Forecasting Cascading Effects in Network Models as Applied to Urban Services Provision Assessment

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Abstract. This paper proposes a method for evaluating the urban services provision based on a block-network city model in the context of cascade effects forecasting. Cascade effects are effects that arise in the urban environment as a result of the local territory development. Such effects can affect unknown quantity of city residents, which must be forecasted. The proposed method combines two approaches to assessing provision: predicting the number of interactions and evaluating provision according to regulatory requirements, as well as assessing the diversity of non-standardized urban services. The approach based on reducing the predicting of interactions to the knapsack problem using the GraphSage graph neural network architecture showed the best performance in evaluating provision with standardized services. Meanwhile, for assessing diversity, an approach based on block-by-block evaluation of the Shannon entropy index was used, followed by the use of weighting coefficients depending on the distance between city blocks.

Keywords: Network modeling · city network model · graph neural networks · spatial analysis · urban service provision · provision assessment · diversity of urban services · diversity assessment · cascade effects · urban development management

1 Introduction

The ongoing process of urbanization creates new challenges for cities in the context of urban development management. Urban services (also known as urban amenities) are one of the key entities of a city as a complex dynamic system, as they define the essence of the urban economy, can stimulate demand for services, and determine the quality of life in the city [1]. Thus, assessing the provision of such services is one way to evaluate the quality of the urban environment and life in the city as a whole. Such assessment is an important step in the development of territory transformation projects in the context of selecting areas for transformation [2] or establishing requirements for the territory [3]. This also raises the question of equitable access to urban services in the context of spatial inequality [4].

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The implemented projects for urban environment transformation do not take into account the impact on the quality of life for residents in other areas of the city in the context of access to urban services. This can lead, among other things, to the overload of existing socially significant facilities. Such negative consequences may accumulate at a distance from the transformed area, causing an accumulating cascade effect. These effects may affect an unknown number of city residents, which nevertheless needs to be forecasted.

There is a need for urban models that allow evaluating the effects of urban environment transformation at the level of the entire urban system as a whole, as well as in the assessment method of city services provision in the context of cascade effects. The block-network model of the city can be applied as such a model.

2 Related Works

The theme is mainly reflected in the literature in an attempt to address the problem of insufficient accessibility of urban services. It can be formulated as the problem of the inability to uniformly provide services to all city residents. Related issues are considered, such as the inequality of access to medical facilities [5], the mismatch between the demand created and the capabilities of services [6], and spatial inequality in access to urban services [7].

There are types of services for which requirements for the level of provision are stipulated in regulatory documents [8,9]. Such services include general education schools, kindergartens, clinics, etc. In particular, the requirements for provision include:

Accessibility radius (in some cases, accessibility time) defines the area within a certain distance from the service that this type of service must normatively provide. The proportion of "those in need" (per thousand population), which directly generates demand for this type of service. The capacity level of the service for a specific area - the level of the number of those in need that the service provides for a given area. In this case, the task of evaluating the provision of urban services to an area may be reduced to the task of distributing the population among urban services of a certain capacity and subsequently calculating the ratio 1:

$$P = \frac{d_{within}}{d_{total}} \tag{1}$$

where d_{within} is the number of people provided for in the accessibility zone, and d_{total} is the total number of those in need. This ratio shows the proportion of people in need of a particular type of service who are provided for within the accessibility zone.

Various approaches are considered for the task of finding the number of interactions, including basic iterative methods [2], gravity models, linear optimization methods [10]. Gravity models can be too sensitive to the parameters of the city

network model [11]. Graph neural networks are also gaining application in this context [10,12].

It is also assumed that the task of distributing people between services can be described as a task of many backpacks, by analogy with the article [13]. Based on this approach, one of the proposed methods for assessing regulatory provision was created. Since the city model is a graph, graph neural networks may be suitable for solving the topic problem. GNN generalizes data on the vertices and edges of the graph well and may be able to determine the hidden dependencies of provision on the demand of people and the capacity of services. GNN can be used to optimize the backpacks cost function.

The approach to assessing provision through the search for the number of interactions is particularly relevant for standardized types of services. However, to assess the provision of an area with non-standardized services, another approach based on diversity or heterogeneity assessment is required. Measures of homogeneity or biodiversity assessment [14] can be applied to such evaluation methods: Shannon entropy, Simpson index, etc.

