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Modeling of Changes in Four Urban Capitals Using Up-to-Date Information Systems and Mathematical Graph-Based Simulative Models for Urban Regeneration (Kaunas Case)

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Abstract: There are numbers of various new infill constructions and renovations occurring in many cities annually that are based more on bottom-up initiatives by various stakeholders rather than top-down initiated plans according to a city master plan. Such infill modifications of urban structure might look small, not very numerous and insignificant at the first glance, but even small changes in a complex system such as a city can cause significant shifts in the functioning of the urban network. The presented research, developed on mathematical graph simulative modeling, including space syntax but not restricting the model to it, and employing the theory of four urban capitals by Lars Marcus, offers a way to analyze how the spatial, social, ecological and economic capitals of Kaunas will change if all the currently confirmed and publicly announced construction projects are implemented. The urban spatial network is seen as an integrator and enabler of interactions between the other three capitals. Each of the capitals is represented by quantitative data in the weighted mathematical graph: spatial capital by the perimeters of buildings accessible from a public space; social capital by the number of inhabitants; economic capital by the mean values of land prices; and ecological capital by the size of green areas and their infrastructure. All the data for modeling of changes in the capitals, except the future land prices, was based on information from implemented and planned projects. In order to predict them, a neural network tool was applied. Considering that changes in the absolute values of capitals are in essence limited by local context (e.g., number of inhabitants, market size, natural geographical conditions, and limits of spatial structure for densification), the idea of a positive synergy between urban capitals is proposed and explained in this article. All the presented simulation models are validated using independent open data as density of points of interests, etc. The results of the investigation reveal that synergy between capitals will decrease in Kaunas and that complex top-down coordination of bottom-up initiated urban projects is needed.

Keywords: mathematical graph model; four urban capitals; infill urban development; modeling of changes; neural network-based predictions; Kaunas

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Citation: Zaleckis, K.; Kamičaitytė, J.; Mlinkauskienė, A.; Jankauskaitė-Jurevičienė, L. Modeling of Changes in Four Urban Capitals Using Up-to-Date Information Systems and Mathematical Graph-Based Simulative Models for Urban Regeneration (Kaunas Case). *Sustainability* **2022**, *14*, 17014. https://doi.org/10.3390/su142417014

Academic Editors: José António Tenedório, Carlos Antunes, Raquel Faria de Deus and Rui Pedro Julião

Received: 23 November 2022
Accepted: 14 December 2022
Published: 19 December 2022

1. Introduction

The aim of this study is to present and validate the attempt to analyze interactions between spatial, economic, social and ecological aspects of urban life primarily using mathematical graph simulative modelling based on the spatial urban configuration of a city. The following aspects of the research are highlighted:

- A complex simulative model, even if based primarily just on spatial urban configuration data, creates a background for better understanding of the functioning of the urban fabric in terms of synergies between spatial, social, economic and ecological aspect.
- Such a simulative model has a predictive power and could be used as an objective part of a decision support system by various stakeholders in urban development.
- The model reflects the complex nature of a city as a system by demonstrating the "butterfly effect" when even relatively small and scattered infill development af-

fects synergies between social, ecological, spatial and economic aspects of urban structure notably.

- The availability of open data and various GIS based technologies means that the presented model can be seen as a part of wider ecosystem of urban planning technologies of the Smart City movement.

There are numerous various new constructions and renovations occurring in Kaunas as in many other cities annually. Under free market conditions, such processes are influenced in both bottom-up ways by various stakeholders (e.g., land and property owners, developers, other participants of the property market, etc.) and top-down ways (e.g., by city master plans). These bottom-up processes of construction and renovation may be seen as insignificant at a whole city scale, but even small changes in a complex system such as a city can cause significant shifts in urban networks. Although construction projects initiated by property developers are quite often primarily focused on economic benefits and lack long-term perspective in terms of sustainable city development, in such situations, it is very important to see and understand the effects of various infill developments in complex urban contexts, thus creating a background for top-down catalyzing actions, targeted support activities, the identification of either positive or negative synergies, etc.

