

Assessment of Spatial Inequality Through the Accessibility of Urban Services

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Abstract. This paper examines a method for assessing spatial inequality through access to opportunities and urban services based on modeling an intermodal graph of accessibility of urban areas. The goal is to obtain ratings on the difference in physical access to services and opportunities on public transport by social groups. This is done by collecting data on the city's residential areas and urban amenities that serve the functions of education, health, sports, and leisure. Calculation of travel time by public transport to the nearest service of each type is carried out using an intermodal graph. The result of the work is an assessment of the accessibility of services in terms of travel time, compared with urban planning standards.

Keywords: Spatial Inequality · Transport Accessibility · Sustainability · Sustainable Mobility

1 Introduction

Until the 1980s, city transport planning focused solely on increasing demand for car travel. As a result, great emphasis was placed on building infrastructure for road transport, prioritizing cars on the roads over public transport. One of the clearest examples of a car-centric urban transport policy is found in the cities of the United States - the sprawl of suburbs and cities in width forces residents to buy a personal car and use it daily as a primary type of transport. As a result of such a policy, many cities in the world have felt all the negative effects of motorization: deteriorating air quality, noise pollution, climate change, traffic congestion, increased deaths due to traffic accidents, inefficient use of urban space, inequality in access to services and opportunities [1]. However, it remains obvious that mobility, safety, and time travel affect the sustainability of cities. An efficient public transportation network is not only the main characteristic of a well-functioning and sustainable city [2], but also the most essential condition for improving the quality of life [3] and spatial equity [4].

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The urban environment is becoming an increasingly important factor for economic and social development. One of the key aspects is the accessibility of urban services, such as schools, medical facilities, recreational facilities, and others. However, the accessibility of these services is not the same for all citizens, and this leads to spatial inequality in the city. Studies show that regions with high mobility exhibit several positive outcomes, including lower levels of residential segregation, income inequality, and greater social capital, as well as better primary schools and family stability [5]. Conversely, efforts to improve amenities in low-public good communities through external policies may exacerbate segregation [6]. Existing studies have looked at access to urban services by car, while accessibility by public transport has not been studied as often [7,8]. Much attention is given to the study of pedestrian and bicycle accessibility, which is an important element of a sustainable and smart city, to vital urban services [9].

In large cities and metropolitan areas, public transportation plays an important role in residents' daily movements. Residents who do not own cars usually need more time and effort to get to their destinations because of the time it takes to walk to and from stops, the frequent stops on routes, and waiting times [10]. Urban policies that encourage and promote the principles of sustainable mobility in cities increase the focus not only on the use of public transport as the mainstay but also on the incorporation of equal access to services and opportunities through planning and monitoring [11].

This article focuses on assessing spatial inequality in the city through the public transport accessibility of urban services. We use data on the public transport network of the city and the location of urban services to evaluate how easy or difficult it is for residents of different city areas to access these services. Our approach not only assesses the accessibility of individual services but also evaluates the overall accessibility of urban services in different city areas.

2 Related Works

At the turn of the 20th-21st century, the problem of urban mobility was considered in terms of criticism of the car-oriented transport policies of world cities. Many works can be considered in two directions:

- A significant study of the problems of international transport (mobility). Such works reveal the problem of urban transport systems.
- The study of sustainable urban mobility in various aspects of the city and its description in such areas as the environment, health, urban planning, and design. In other words, sustainable mobility is perceived as an integral part of other urban systems.

Many cities are dependent on the constant use of private vehicles, with courses the lose their functionality and efficiency and become inconvenient for people [1]. The discrepancy between transport demand and the capacity of urban transport networks creates congestion in the road infrastructure [1]. These problems negatively affect the health and mobility of citizens.

The issue of sustainable mobility in terms of transport systems is considered in detail in the work of P. Newman and D. Kenworthy "Sustainability and Cities" [12]. The authors provide the concept of sustainable development and how it applies to cities with heavy car dependency, consider the changing urban economy in the information age, and describe the extent of car dependency worldwide. Great emphasis is placed on the study of the effect of reverse demand in transport planning. City administrations that pursued a car-oriented transport policy (an increase in street and road networks) actually created in the future an even greater burden on the road network, which it could not cope with [12]. From this, we can conclude that the problem of traffic congestion cannot be solved by developing and expanding road networks - owners of private cars who refused to travel because of traffic jams were motivated to use a personal vehicle, thereby increasing the load on highways and roads, resulting in more congestion.

