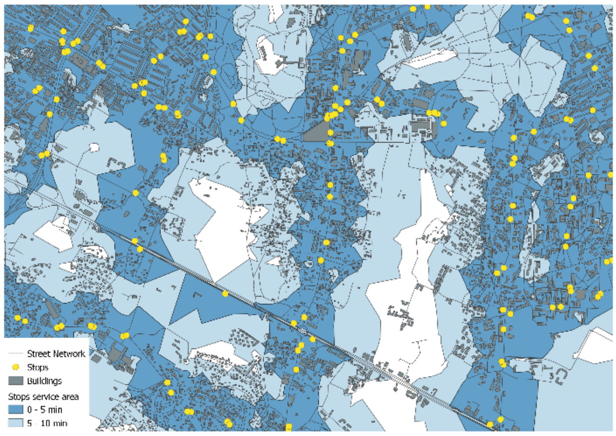

Figure 5. Service area of public transport stops in Southern areas.

The Network Analysis of the subway system shows the actual serviced areas around each station (Figure 6) and the buffer analysis shows how it was calculated by the city (Figure 7). A significant share of the population is in the 5- and 10-minute impedances. The comparative analysis of the Network Analysis and the buffer analysis shows very clearly the difference between the two approaches (Figure 8). If we take a look at the Network Analysis of the subway stops at the southern part of the city centre, the aerial circles include almost the whole Ivan Vazov neighbourhood in the 10-minute impedance, although there is a sport centre on the corner without pedestrian passages with open access (Figure 9). The Network Analysis is much more accurate and shows the real service area in the selected impedance.

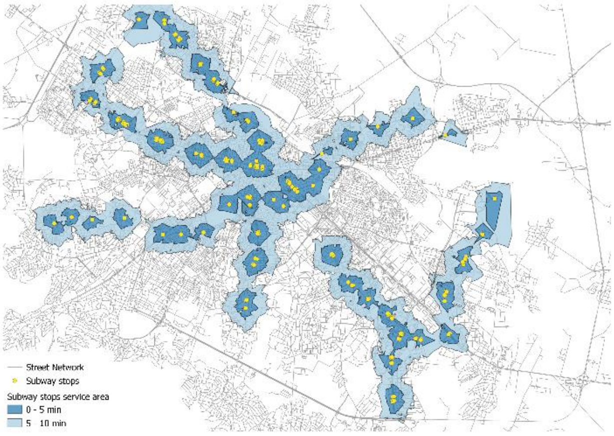

Figure 6. Network Analysis service area of subway stations.

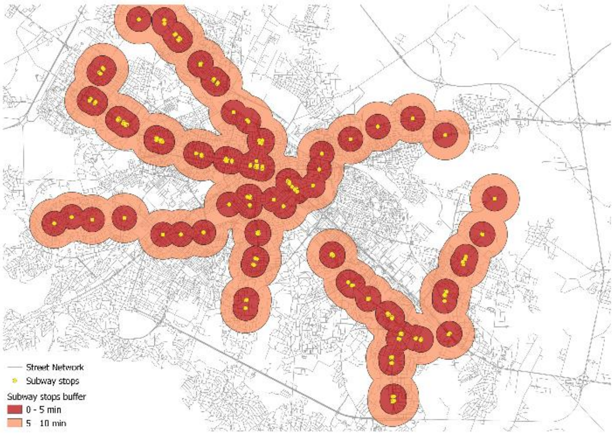

Figure 7. Buffer service area of subway stations.

