Assessment of Spatial Inequality in Agglomeration Planning

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Abstract. The paper considers the problem of spatial inequality of agglomerations. The paper proposes an approach to the estimation of spatial inequality based on the intermodal transport graph and data on the placement of urban services in the agglomeration cities. This approach has been experimentally tested on the agglomeration of St. Petersburg. The result is an assessment of the influence of cities in relation to each other, as well as the evaluation of each city by the availability of a particular type of service.

Keywords: Network modeling · City graph · Agglomeration · Settlement system · Urban planning · Urban Environment Model · Informational Model · Algorithms on Graphs · Urban Neighborhood Model · Urban Environment Model · Urban Neighborhood Centrality · Urban Neighborhood Profile

1 Introduction

The article is about spatial inequality of urban agglomerations. The spatial inequality is defined as the socio-economic inequality of the population caused by differences in the development of territories. Such distinctions, in turn, can be caused not only by geographical, but also historical, cultural and other reasons [1].

The concept of spatial inequality is closely connected with the assessment of the quality of life for the population of the studied territory. There are many studies on the implementation of such an assessment in terms of one or more factors – for example, the level of income or level of education [2], but there is no consensus among researchers on the rules for building a comprehensive assessment of the quality of life for the population of a particular territory. This is partly due to the fact that there is no unified definition of what "quality of life" is and what parameters it includes. In particular, the following groups of parameters can be identified [3]: physical, mental, psychological, social, cultural, economic, political and environmental, but there is no clear understanding of how they can be formalized to build an integral assessment for the purpose of comparing different territories with each other.

The heterogeneity of the quality of life is clearly manifested when considering such urban systems as agglomerations. The concept of "agglomeration" itself is quite vague: it is not part of a formal administrative-territorial division and has no clear boundaries.

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In this regard, the same agglomeration, depending on the chosen approach to defining its boundaries, may include different towns and villages [4]. An urban agglomeration is a group of cities that are territorially close and have stable economic, labor, recreational and cultural relations [5]. The region where an urban agglomeration is located should have a highly developed transport infrastructure, be spatially compact and economically closely integrated [6]. Urban agglomeration is a natural stage of urban development and urbanization, when cities in specific regions begin to "cooperate", not just compete with each other [7]. Urban agglomerations have some characteristics, such as the integrity of economic markets, functional connectivity of territories, which are achieved due to the developed transport infrastructure [8].

This paper studies the concept of spatial inequality of territories and proposes an approach to its assessment for agglomerations based on the construction of the transport graph and data on the availability of services in the cities of agglomerations. Experimental testing of the method was carried out on the example of the agglomeration of St. Petersburg (Russia), which includes a number of territories of the city itself and the surrounding cities of the Leningrad Oblast. This agglomeration is the second largest in the Russian Federation (after Moscow agglomeration) and is of interest for the study partly because of the known heterogeneity of population on its territory.

2 Territorial Dissimilarities in Settlement Systems

The settlement system in this paper is defined as a set of settlements that are territorially close and functionally interconnected [9]. One of the actual problems both within one and between several settlement systems is the differences in the quality of settlement life caused not only by geographical differences of territories, but also by the historically established socio-economic disparities in their development.

On one scale of consideration, agglomerations can be chosen as a settlement system. In general, agglomerations can be defined as sets of cities and surrounding territories, united by stable links of various types (labor, cultural, infrastructural) between their populations. However, the delimitation of the boundaries of agglomerations, as well as the boundaries of other settlement systems, is subject for a discussion due to the lack of a unified approach among researchers.

2.1 Approaches for Delimitation of Agglomeration Borders

The question of delimitating the boundaries of agglomeration depends on which processes are chosen as fundamental for the formation of such a system of human settlement. The two main categories of approaches to defining the concept of agglomeration can be distinguished as economic and functional [10].

The economic approach is based on statistical data on the socio-economic processes in which the territory in question is involved. Such data for agglomerations can be the following [11]:

- number of cities with population over a certain threshold;
- per capita GDP;
- non-agricultural industries' impact on the GDP;

- clear distinction of economic belts of certain transportation radii.

The functional approach is based on actual data on the human settlement and interconnections between settlements. The advantage of the approach is a broader set of data that is publicly available: the number of population of territories and their parts, the characteristics of transport infrastructure, the location and parameters of services – locations of interest to the population satisfying certain needs. In this regard, this approach was chosen for the construction of the agglomeration assessment model in the framework of this work.