Currently, there are about 40 biodiversity assessment indices. At the same time, each index either emphasizes the species richness or the degree of dominance of one species over others [15]. These indices can be divided into several groups, one of which is a group of indexes based on the relative abundance of species. To comply with this framework, it is advisable to pay attention to those that show not the degree of dominance of one species over another, but those that emphasize the species diversity in a particular territory. Such indices include the Shannon index and the Brillouin index.

The Shannon index is a measure of biodiversity based on the number of different species present in a particular area and the territory in which they are located. The index is calculated according to the formula 2:

$$H = -\sum_{i=0}^{N} p_i * log_2 p_i \tag{2}$$

where

- H - the Shannon index;
- p_i - the proportion of objects of the i-th type;
- N - total number of objects.

Compared to the Shannon index, the Brillouin index is rarely used to assess the diversity of objects, as it is difficult to calculate. The Brillouin index is used when the full composition of the community is known in advance and the sample itself is not random or small. The calculation takes place according to the formula 3:

$$HB_{max} = \frac{lnN! - \sum_{i=0}^{N} ln * n_i!}{N} \tag{3}$$

where

– HB_{max} - The Brillouin index;
– n_i - the number of objects of the i-th type;
– N - total number of objects.

Predicting cascade effects involves assessing changes in urban service provision indicators that occur in the city due to the transformation of the urban environment in a local area. Unfortunately, such effects are not tracked in existing provision assessment methods. There is a need for the creation of a method for assessing urban service provision that allows tracking the cascading effects of changes.

3 Method

To forecast cascade effects in the context of urban service provision, a comprehensive provision assessment method has been developed, aimed at evaluating potential changes in urban areas. The method is presented in Fig. 1. The result of the method consists of spatial data layer, describing the change in block-network city model provision. Negative assessment values indicate a decrease in the provision value, while positive values indicate an increase. Thus, the conclusion can be made on the impact of the development scenario.

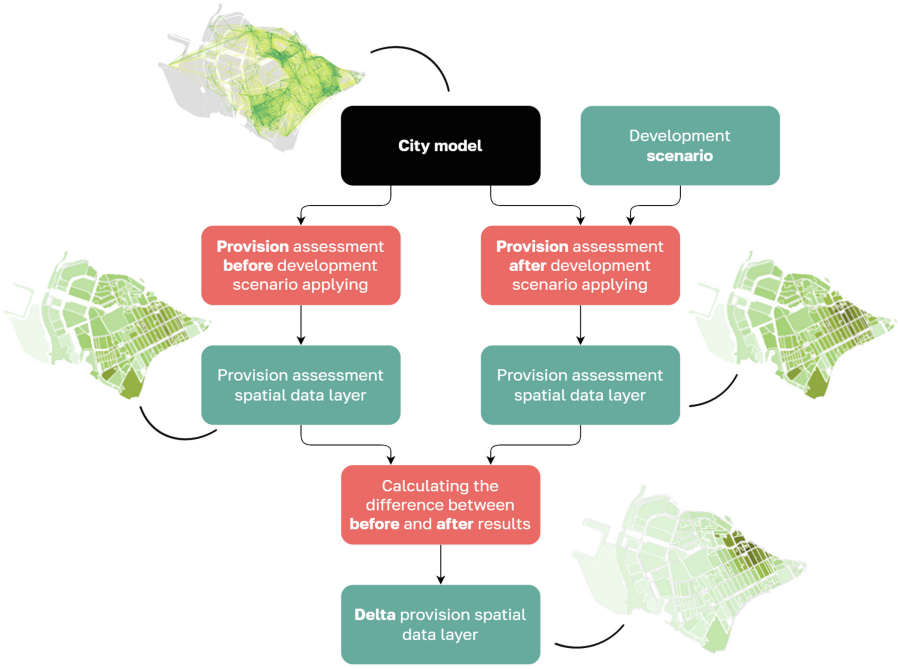


Fig. 1. Method for evaluating cascade effects

The method for evaluating cascade effects mostly relies on the urban service provision assessment method presented in Fig. 2.