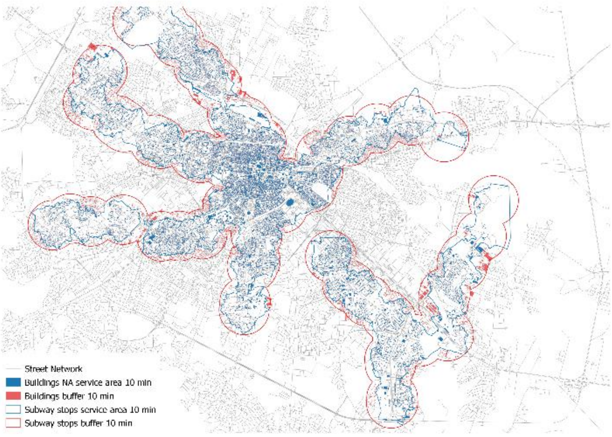

Figure 8. Comparison of accuracy of included buildings in the isochrone impedance in Buffer and Network analysis.

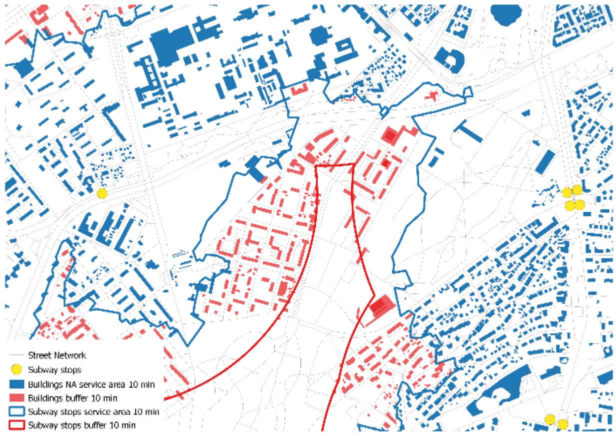

Figure 9. Comparison of accuracy of included buildings in the isochrone impedance in Buffer and Network Analysis for Ivan Vazov neighbourhood.

Another example is the Industrial area around Tsarigradsko shose. The Druzhba station is expected to provide access to the workplaces located around it (Figure 10). The Network Analysis shows a lack of pedestrian infrastructure, meaning that the station does not meet the initial expectations of 10 minutes accessibility to the workplaces.

Figure 10. Comparison of accuracy of included buildings in the isochrone impedance in Buffer and Network Analysis for Tsarigradsko shose.

The pedestrian accessibility to the green system of the city was also assessed by applying the Network Analysis. The results show that the south and eastern part of the city centre is served by more green spaces (Figure 11). Although the western and northern parts of the centre still have access to green space under 10 minutes, the spaces are small and are not sufficient for proper recreational activities. Inner southern and eastern neighbourhoods are well covered by the two big parks – Borisova garden and Yuzhen park.

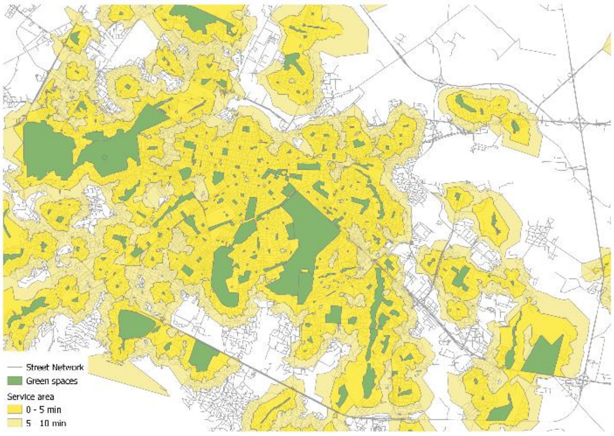

Figure 11. Network Analysis service area of parks.

In the west part of the city lies Lyulin district, which is the largest district by population in Sofia (Figure 12). Most of the buildings are multistory panel buildings, creating a typical modernist urban environment with large spaces between them. In the Southern part of Lyulin, Zapaden park is located, and the analysis shows that only a small area of the district is served by it. In the inner areas only a few green spaces are located, which does not satisfy the need for parks. A possible solution is to turn the spaces between the buildings into small parks and gardens.