Studies of transport systems in the US and the UK by Robert Noland and Lewison Lehn contain calculations and measurements of the reverse demand effect: a 10% increase in road capacity increases car traffic on the road by 2.9% in the short term [13], and even more in the long term - up to 10% [14].

Summarizing the above, we can recall the Downes paradox, which was identified by the American economist Anthony Downes back in 1962 - the expansion of the road network provokes an increase in traffic jams and congestion instead of reducing them, especially if public transport is not a priority in urban planning [15]. The cheaper and more attractive a private car becomes to use, the more people will use personal transport, thereby increasing the load on the road network. Due to the provoked demand effect in the US, traffic congestion increased by 144% from 1993 to 2017 [16].

The Downes-Thomson paradox essence is that the weighted average speed of personal vehicles on the road network directly depends on the speed at which users of off-street public transport get from the starting point to the endpoint (meaning the railway, metro, buses, and trams moving along the dedicated lane). There is a Downes-Thomson paradox due to the transition of passengers from public to personal transport under the influence of pent-up demand. The outflow of passengers from public transport reduces the profits of its operators and forces them to increase intervals, which forces other passengers to switch to private vehicles. However, at the same time, the traffic situation is also deteriorating - believing in the improvement of the traffic capacity of the road during rush hours, drivers who previously tried to use the road outside peak hours begin to use it. Both of these factors upset the transport balance, resulting in an explosive increase in the flow of vehicles on the widened road, causing even more congestion and deteriorating public transport services [15] [17].

A separate Pigou-Knight-Downs paradox is a consequence of the Downs-Thomson paradox that, in the presence of public transport, an increase in the capacity of public roads leads not to an improvement, but to a deterioration in the traffic situation [18]. A similar effect was shown by Dietrich Braes in the so-called Braes Paradox: according to it, adding alternative paths to a transport

network with independent ("selfish") load distribution on its elements can reduce its efficiency [19].

Mobility is one of the key indicators of urban areas, determining the speed and movement comfort of all people in the city. Sustainable mobility is an important part of UN SDG 11 (United Nations Sustainable Development Goals). This goal assumes by 2030 the introduction of the practice of using universal public inclusive transport, improving road safety, and reducing the negative environmental impact of transport systems on the environment [20]. All the ideas of the SDGs imply a close relationship between all areas: the measures and actions of any goal have a positive effect on the implementation of other goals. Sustainable mobility involves the development of:

- pedestrian infrastructure, promoting the priority of pedestrians in cities;
- public transport;
- alternative modes of transport.

The city is a space for every resident of the city, and public transport uses it more efficiently than private vehicles. Public transport frees up road space for use by all residents of the city and reduces the level of street congestion, which makes cities unattractive places to live and work. The distribution of street space between modes of transport is determined by carrying capacity - the number of passengers that one or another system is able to provide for one available lane. The carrying capacity of a 3.5 m wide lane for a bus and bicycles is approximately the same - about 4 thousand consumers per hour, which is about 4 times higher than the carrying capacity of road transport (about 1000–1200 passengers per hour) [21].

Studies show that when transported by bus, pollutant emissions can be reduced by 1.3-5 times compared to transportation by individual cars, and when transported by rail (taking into account energy production) - by 4-1000 times [22]. Electric public transport, taking into account the generation of electricity at power plants, emits ten times less pollution than personal automobile transport [23].

The impact of sustainable mobility on the ecological situation in cities is considered within the framework of the theory of "urban metabolism" in the book "Understanding Urban Metabolism". The ideas of urban metabolism see the city as a system that exchanges and transforms energy, water, carbon, and pollutants in cities. The authors argue that the understanding of all urban processes is directly related to urban planning [24]. The key characteristics in the concept of developing a sustainable city should be safety, the level of pedestrianization and transport accessibility of territories, and livability. The authors point to a clear relationship between an ecological approach to mobility and reducing the negative impact of transport systems on the environment, reducing the consumption of urban resources and energy, as well as emissions of harmful substances [24].