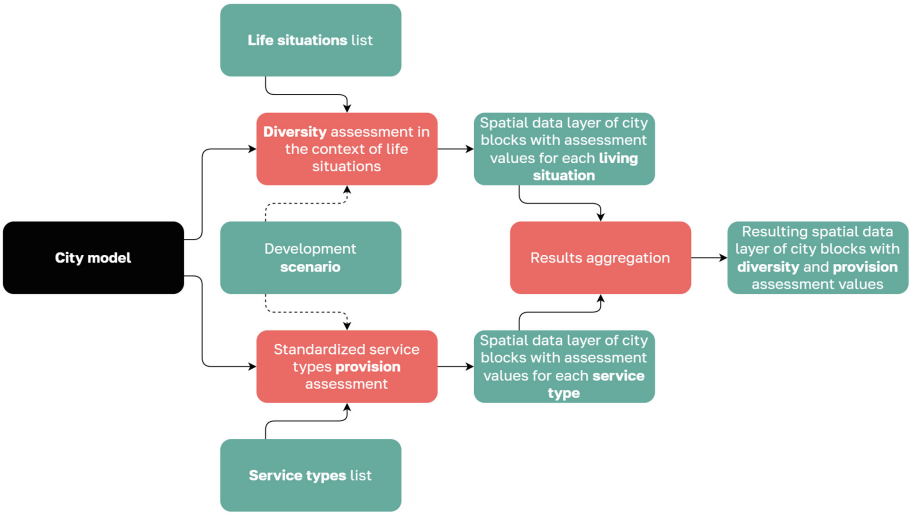


Fig. 2. Urban service provision assessment method

The method utilizes the following input data:

- A city model represented by the block-network model from the BlocksNet library [16].
- A territory transformation scenario describing changes in the local area, including services or population numbers.
- A life situation represented by a list of services relevant to city residents at a specific point in time.

Thus, the provision assessment method can be divided into several stages:

- Provision assessment for standard types of services;
- Diversity assessment in the context of life situations;
- Aggregation of results into a final spatial layer.

3.1 Block-Network City Model

Block-network city model is used to perform cascade evaluation. The model is presented by a complete graph, where:

- nodes – city blocks;
- edges – paths between city blocks on an intermodal graph, where edge weights present travel time.

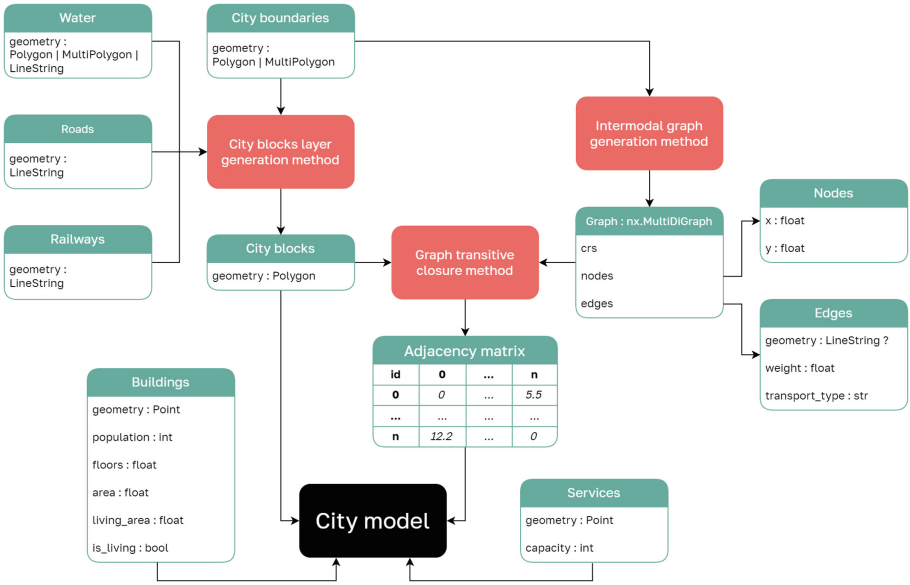


Fig. 3. Block-network city model initialization pipeline

City model initialization pipeline in BlocksNet Python library [16] is presented in Fig. 3. Data available for the provision assessment is described in "Buildings" and "Services" parts.

By default the BlocksNet city model consists of various service types, (such as schools and kindergartens) and its standardized parameters (accessibility time and demand value per 1000 population). These service types describe kinds of services, that can be added to the model.