The objective of the presented research is to present, validate and discuss a simulative model which would allow an analysis and prediction of the effects of urban regeneration and infill development on the complex functioning of a city based on open data.

As a city is a very complex phenomenon [1], when we try to comprehend it and understand and model its changes, a systemic approach that allows us to understand the interconnectedness of all the city elements and components at different scales can be helpful. According to the theory of interdisciplinarity [2,3], a systems approach provides an orientation to looking at the whole problem and its relationship to its parts. Everything is interconnected and systems-based thinking emphasizes that problems have many dimensions. There are many factors involved in any problem, and there can be various types of connections between them. Applying this paradigm, a city can be divided into various "systemic layers" that have their own research theories, methods, and approaches, and at the same time, they are interconnected and integrated:

- Public spaces. Public spaces are defined as spaces of street culture and encompass streets without intensive transport in the old town, pedestrian streets, squares, parts of green spaces near developments when they are cut by paths oriented to the attraction centers, pedestrian zones near important streets in which the formation of multifunctional corridors occurs similar to those according to models of New Urbanism [4], public spaces near shopping centers, etc. [5], i.e., these spaces are universally accessible and offer opportunities for people to meet other people and interact with them. Public spaces and their systems are analyzed from visual, spatial, compositional, social, functional, psychological, and other points of view in order to understand what makes a good public space [6–9].
- Nature frame and green infrastructure. Nature frame is a concept developed in the middle of the 20th c. by geographers [10], and landscape architects and ecologists [11,12]. The natural frame is an integral network of natural ecological compensation territories, which ensures the ecological balance of the landscape as well as natural connections between protected territories and other environmentally important territories or habitats and the migration of plants and animals between them [10]. When analyzing urban morphology, natural determinants and human made determinants are designated, and natural areas are usually protected as eco-compensational areas intertwining with urbanized areas. Other concepts such as a green infrastructure [13] and ecological services [14] are also important in analyzing and planning cities and their renovation and regeneration, particularly to increase the ecological potential of urbanized areas and provide material and non-material benefits for human beings in cities.
- Transport infrastructure, sustainable mobility. The characteristics of transport systems affect the morphological type, size of the urban structure, its liveability and its

functioning [15]. Sustainable mobility is one of sustainable development goals of every city in the world. In order to analyze and plan city transport infrastructure, many quantitative and qualitative indicators must be established and evaluated. The newest research [16] attempts to integrate the development of transport and urban spaces systems by proposing sets of indicators describing sustainable transport and city development of, for example, the road system (turnover, infrastructure spatial features, public transport infrastructure, transport demand, modal split, etc.) or the space system (safety, comfort, use frequency, time, aesthetics, etc.).

- Social context and social infrastructure. The social dimension is an important part of the sustainable development concept, and the social environment encompasses the immediate physical surroundings, social relationships, and cultural milieus within which defined groups of people function and interact [17]. Social infrastructure includes culture, education, public health and safety, sports and wellness, recreation and tourism, religious sites, administrative areas, and other objects of public use [15]. When measuring city sustainability [18], the social aspect is represented by a range of indicators, e.g., education, sanitation, health, quality of public spaces, etc.
- Urban frame, building typology and urban composition. The urban frame and urban composition represent the most functionally, spatially, and visually distinguishing part of the urban structure that helps to organize spatial environments into recognizable and unique coherent patterns. Building typology describes buildings according to their similarity of function and form. The research methods can be classified into the following types: methods evaluating the overall impression of the spatial patterns, and methods dividing it into parts, i.e., structural quantitative and qualitative methods, complex methods based on expert and non-expert judgement, etc. [6,15,19–21].
- Historical context and cityscape identity. The historical context of the city partially defines its identity and provides it with a historical background. However, a cityscape identity is a more complex phenomenon. To establish a city-scape identity, it is necessary to integrate subjective (human) and objective (physical) aspects, physical and virtual environments that represent it, etc. In the scientific literature, existential (place), spatial, personal, and cultural dimensions of the concept of landscape identity are distinguished [22], which are important for the overall perception and evaluation of landscape identity. Considering this holistic approach [23], cityscape identity is analyzed and evaluated using various theories and methods with different disciplinary origins. These include the theories of semiotics and cultural-historical artefacts [24,25] for distinguishing physical components as cultural symbols formed through history. The experience and perception of place is analyzed by sociological surveys applying the theories of K. Lynch [26] of mental city images, the S. Shamai [27] model of "sense of the place", and the semantic differential measurement developed by Ch. Osgood [28].