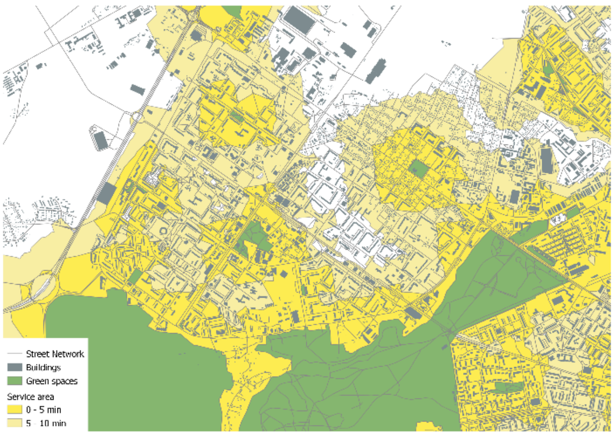

Figure 12. Network analysis service area of parks in Lyulin.

The southern part of the city, yet still north of the ring road, shows the worst results (Figure 13). This area also showed poor results in pedestrian access to public transport. The total absence of parks presumes the lack of access to green areas. This is another indicator that shows the need for a more holistic approach to this area, having in mind that it is still attracting investors as there are empty lots within a zoning regulation for construction.

The Urban Network Analysis was conducted with a Reach, counting the number of destinations (buildings) around each building within a search radius of 400 m. Neighbourhoods with small-scale but densely located buildings received higher scores. The analysis shows potential local centres but, in order to provide more insights about the urban environment, more parameters are needed such as residents, workplaces, volume, and activities which could be weighted.

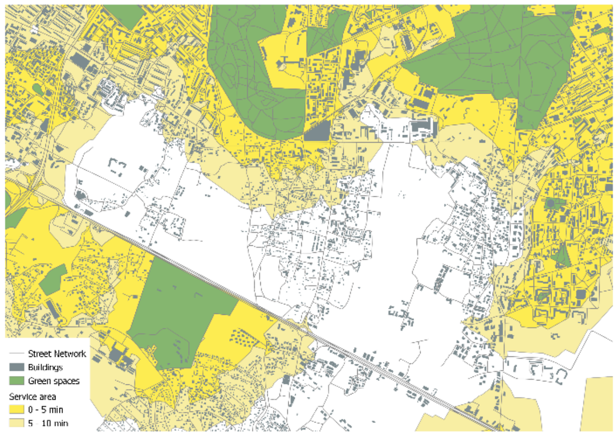

Figure 13. Network Analysis service area of parks in South areas.

The Space syntax shows, as expected, that the streets with the highest values of integration are from the primary street network, which makes the connections between the neighbourhoods of the city and the national road network outside Sofia (Figure 14). High integration is also observed in the central part of the city. This is due both to the radially circular structure of the primary street network and good communication with other parts of the city and to the orthogonal structure of the secondary street network, which distributes the traffic evenly. The neighbourhoods in the Southwest direction, along Tsar Boris Treti Blvd. and Bulgaria Blvd., such as Hipodruma, Belite Brezi, Buxton and Strelbishte, also show good integration due to the dense street network where route alternatives could be found. All neighbourhoods outside the ring road of Sofia are characterized by low values. Most of them rely on a single street to connect to the other parts of the city. In addition, the lack of efficient public transport explains the congestion on those segments.

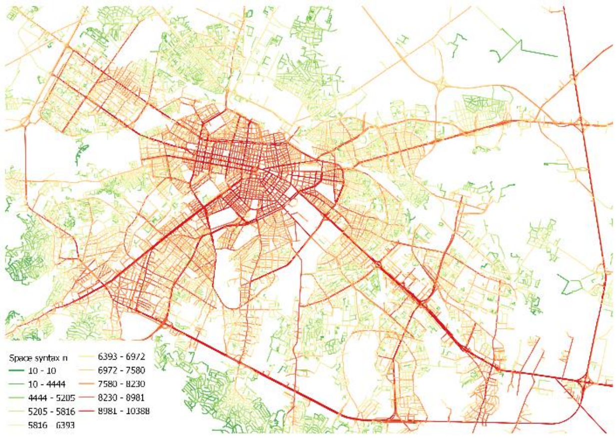

Figure 14. Spatial Syntax Integration Analysis without Search radius.