It is also necessary to note the importance of the efficiency of public transport as one of the key aspects of sustainable mobility within the framework of a transit-oriented concept [25]. The importance of the transport "framework" is

indicated, which includes high-speed isolated public transport routes in the planning structure of the city [25]. The paper emphasizes the idea of the importance of transit points, around which it is most profitable to place trade facilities, business centers, and compact housing. Such a planning structure is multifunctional and allows minimizing the load on the transport network due to the presence of everything necessary in one area [26].

The concept of a compact city is closely related to the idea of transit-oriented development: the compact location of residential, social, and economic facilities in the city contributes to the development of achieving a balance between the negative and positive effects of high population concentration [27].

Transport planners have developed a strong tradition of using the scientific method to solve urban transport problems using the classical deductive approach (gathering data, defining goals and objectives, forecasting future needs) [28]. This approach takes land use as a given and does not suggest that transport planners should advocate land use change to create a more efficient transport system. However, from a sustainability perspective, urban transport planning cannot be considered in isolation from land use and the environment without compromising the goal of sustainability [29].

Urban areas have an important criterion in terms of mobility - transport accessibility [30]. Traditionally, transport accessibility has been defined as "the potential for interaction" [31] and can be thought of as the extent to which land use and transportation systems allow people to get to their destinations, to 'connect with each other' through a combination of transport modes [32]. This indicator can be considered as an important social score that reflects the quality of life of people in cities for sustainable smart development [33,34]. The vitality of urban areas depends largely on the quality of the environment, the availability of urban amenities, and their accessibility in particular [30].

Modern urban planning must pay great attention to the development of places with high accessibility and to improving the efficiency of public systems [35]. Quick access to city services is one of the main targets of the 11th UN Sustainable Development Goal (Sustainable Cities) [36]. There are differences in urban planning between mobility and accessibility. The first is associated with increased efficiency of transportation systems, and the second with improved access to opportunities and services that meet the needs of city residents [37]. But mobility is inseparable from accessibility since access depends largely on the "quality" of the network. The goal is not just "movement," but "access" to goods and services. Research shows that accessibility "planning" should be based on high levels of connectivity between urban functions (services) and improved quality of life, rather than on predictions of future traffic volumes and congestion [38,39].

There are several types of accessibility [39,40]:

- Accessibility of the transport system (physical access) depends on the time, distance, and effort required to reach the network.
- System-facilitated accessibility, which evaluates the user's ability to get to a destination and includes the cost of travel time.

– Integral accessibility, which considers access to the number of possible destinations.

3 Method

This section presents a method for assessing spatial inequality in access to urban services. Inequality is assessed through the transport accessibility of a residential neighborhood (block) to the nearest service of each type. The intermodal graph developed at the Urban Data Analysis Lab at ITMO University is used to calculate the transport accessibility of services [41]. Intermodal routes consider providing greater flexibility in the movement of citizens when modeling the transport accessibility of the urban environment. Travel time calculations do not include the use of personal or shared transportation, including micro-mobility. For each type of service, the accessibility time is scaled in accordance with city planning standards [42]. Based on the time value to the nearest service, each living block is assigned a score. The proposed method is considered in Saint Petersburg, Russia's second most populous city. It's located in the northwest of the country on the Gulf of Finland and the Neva River estuary. Population: 5,598,486 (2023) people.

3.1 Data

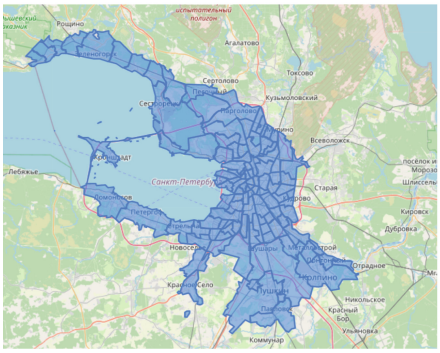
To model spatial inequality through transport accessibility, the following data are needed: a geo-layer with urban blocks, services, residential buildings, data on public transport stops, pedestrian and public transport routes. The spatial unit for which the accessibility of services will be assessed is a block. To get the city blocks, it is necessary to have geolayers with administrative and district boundaries of the city, geometry of water bodies (rivers, canals, bays, etc.), graph of the street and road network. The data sets of city boundaries and its blocks, street and road network, residential buildings, urban services, and appropriate tags from the open map service OpenStreetMap (OSM) [43] are uploaded. To build an intermodal transport accessibility graph, we require data on transit routes, stops and walking routes [41].