2.2 Spatial Inequality Problem: Case Study and Countermeasures

One of the reasons of spatial inequality is different opportunities for earning money between more advantaged areas with more amenities and services and peripheries and rural areas that become poorer in comparison. Mastronardi and Cavallo's study demonstrates that income inequality appears to be greater in "densely populated urban centers with a high incidence of tertiary activities and young population" [12].

However, it would be unreasonable to avoid creating urban centers since while rural areas exhibit lower inequality, they also often lack basic healthcare, education, and mobility services. In fact, setting up infrastructure in sparsely populated areas would be too costly. So, rather than abolishing metropolises, Mastronardi and Cavallo suggest redistributive policies that are supported by policies that affect market functioning, corporate governance, intergenerational transmission of advantages and disadvantages, and the link between structural and sectorial policies [12].

Other studies also demonstrate that "high mobility areas have (i) less residential segregation, (ii) less income inequality, (iii) better primary schools, (iv) greater social capital, and (v) greater family stability" [13] while "policies that exogenously improve amenities in low-public good communities may increase segregation" [14]. Besides, as the model of Sun et al. suggests, market-driven residential redevelopment tends to exacerbate spatial inequality through facilitating income sorting (concentration of people with high income in the advantaged areas) [15].

Reducing the spatial inequality of agglomerations can be carried out in different ways:

(1) local actions – adding new opportunities for the population by creating new services in needy settlements;
(2) connecting actions – improving the transport connectivity of the agglomeration through measures to improve its transport system;
(3) administrative actions – by means of dispositive correction of the composition of agglomerations through stimulating measures for the settlement of people.

3 Spatial Inequality Modeling

Cities located outside the agglomeration core cannot always provide the full range of services and opportunities to residents that are available in the "center" [16, 17]. There are several common reasons why residents of peripheral cities travel to neighboring or central cities [18]: work, education, retail, recreation.

In this paper, spatial inequality is assessed through the accessibility/sufficiency of large shopping and entertainment centers. Travelling from one city to another within an agglomeration for the purpose of shopping is one of the most common after work and study [18]. Data on labor migration is not openly available, so it is not expected to be used.

Retail trade is an important component of the urban economy. Large objects of trade can have a wide service area and a large temporary transport accessibility (from 30 min) [19]. Cities and towns where such shopping centers are located can be points of attraction, serving the needs of neighboring territories.

3.1 Selected Agglomeration Description

St. Petersburg agglomeration (the second largest in Russia) was chosen for the analysis due to the known heterogeneity of population on its territory. The selected agglomeration is shown on Fig. 1.

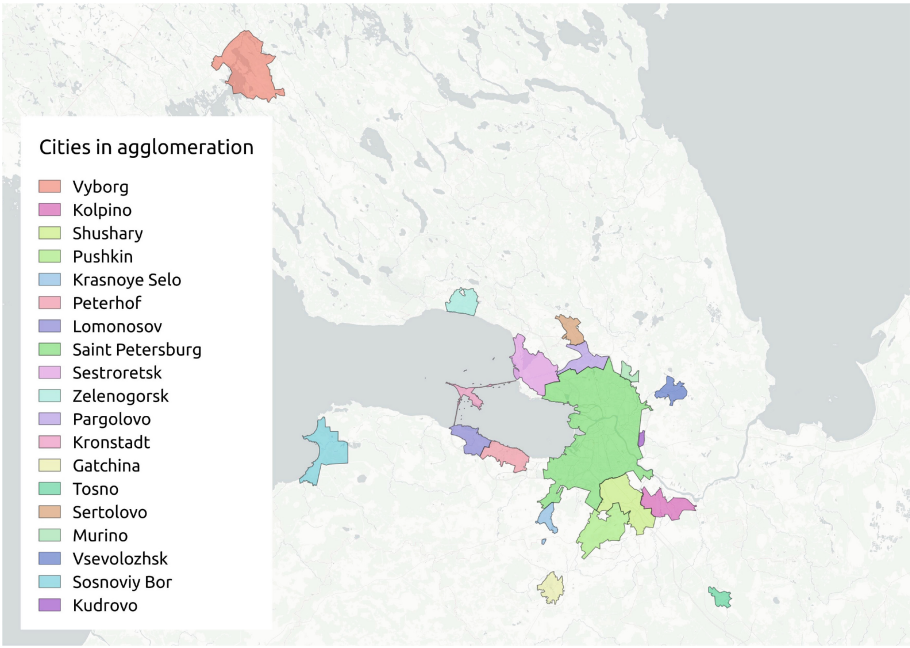

Fig. 1. Saint Petersburg agglomeration

For the analysis and assessment of spatial inequality, the cities and settlements that are part of St. Petersburg and the Leningrad Oblast were selected according to the studies dedicated to the identification of the boundaries of the St. Petersburg agglomeration [16, 18]:

- St. Petersburg (Central, Admiralteisky, Petrogradsky, Vasi-leostrovsky, Kalininsky, Krasnogvardeisky, Nevsky, Frunzensky, and Kirovsky administrative districts as a whole; Primorsky district without the municipal entity Lakhta-Olgino and the settlement of Lisy Nos; Vyborgsky district without the settlement of Levashovo and Pargolovo; Moscow district without the territories of Aviagorodok and Pulkovo; Krasnoselsky district without Krasny Selo and Gorelovo);
- cities within the administrative boundary of St. Petersburg (Kol-pino; Pushkin; Peterhof; Shushary; Krasnoye Selo; Kronstadt; Pargolovo; Lomonosov; Sestroretsk; Zelenogorsk);
- cities within the Leningrad Oblast (Gatchina; Vyborg; Vsevolozhsk; Sosnovy Bor; Sertolovo; Murino; Tosno; Kudrovo).

3.2 Data Selection and Preprocessing

To model the spatial inequality of the St. Petersburg agglomeration the following data are needed:

- population and cities in the agglomeration;
- about shopping and entertainment centers and their areas;
- intracity and external public transport routes.

Population data are taken from the Federal State Statistics Service of the Russian Federation Rosstat according to the results of the census for 2020 [20]. Geometries of the agglomeration cities and data on shopping centers were obtained using the open mapping service OpenStreetMap (OSM) [21]. The routes and stops of intracity (bus, trolleybus, streetcar, metro) and external (trains and electric trains) public transport are also taken from OSM by appropriate tags. The CityGeoTools library for modeling the intermodal graph [22] is used to calculate the time of accessibility of shopping centers and travel time between cities.

3.3 Accessibility Graph: Algorithm and Construction

A public transport graph was used to model service availability. The general scheme of the algorithm is shown in Fig. 2:

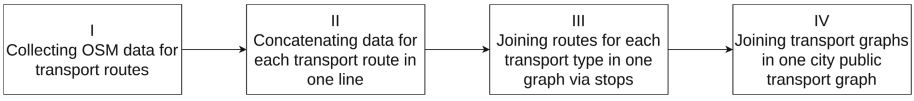

Fig. 2. General outline of the algorithm

The first step is to select the types of transport used for modeling, as well as the cities included in the agglomeration. Types of public transport selected for modeling

the intermodal transport graph: tram, trolleybus, bus, train, subway. It is necessary to consider intra-city modes of public transport, as accessibility is modeled between the centers of cities. In this paper, we have not considered accessibility by private car, as this was not the purpose of the work.

At the second stage, an intermodal graph was constructed for each city. The general scheme of graph construction for one city is shown in Fig. 3 below:

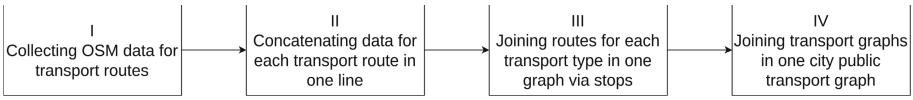

Fig. 3. Graph modeling algorithm for one city

The graph modeling algorithm is taken from the work [23]. At the first stage, routes and stops for the selected type of transport are loaded from OSM. Then they are combined into a single network for each type of transport. At the end, all types of transport are combined into one network, forming a single graph. The weights of the edges is the time between the nodes (PT stops) of the graph. The difference from the work [23] in this case is that to build a graph for agglomeration it is necessary not to cut the transport routes by the geometry of the city, as it is done in the mentioned work (but it is possible to limit them by the geometry of the selected area to discard unnecessary information). Thus, a route from the OSM data relating to a city can go beyond the city, for example,