3.2 Standardized Service Types Provision Assessment

The task of distributing people among services for provision assessment can be described as a multi-knapsack problem. Such a problem can be solved using a graph neural network [13]. The following are analogies of terms related to the provision task:

- Knapsack: A block-service aggregating services with a specified capacity.
- Weight: Demand generated by the population of a residential block for the block-service.
- Cost: Travel time between a residential block and a service block.

Figure 4 shows a diagram of a two-dimensional matrix, the values of which have to be found when solving the population distribution problem.

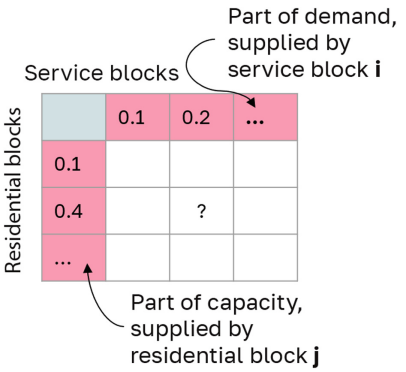


Fig. 4. Urban service provision assessment method

The minimized loss function is presented as follows:

$$\text{final_loss} = \text{prices_loss} + \text{space_violation} - \text{used_space} \tag{4}$$

where:

- $\text{prices_loss} = \sum_i^n pred_{ij} \cdot dist_i$ – a parameter penalizing the model for selecting too distant blocks during distribution.
- $\text{used_space} = \sum_j^m pred_{ij} \cdot demand_j$ – a parameter indicating the amount of satisfied demand.
- $\text{space_violation} = \sum_i^n Relu(usedspace_i - capacities_i)$ – a parameter preventing the network from predicting values exceeding block capacity.
- *pred* is the prediction $n \times m$ matrix (n residential blocks, m service blocks) of the model.
- *dist* is the vector of distances from the i-th residential block to each of the service blocks.
- *demand* is the demand vector for each residential block.
- *capacities* is the vector of capacity values for each service block.

The final loss function can be interpreted as follows: it is necessary to maximize provision with limited service capacities and taking into account the choice of the nearest service as the preferred one.

As a result of the method's execution, based on the obtained values in the two-dimensional demand matrix, an assessment of provision for the selected service type can be reconstructed before and after the application of the territory development scenario. The difference in provision values reflects the cascade effect of the specified development scenario.

3.3 Service Types Diversity Assessment in the Context of Life Situations

The diversity assessment is conducted in the context of life situations that may be relevant to city residents at different periods in time. For each such life situation,

a list of supporting types of urban services (including non-standardized) can be determined. Assessing the provision of such service types involves evaluating the diversity of these service types in the selected block, calculated as follows:

$$D = -\sum_{i}^{n} \frac{H_i}{r} \tag{5}$$

where:

- $H_i = -\sum_{j}^{S} \frac{n_j}{N} \log_2 \frac{n_j}{N}$
- n_j – the number of services of the j-th type.
- r – the distance (travel time) between the selected block and the i-th block (in case it is the same block, the distance is taken as 1).
- S – the number of evaluated service types.
- N – the total number of services in the given block.

The result of the method is a spatial layer of city blocks with the obtained diversity assessment for each block. The difference in the diversity assessment resulting from the application of the territory development scenario and the obtained diversity assessment reflects the cascade effect of the specified development scenario.

4 Results

4.1 Input Data

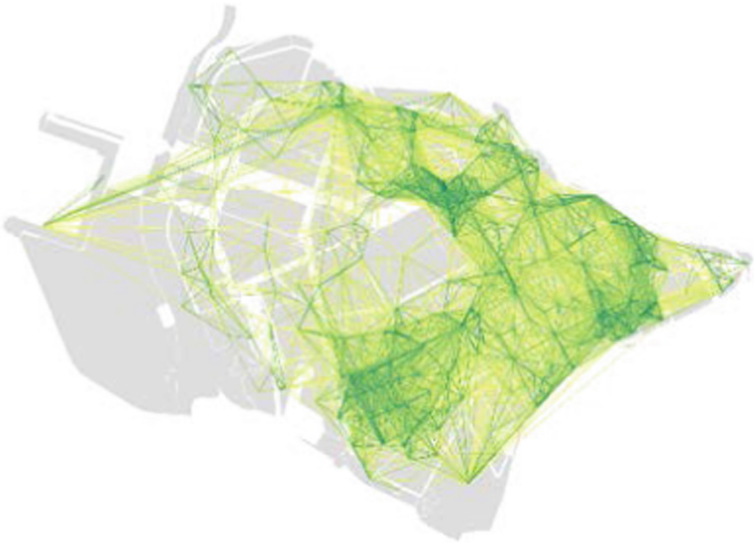
As sources of input data, the OpenStreetMap service and the "Digital Urbanism Platform" of ITMO University were utilized. The data were adapted to the specifications of the block-network model in the BlocksNet library [16], on which the method investigation was based. The initial research area selected was the territory of Vasilievsky Island, St. Petersburg. The resulting model is presented in Fig. 5. Service types are also described in Table 1.