3.2 Construction of Living Blocks

The spatial unit for which the accessibility of services will be assessed is a block - a section of an urbanized area, bounded on all sides by the street and road network. To obtain the geometry of blocks, geo-layers of the administrative boundaries of the city, water bodies (rivers, lakes, etc.), as well as the city's road network, are needed. Figure 1a shows the boundaries of the municipalities of Saint Petersburg in the form of a map obtained from OSM. Figure 1b shows the geometries of all water bodies. Using the OSMnx [44] package to work with spatial data, a graph of the Saint Petersburg street and road network is unloaded (Fig. 1c).

The geometries of roads and water bodies are cut from the geometry of the city. Objects of the MultiPolygon type may appear - several polygons combined into one object. They need to be divided into separate polygons.

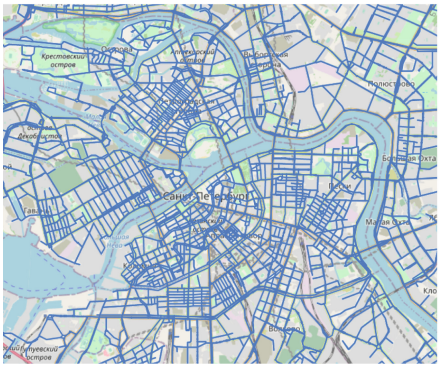
The result is shown in Fig. 1d. These blocks may not coincide with the division into land plots, as in the cadastral register. Data on living buildings and city services are added to the received blocks on the map. Blocks in which there are residential buildings are shown in Fig. 2a.



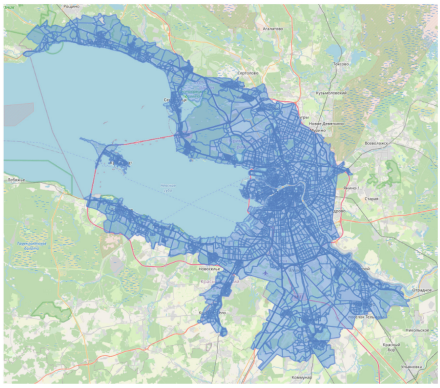
(a) Geolayer with the boundaries of Saint Petersburg municipalities