According to the above-mentioned, even simplified, representation of a city as a complex phenomenon, it is evident that there are many factors operating in a city that are difficult to model and study simultaneously. Therefore, we need theories and approaches allowing us to indicate, assess and model interrelated changes of different systems making up the city totality.

The structure of complex systems can be analyzed from many perspectives. Not all of them can be revealed or described as relationships between elements. There is, therefore, always a risk of overlooking important relationships on which the territorial organization of the system depends. It is even more difficult to analyze the functioning and dynamics of the system, even though it is possible to express all these aspects in terms of individual relationships. It is possible to take different approaches to the study of a single system (e.g., economic, geographical, sociological, etc.) by looking at only a particular section of the system, selecting the relevant characteristics according to the task at hand, and describing them in terms of relationships.

A system is generally considered to have a single structure, which can be analyzed from different angles, e.g., by building different models of the same system. Sometimes, for simplicity, these sections are referred to as different system structures, e.g., hierarchical, economic, etc.

The structure of system relationships is based on the concept of a system as a single object whose properties are the sum of the properties of its elements. The structure of relations in a territorial system is characterized by a particular diversity. Even in small and relatively homogeneous territorial systems, the nature, extent, importance, number of branches, etc., of the links vary considerably.

Linkages can be direct or reverse, cover all or part of a territory, be permanent or temporary, and be variable. Permanent links are links that do not change during the functioning of the system of a given structure, but which, if broken, cease to function and practically disintegrate. Variable (flexible) relationships can change as the system functions, which does not break down the structure of the system, so the system can adapt to certain changes. The purpose of the variable links in the system is to maintain a dynamic equilibrium and interaction with the outside of the system. The research of spatial systems is, therefore, a very complex task that requires the use of digital methods [29–31].

The theoretical background of the presented research is based on three cornerstones. The first cornerstone is set by the actualization of the idea of a city as a network by Dupuy: "Urban networks, ... are widely discussed, but there has hardly been debate on what constitutes an urbanism of networks. It is time to shift network urbanism from the realm of general debate to that of identifying the task-specific tools and techniques required for its implementation" [32].

The second cornerstone is defined by a specific approach to modeling of complex systems which is well and fully presented by Michael Batty in his book *The New Science for Cities*. He says that "In a world now dominated by communications and in a world where most people will be living in cities by the end of this century, it is high time we changed our focus from locations to interactions, from thinking of cities simply as idealized morphologies to thinking of them as patterns of communication, interaction, trade, and exchange; in short, to thinking of them as networks." [33]. The essential tool for modeling complex urban networks, according to Batty, is mathematical graph theory which can describe urban areas, or any network, as made of nodes and links. It is important to note that a mathematical graph model could be considered as a kind of simulative model suitable for description and modeling of complex systems. Such models demonstrate a very large number of elements and self-organization as cities do. Depending on the modeling purpose, a street, segment, crossroad, building, or cell of public space could be seen as a node and the functional or visual connections between them as links. The calculation of importance or centrality of the nodes is the essence of the Graph theory, as rooted in the proposals by Linton Freeman [34], which he generated while analyzing social networks. The three centralities proposed by him are the following:

- The degree centrality is the number of links with neighboring nodes. Nodes with a larger number of connections are considered as more important, e.g., the number of "friends" in social media networks or the number of intersecting streets in a city.
- The closeness centrality is a sum of distances from each node to the rest of the network. A smaller sum indicates greater importance as it shows higher closeness of the node to the rest of the network.
- The betweenness centrality is a sum of the shortest transit journeys between pairs of all nodes which choose the calculated node as a transit route. A higher value indicates greater importance of the node because of the larger transit flow it attracts.