Table 1. Service types defined in the block-network city model

Service type	Kindergartens	Schools	Hospitals	Pharmacies	Polyclinics
Demand (per 1000 population)	61	120	9	50	27
Accessibility (min)	10	15	60	10	15



(a) Visualization of the model in terms of services and buildings



(b) Visualization of the model in the context of a graph

Fig. 5. Block-network city model

4.2 Provision Assessment

The provision assessment was conducted for the school service type. The Graph Neural Network architecture Unet was utilized, enabling the prediction of targets for provision assessment results obtained through solving a linear optimization problem. Due to excessive smoothing, this approach produces overly smoothed values and fails to capture the dependency of provision on the population count. The results of the architecture are presented in Fig. 6.

Since city residents do not always go to the nearest service, an architecture was chosen to more realistically model this behavior. The architecture based on random walks was selected for this purpose. The network shows results different from U-Net, but they are challenging to interpret due to the randomness of the walking process. The provision assessment result is presented in Fig. 7.

The provision assessment based on solving the knapsack problem showed the best results. The graph neural network was trained based on the GraphSage architecture, allowing it to handle large graphs. It was decided to use coefficients

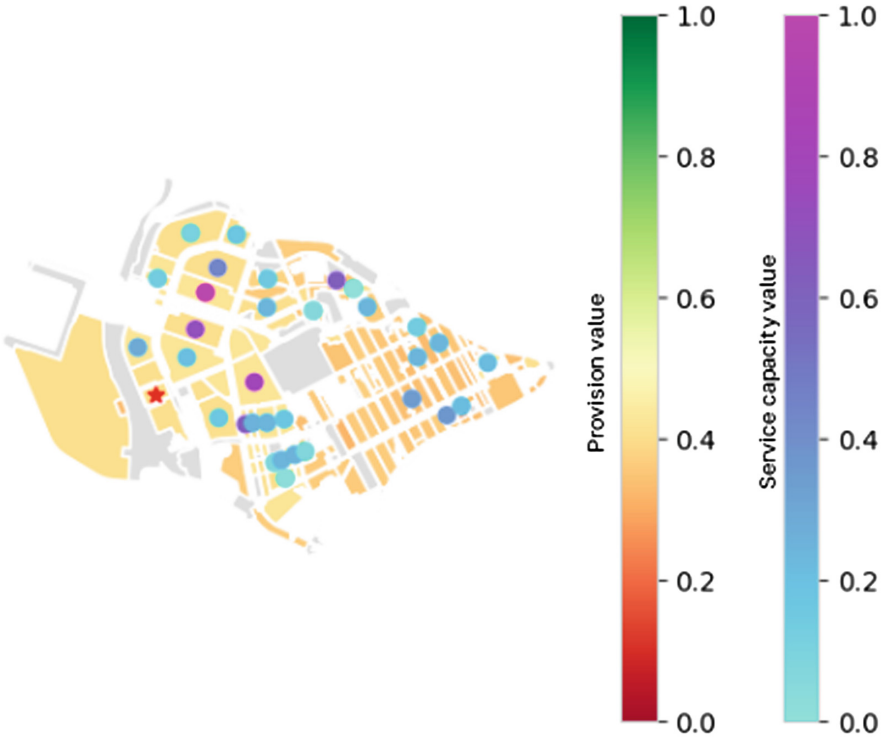


Fig. 6. Provision assessment based on U-Net architecture

that increase the penalty cost for choosing blocks outside the accessibility zone of the selected service type. However, the model performed best without modifying the coefficients both in terms of provision assessment and cascade effects. Figure 8 demonstrates the results of changes in the schools provision assessment. A negative delta value indicates a deterioration in the provision assessment, corresponding to the assumption that the provision level decreases with an increase in the population of the block, creating a burden on other blocks.