(b) Geolayer with boundaries of water bodies in Saint Petersburg



(c) Geolayer with the Saint Petersburg street and road network

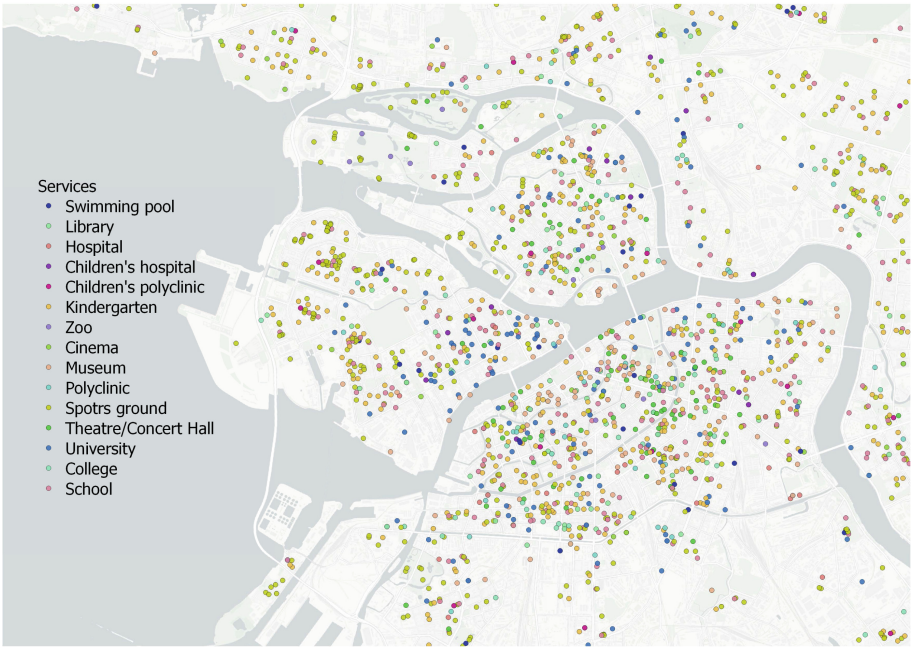


(d) Geolayer with Saint Petersburg blocks

Fig. 1. Obtaining city blocks



(a) Geolayer with living blocks



(b) Geolayer with city services

Fig. 2. Data on living blocks and city services

3.3 Intermodal Transport Accessibility Graph

The intermodal graph for calculating travel times by public transport has been compiled using the City Geo Tools spatial data library [45] and the method described in the paper by the staff of the Urban Data Analysis Lab at ITMO University [41].

Datasets about the pedestrian urban network and public transport routes are uploaded using appropriate tags from OSM. The datasets contain: coordinates of pedestrian sections, coordinates of transport routes, and corresponding public transport stops.

Pre-processing of the uploaded data is required [41]:

1. Transform linear objects into a coherent pedestrian network and into a coherent network of public transport routes;
2. Projecting the points of stops onto the lines of the respective public transport routes and the nearest lines of pedestrian sections;
3. Partitioning linear features at the projected points and adding linear sections connecting the point projections to the pedestrian urban network dataset;
4. Calculating the lengths of linear segments of pedestrian and vehicle routes and their travel times based on the average speed of a pedestrian or vehicle;
5. Obtaining a graph by combining the pedestrian graph and the public transport graph at the vertices corresponding to stops.

The edges of this graph are the pedestrian ways, and public transport routes are the nodes are the points of connection between the pedestrian sections and public transport stops (Fig. 3).

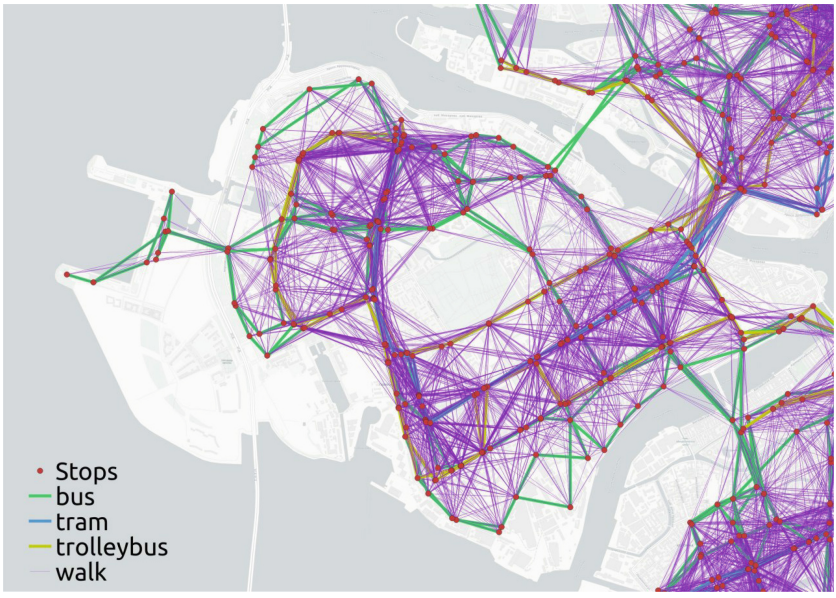


Fig. 3. Intermodal transport graph

3.4 Calculating Accessibility Times

To calculate the travel time between all the city blocks, the city blocks and the intermodal transport accessibility graph must be mapped. For each city block, a centroid is constructed, and the nearest node on the graph (the beginning of a pedestrian route or a public transport stop) is searched from it. From this node the distance and time on the intermodal graph to all other nodes that represent other city blocks is calculated using the Dijkstra algorithm [46]. Unlike similar methods, Dijkstra's algorithm searches for the optimal route from one given node to all other nodes. Along the way, it calculates the path length - the total weight of the edges it passes along this route. The result is a similarity matrix of distances among all blocks.