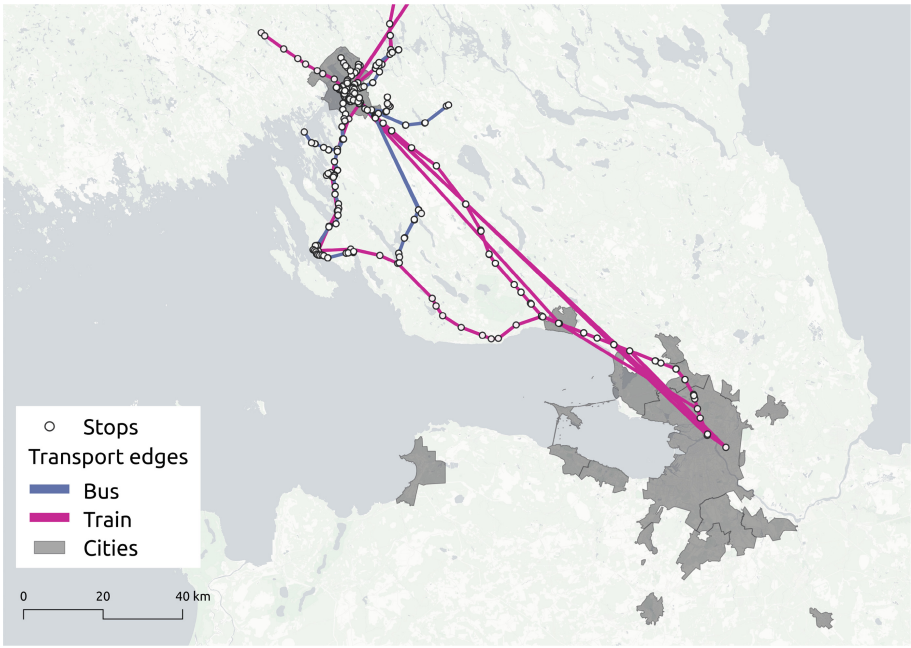

Fig. 4. Transportation routes outside the city

when a bus or train travels from one city to another. This change made it possible to obtain data on connections between cities.

The transport graph for one city, without cutting the routes by the city boundaries is shown in Fig. 4.

It is important to note that Vyborg and St. Petersburg are connected by a high-speed train line. The most distant from the other cities of the agglomeration, still connected to the analyzed city centers, is Vyborg. Since in the current method the train speed is the same everywhere in the graph, the weight of the edge was manually changed in order to highlight the line. The high-speed train line on the transport subgraph is highlighted for clarity in Fig. 5. Such a line exists only between these two cities in the agglomeration and this reflects the inequality of the spatial component of the equity in high-speed railways (HSR) [24]. Thus, this train allows Vyborg to be a full-fledged part of the St. Petersburg agglomeration and maintain a good level of influence in the cotext of social services, such as aforementioned “malls”.



Fig. 5. High-speed train between Vyborg and St. Petersburg (the core of the agglomeration)

After obtaining the transport graph of one city, it is necessary to connect it to the graph of the neighboring city. However, we cannot be sure that one route in the graph of one city ends where the next route of another type in another graph begins. This mismatch can be seen in the following Fig. 6:

In order to connect the graphs of the two cities it is necessary to take into account the possible transfers between one or more modes of transport. Thus, the nearest nodes of the graphs (stops) within a radius of 100 m were connected by a line. This connection



Fig. 6. Non-intersecting transport graphs of cities; and united non-intersecting transport graphs of cities

reflects the possibility of walking between stops. Accordingly, the weight of such an additional edge will be the Euclidean distance between the points (the length of the edge) divided by the speed of a pedestrian. It should be noted that in this case it was not possible to construct a path between two selected points on the pedestrian graph, because sometimes transport routes end at the stations, where there is no pedestrian graph.

As a result, a transport graph covering the entire St. Petersburg agglomeration was obtained, which is shown in Fig. 7:

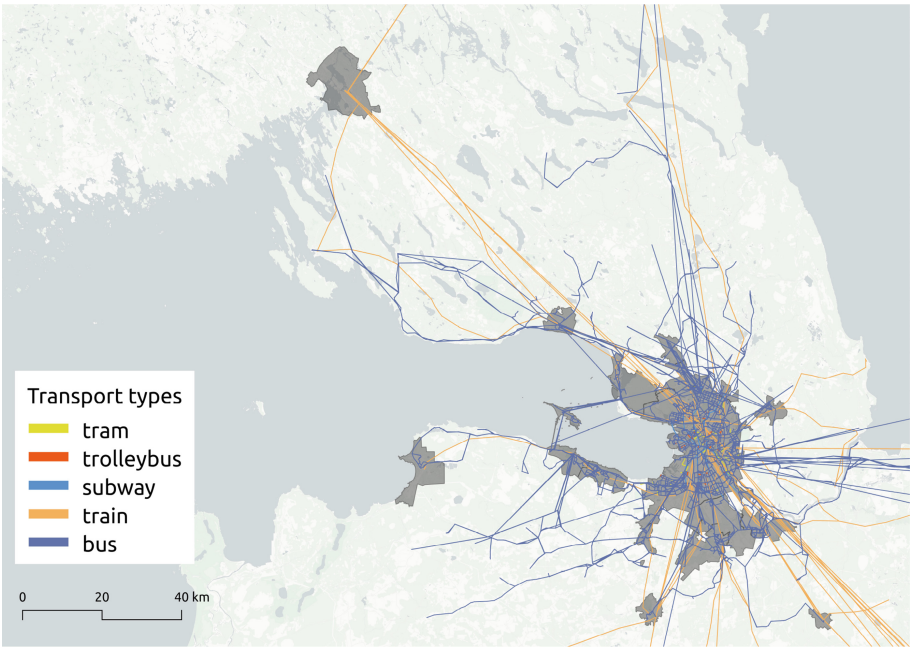

Fig. 7. Transport graph for the St. Petersburg agglomeration

In order to calculate the distances between cities on the transport graph it is necessary to use the following algorithm, as is shown in Fig. 8:

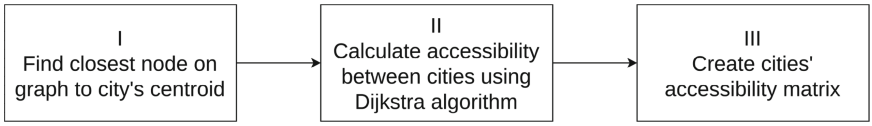

Fig. 8. The algorithm for calculating accessibility between cities

This algorithm calculates accessibility between cities by different types of transport using transfers between them.

The distribution of shopping centers in St. Petersburg and Leningrad Oblast by area is shown in Fig. 9:

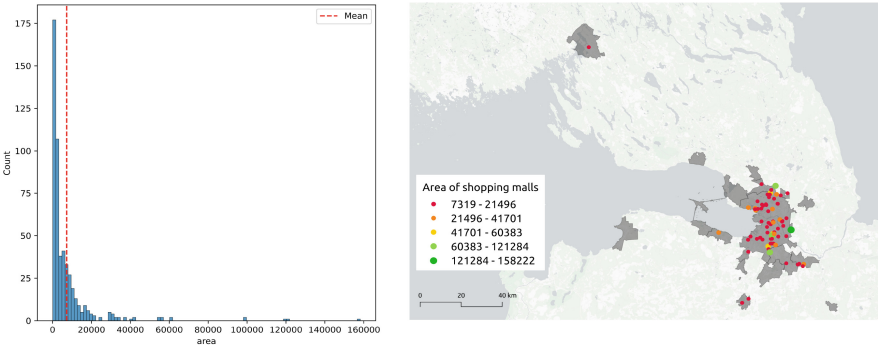

Fig. 9. Distribution of Shopping Centers in Leningrad Oblast by area and distribution of shopping centers in Leningrad Oblast with area larger than average

Since the OSM data does not always accurately reflect reality and there may be small shopping centers under the mall tag, and to reflect the fact that people are more likely to go to another city for a large shopping center, only shopping centers with a larger than average area in the Leningrad Oblast were selected. The distribution of all malls and only those whose area is larger than the average is shown in Fig. 9.