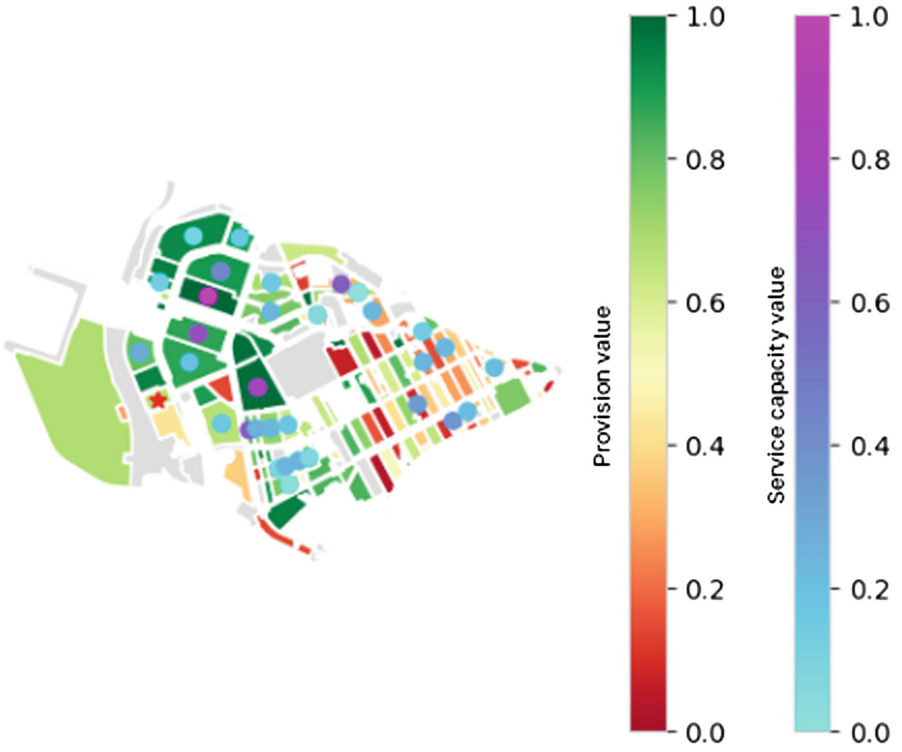


Fig. 7. Provision assessment based on random walk

The advantages of this approach include unsupervised learning and flexible adjustment of training rules. However, problems may arise when dealing with a large number of city blocks, particularly concerning the manipulation of small float values.

4.3 Diversity Assessment

The diversity assessment was conducted for the life situation 'Feeling unwell' which includes the following city service types:

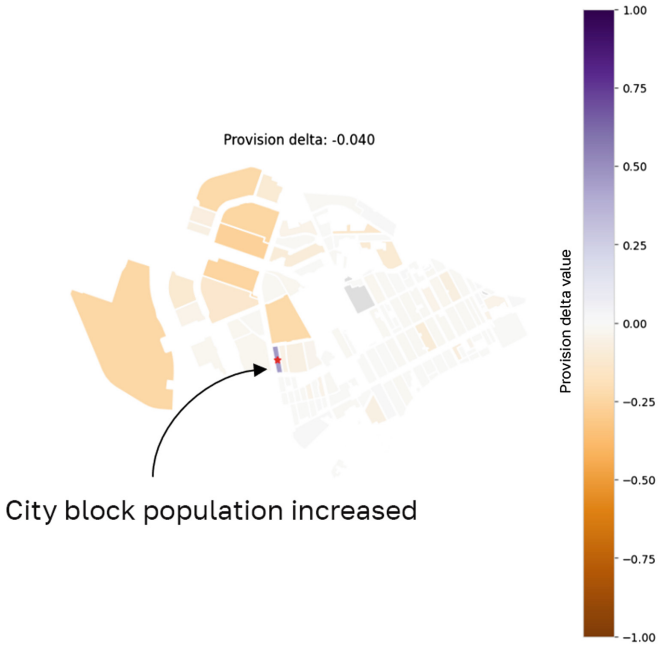


Fig. 8. Provision assessment delta based on GraphSage architecture and minimized loss function

– hospitals;
– polyclinics;
– pharmacies.