3.5 Calculating the Travel Time to the Nearest Service of Each Type for Each Living Block

A list of services with accessibility times is shown in Table 1. To calculate the travel time to the nearest service for each living block, the following steps must be performed:

1. From all the blocks in the horizontal similarity matrix, select only residential blocks (i.e., those with residential houses);
2. For each type of service, a different similarity matrix of times between blocks is produced;
3. Then, in the matrix, the blocks with no services are deleted vertically;
4. For each residential block, the closest service of each type by the lowest time value is found, and the time attribute is added to each living block.

It is worth noting that if the nearest service is located in a living block, the value of the in-transit time is 0.

Table 1. City Services

City infrastructure	City function	Type of service	Accessibility time
Leisure infrastructure	Culture, entertainment, creativity	Library	up to 30 min
		Zoo	up to 60 min
		Cinema	up to 60 min
		Museum	up to 60 min
		Theatre/Concert Hall	up to 60 min
Leisure infrastructure	Sport	Swimming pool	up to 30 min
		Sports ground	up to 30 min
Social infrastructure	Healthcare	Hospital	up to 60 min
		Children Hospital	up to 60 min
		Children's Clinic	up to 15 min
		Clinic	up to 15 min
Social infrastructure	Education	Kindergarten	up to 10 min
		University	up to 60 min
		College	up to 60 min
		School	15–30 min

3.6 Scoring Accessibility

For each block, an accessibility score is given according to the travel time to the nearest service of each type (Table 2). For the basic accessibility time values are taken from the urban planning standards of Saint Petersburg [42]. If the block is provided with service within the time accessibility according to the standard, then the accessibility score is considered to be normal. If less time is spent than according to the standard, then the accessibility score is considered high, and if more time is spent than according to the standard, then low.

Table 2. Time accessibility of city services

Accessibility time of city services					
Accessibility time	**Up to 10 min**	**Up to 15 min**	**Up to 30 min**	**Up to 60 min**	
Services	Kindergarten	Children's Clinic, Clinic	School, Library, Swimming pool, Sports ground	Zoo, Cinema, Museum, Theatre/Concert Hall, Hospital, Children hospital, University, College	
	0-4 min	0-5 min	0-10 min	0-20 min	5 (High)
	4-7 min	5-10 min	10-20 min	20-40 min	4 (Good)
	7-10 min	10-15 min	20-30 min	40-60 min	3 (Allowable)
	10-14 min	15-20 min	30-40 min	60-70 min	2 (Low)
Score	More 14 min	More 20 min	More 40 min	More 70 min	1 (Poor)

If the value of the time to the nearest service is equal to the boundary value, then the accessibility score is set to a large value. The overall assessment of the transport accessibility of the block is calculated according to the arithmetic mean. The assessed results of accessibility of each type of service are put on the map and highlighted with colors according to the score.

4 Results

The method presented above is applied to selected types of services in Saint Petersburg (Table 1). Figure 5 shows, as an example, the assessments of kindergarten accessibility for living blocks.

The blocks are colored according to the accessibility of the nearest service. The results show that there are more living blocks in the central part of the city (Fig. 5a) with the accessibility of 3 and above points. However, the distant blocks from the center (Fig. 5b) have poor accessibility to kindergartens, which may be due to the small number of services themselves. Consequently, residents of remote areas have unequal access to kindergartens in terms of travel time.

The accessibility of each service individually indicates that, in a block of determination, a group of people will spend more/less time getting to the service.

In neighborhoods where services have better accessibility, residents are potentially less stressed to get to the needed service. As accessibility times increase, so does the inequality between residents in different parts of the city. If the travel time to a destination by public transportation is too long, it is likely that residents will use private motorized transportation more often. This eventually encourages the irrational use of cars, and the functionality and efficiency of the city are lost.

All the selected services are divided into 4 groups according to the accessibility time according to city planning standards - up to 10, 15, 30 and 60 minutes (Table 2). For the obtained results the distribution of the accessibility time was made (Fig. 4). Group 1 service accessibility time satisfies the requirements of urban norms [42] for residential neighborhoods to the extent of 43.43%, Group 2–33.87%, Group 3–75.5% and Group 4–77.25%.