In order to estimate the spatial inequality in the agglomeration, it is necessary to calculate the inequality coefficient:

Let K - be the number of cities in the agglomeration:

- $link_{ij}$ - normalized connectivity between cities i and j. Constraint: $link_{ij} < 120min.$; *Services* - the number of services in the city;
- I_i - the inequality indicator for the selected city;

Population - the population in the selected city.

$$I_i = \frac{Services_i}{Population_i} + \sum_{j=1}^{K} link_{ij} \cdot \frac{Services_j}{Population_j} \quad (1)$$

In this paper, we use normalized weighting coefficients, because we compare cities only within the agglomeration and not with the target value. As a result of calculating the coefficient of spatial inequality between the cities of the St. Petersburg agglomeration, we obtained an estimate for each city based on its distance from the other cities and the number of services in the considered and the nearest cities. The right side of the equation is shown in Figs. 10 and 11. Figure 10 shows directly the weighting coefficient of the connection between the cities ($link_{ij}$). Figure 11 shows the impact of cities on each other, taking into account transport connectivity and the presence or absence of the services in question. The results are presented as a map in Fig. 12 below. The values of the obtained indicators are presented in Table 1.

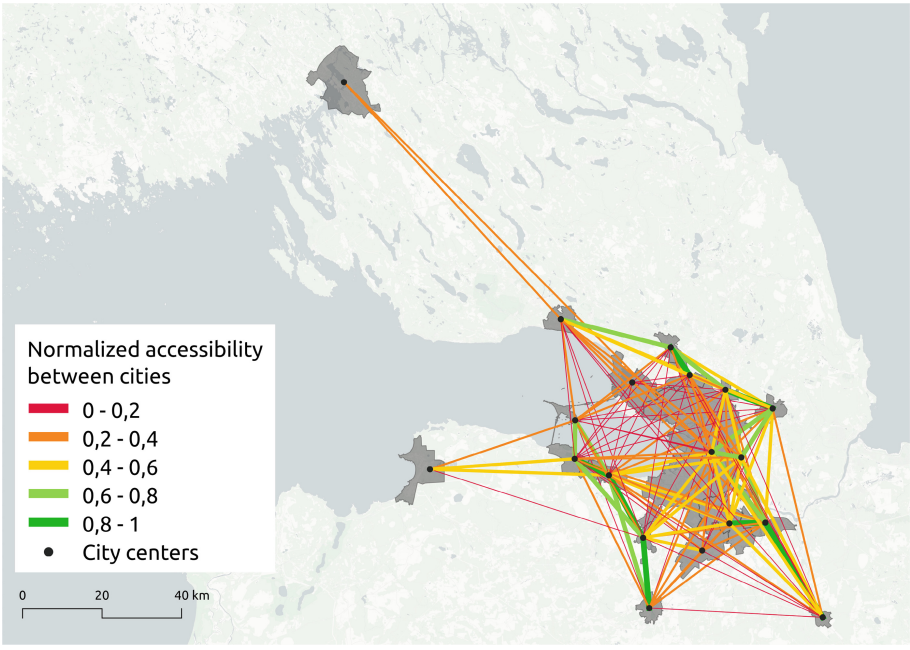

Fig. 10. Normalized weight coefficient of transport connection of cities in the agglomeration