The initial diversity assessment based on the Shannon entropy index yields non-zero values only for areas containing services related to the life situation. The diversity assessment result is presented in Fig. 9. Cascade effects are not observed since the assessment is conducted independently of other city blocks.

There was a hypothesis that, for diversity assessment, it is necessary to consider not only the services within the city block itself but also those within a certain accessibility radius from it. Diversity assessments were made for accessibility zones of 5, 10, and 15 min from the city block. The results are presented in Fig. 10.

The diversity assessment as a weighted average of the Shannon entropy index on connected city blocks allows considering the accessibility of other services at a distance. A cascade effect is observed, opposite to the effect observed in the case of provision assessment with standardized service types. The result is presented in Fig. 11. With the addition of new services, diversity assessment improves most for nearby blocks and weakens at a distance.

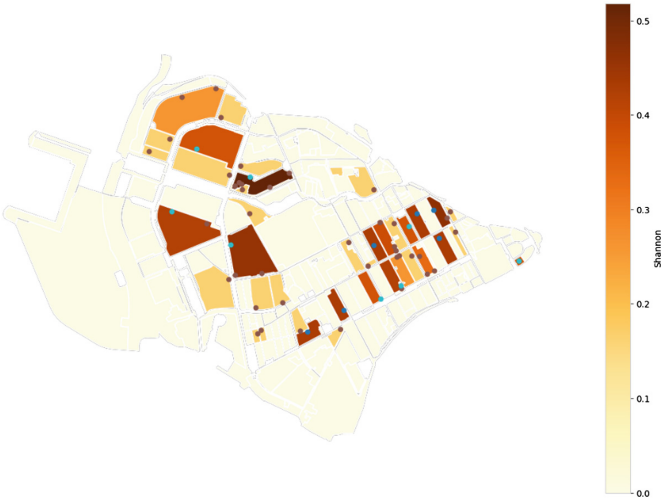
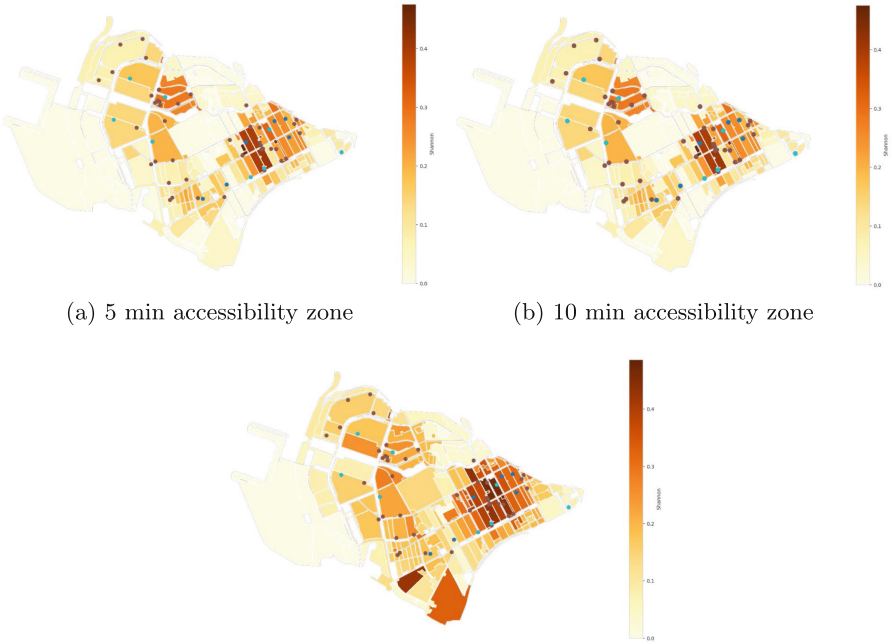