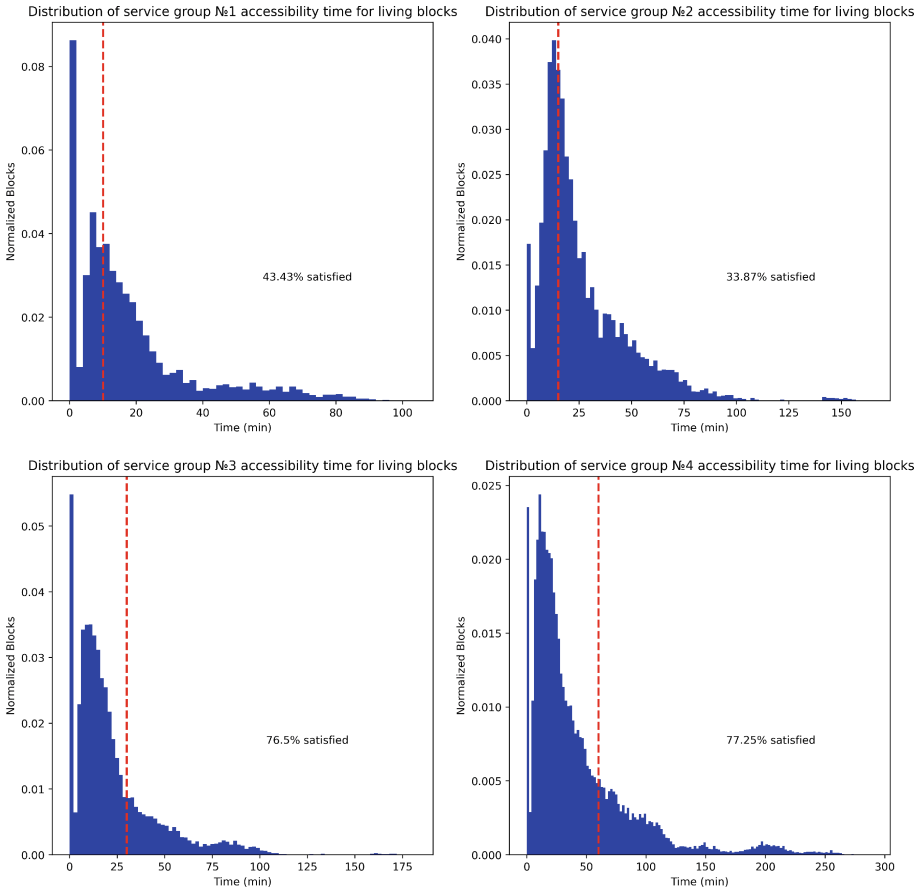
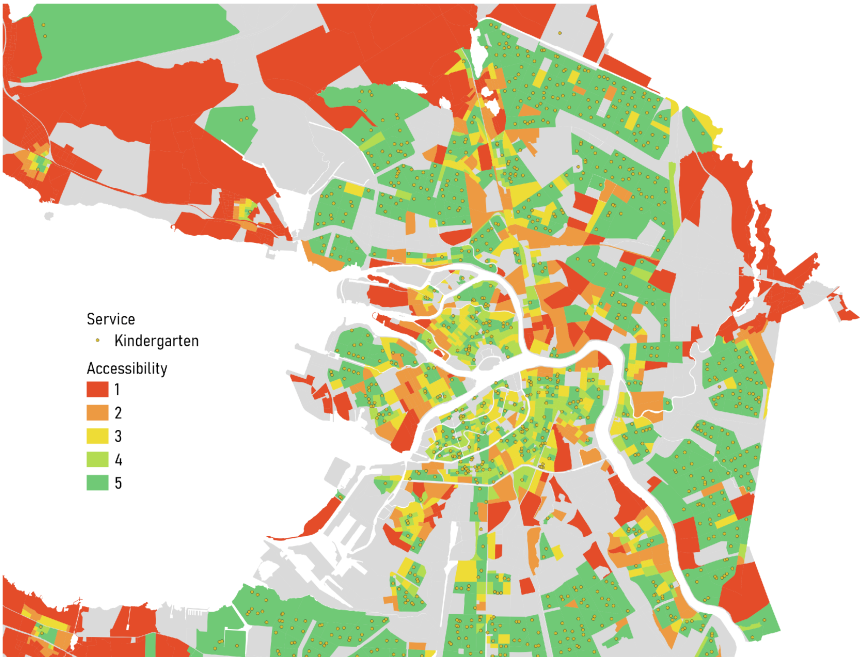
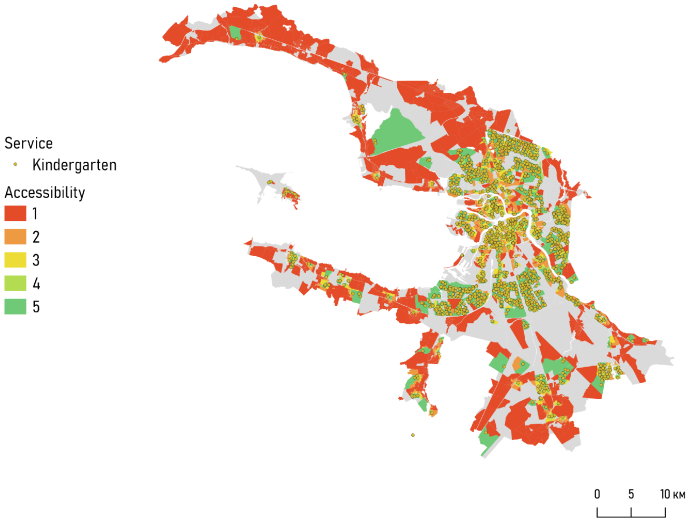