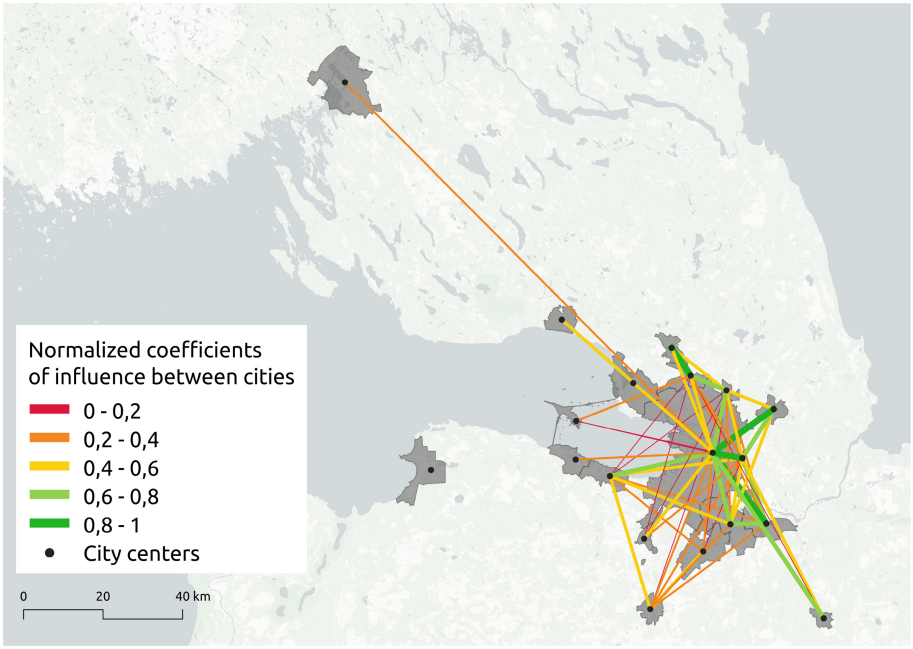

Fig. 11. Weights of influence of cities on each other

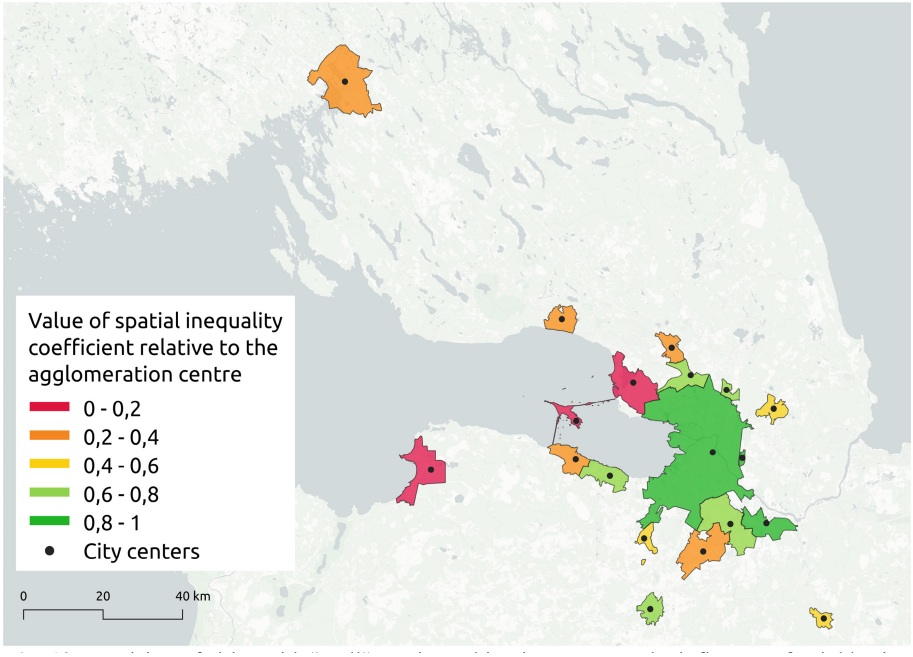

Fig. 12. Provision of cities with "mall" service, taking into account the influence of neighboring cities

Table 1. Indicator threshold values

Minimum value	Maximum value	Description
0	0.2	The territory practically lacks the necessary number of places providing the service; the transport connection with the neighboring territories provided with the service is very poor
0.2	0.4	There are few or almost no service points in the area, but the transport connection to the neighboring service areas is good
0.4	0.6	The area is well provided with the service and has stable transportation links with neighboring areas, compensating the lack of its own needs
0.6	0.8	Territory is well provided with the service, covering its own needs, but cannot cover the needs of neighboring areas
0.8	1	Territory is provided with the service to the extent that fully covers its and neighboring territories' needs

4 Discussion

The calculation of the indicator in this paper is based on the transport graph of the region and data on the location of individual services. The indicator allows to compare the spatial inequality of individual cities of the agglomeration and thereby identify the most problematic places. Solutions to reduce the spatial inequality can be either adding new service points to the cities with the lowest index value, or improving their transport connections with neighboring cities with the best index values through the development of intercity transport infrastructure.

At the same time, real passenger flows and the capacity of service points are not taken into account due to the lack of detailed data. In addition, transport interconnections are considered as potentially possible for the existing infrastructure - in reality, without a survey it is difficult to predict the purpose of trips of specific passengers, i.e. the demand for specific services and the need to move between the cities of the agglomeration for a specific service. This aspect should be considered in further studies of intra-regional spatial inequality.

5 Conclusion

The paper considers the concept of urban agglomeration, spatial inequality. The assessment of spatial inequality was carried out by constructing an intermodal transport graph with the selected type of service on the example of "mall" and its application on the example of St. Petersburg agglomeration.

As a result of modeling, it was possible to see the influence of cities on each other in the agglomeration, taking into account their transport connectivity. It can be seen that the

cities that are closer to the center of the agglomeration are not equal to the more distant cities. This happened due to their poor connectivity and the lack of points of attraction (selected services) within these cities.

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