The analysis with a restricted Search radius of 400m discovers the integrated streets at a local level (Figure 15). The centre is again well-connected, due to the orthogonal street network. Well-integrated areas are seen in some neighbourhoods such as Lozenets, Ivan Vazov, Strelbishte, Iztok, Geo Milev, Reduta, Hadji Dimitar and Nadezhda, and single streets such as Acad. Boris Stefanov in Studentski Grad, Ivan Asen Second in Yavorov are clearly outlined. Due to their good integration within a radius of 400 m, these areas are or have the potential to be local service centres.

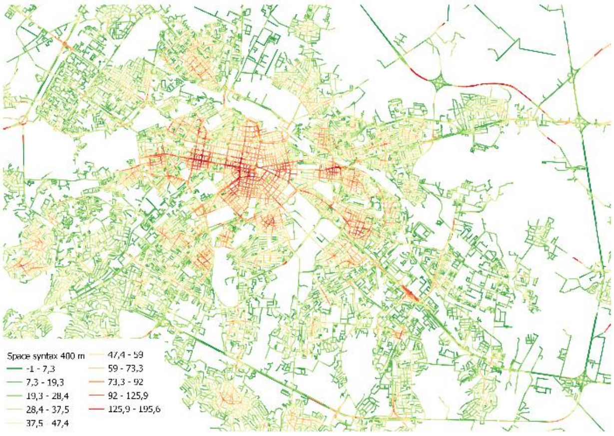

Figure 15. Spatial Syntax Integration Analysis with Search radius of 400 m.

The spatial analysis of commercial establishments shows an overlap with some of these areas, which proves the dependence and importance of good integration of the street segments at the local level with the location of shops, restaurants and other businesses. The presence of such facilities contributes to the development of neighbourhoods with a variety of functions, in which residents can have access to basic needs without having to travel long distances. Some of the areas are well connected, but they do not provide enough facilities. This is due to the nature of the development of the urban environment, which is another factor in the formation of service centres. These are the places with potential for business development that would create a full-fledged, vibrant neighbourhood. The analysis also shows the areas that need physical intervention and building new connections to increase integration at the local level. The historical development of the spatial structure of Sofia is due to several settlements, which through their growth are physically connected. In some parts, this connectivity is not of high values, the urban environment is not dense enough and streets are missing.

6. CONCLUSION

The presented study proves the effectiveness of Spatial and Network Analysis for the assessment of pedestrian accessibility. Such analyses could be a solid base to propose relevant measures for the improvement of the urban environment, considering the specifics of the different urban areas. Aiming for more pedestrians means aiming for more public transport, along with neighbourhoods providing more diverse activities in walking distance around the residential buildings. Well-integrated street segments on the local level are suited and naturally attract businesses. Providing proper infrastructure is also a key factor in this process, especially in areas where an investment activity exists or is expected in a near future. The quality of the pedestrian infrastructure is another factor of utmost importance that should be considered in further research on pedestrian route choice. The future work also considers the functional parameters of the buildings and elaboration on criteria to model their impact on the route choice of the pedestrians.
This research does not take into account the condition of the pavement, accessibility for the disabled or other on-the-street elements. It shows an initial macro-scale analysis of the network, which could be further detailed with more specific location-based analyses.

Although Sofia showed good accessibility results, some areas were detected where fully integrated measures are required. They need to be implemented only after proper analyses are conducted, which should be based on proven methodologies that do not create false expectations. These analyses are essential for the efficient spending of public funds and the development of infrastructure projects.

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