Fig. 4. Distribution of the accessibility time for living blocks



(a)



(b)

Fig. 5. Accessibility of Kindergartens

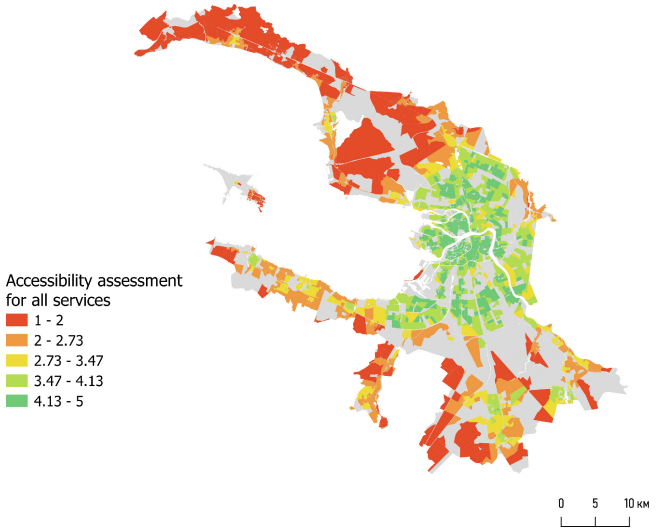


Fig. 6. The overall assessment of the service accessibility

5 Discussion

The approach to the assessment of spatial inequality through the accessibility of urban services allows one to assess in which parts of the urban area under study social groups can potentially be stressed with access to urban benefits. The proximity of a service is not the main criterion of choice for city residents. Complex and costly demand models are used to account for such complex aspects as a choice, behavior, and people's preferences. However, it is not always possible to predict what urban services people will use. That is why the closest service is worth considering as the minimum base or basis that can be provided by the territory.

6 Conclusion

In the course of this work, it is possible to propose a method for assessing spatial inequality through access to urban services, using open data sources. This approach allows to see the weak spots, where there is unequal access to urban amenities, in combination with settlement models and methods for estimating transportation in a city, such as the average travel time, and transport connectivity. It is possible to obtain an estimate of transport accessibility using an intermodal transport graph, which considers not only public transport routes but also pedestrian routes. This allows a more accurate estimation of travel time to a service that is within walking distance and to a remote service on PT. On the basis of this method, plans can be proposed not only for the development of the public transport system but also for land use, and the placement of new service points.

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