Fig. 9. Diversity assessment based on Shannon index

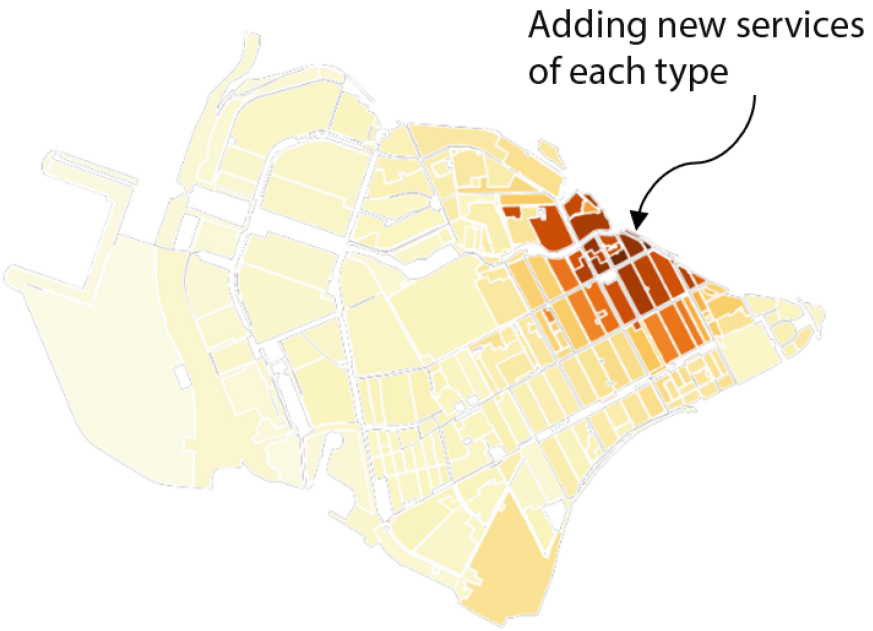


(a) 5 min accessibility zone

(b) 10 min accessibility zone

(c) 15 min accessibility zone

Fig. 10. Diversity assessment based on Shannon index and extended accessibility zone



(a) Diversity assessment delta

Fig. 11. Diversity assessment

5 Discussion

The approach to assessing standardized provision through solving the backpack problem exhibits several advantages, including the ability to operate independently of a teacher, the flexibility to configure learning rules, and the potential to manifest cascading effects. However, certain drawbacks are associated with this approach, such as limitations imposed by the number of blocks in the model. Challenges may arise when dealing with a substantial quantity of services, as the network may need to output very small values.

The limit to the number of blocks can be solved by changing the architecture of the model. Perhaps there are approaches that allows teaching a network with an arbitrary number of outputs. The method reflects cascade effects, but perhaps the result can be stabilized by applying special layers of the neural network that are specifically suitable for the task of assessing security. For example, it would be possible to develop a special aggregation function for convolutional layers or combine two data parameters, capacity and demand, into one parameter using a change reduction algorithm such as PCA or t-SNE.

It is also worth noting the peculiarities in the behavior of the standardized provision function itself. Thus, the function may nonlinearly respond to linear input. Primarily, this can be manifested in an increase in the provision assessment with an increase in the population in the city block, as presented in Fig. 8.

Such counterintuitive behavior of the function is primarily associated with the fact that existing urban services in the city block or its vicinity can supply the increased load, thereby increasing the value of the provision ratio 1. In practical terms, if we consider the neighborhood outside the urban context, this may mean that the neighborhood can accommodate an additional number of residents considering the existing urban services.

The difference in diversity assessment from standardized provision assessment lies in more evident response to local changes in the urban environment. As seen in Fig. 11, the emerging cascade effects attenuate as one moves away from the transformed city block. However, such attenuation will be heterogeneous, with some city blocks reacting more acutely to the transformation than others. However, it is difficult to quantify the effect on the life of residents.

The diversity assessment method, meanwhile, relies mostly on life situation concept, thus making it impossible to assess specific service type diversity of a city block. Further services categorization may be needed in the context of a certain service type.

6 Conclusion

As a result of the research, a provision assessment method has been developed, allowing for forecasting the impact of potential changes in the territory in the context of the entire city. The method can be applied to evaluate proposed urban environment transformation projects in the context of urban service provision. This assessment can be conducted during the master planning requirements generation step. Additionally, one of the potential applications could be the use of the method in optimization tasks as an objective function. Thus, the method can be useful in tasks related to optimal urban service placement or generating optimal urban development scenarios.

Two approaches to assessing provision with types of services have been considered: through diversity using the Shannon entropy index and through the search for the number of interactions between services and housing. Further development of the method may involve the use of graph neural networks to assess diversity based on the spatial distance between services and their parameters.

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