The space syntax theory developed by Bill Hillier applies and develops the calculation of node centralities for urban analysis and further modeling [35] by introducing more indicators, normalization of the results and offering simulative modeling rules for interpretation of calculated graph centralities as follows:

- Symmetry is described as " ... the property that if A is a neighbor of B, then B is neighbor of A" [36]. Symmetrical relations between nodes mean that if they as spaces or buildings have symmetrical relations to each other created by short distance and direct links, they bring people, activities, functions together and create more multi-functional, diverse zones in a city.

- Depth "... exists wherever it is necessary to go through intervening spaces to get from one space to another" [36]. More depth creates more asymmetry, thus segregating people, activities, functions, etc.
- Movement economy theory is "... built on the notion of natural movement, proposes that evolving space organization in settlements first generates the distribution pattern of busier and quieter movement pattern flows, which then influence land use choices, and these in turn generate multiplier effects on movement with further feedback on land use choices and the local grid as it adapts itself to more intensive development" [35]. Patterns of various attraction zones could be identified using mathematical graph centralities.

Space syntax has attracted various criticisms [37,38] which should be taken into consideration, but because "all models are wrong, but some are useful" [39], the most important question is if the space syntax model is working in the context of precise research. It should be noted as well that the criticisms were mainly addressed to the early forms of space syntax analysis focused on axial graphs [40] which were later improved and replaced by segment graphs [41]. However, the syntactic models used here are validated a few times during the research presented.

The third cornerstone is based on the theory of four urban capitals—an analytical theory of urbanism developed by Lars Marcus [42] where he describes a city as the interaction of four capitals: spatial, social, economic, and ecological. "... spatial capital in this sense has a fundamental impact, not only on economic capital, but also on social and ecological capital" [42] according to Marcus. We generalize the urban capital definition for further investigation as follows: capital is the potential for interaction between its "cells" (people and people, buildings and nature, land exchange values, buildings and public spaces), which is enabled by spatial structure and brings people, activities, and objects together. More potential interaction is by default seen as bigger capital. Definitions of the capitals are presented in Figure 1. All four capitals could be described on the basis of networks: a network of spaces, a network of humans, a network of land plots, and a network of ecological areas.

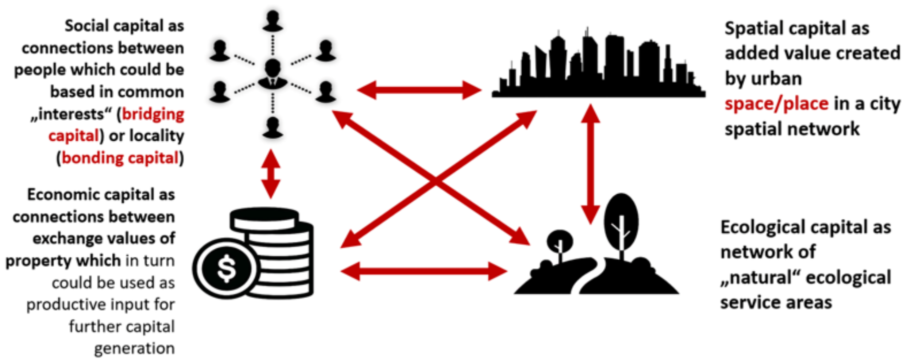

Figure 1. Definitions and interactions between capitals.

Based on the general literature review presented in the introduction, we conclude that, for the investigation of transformations caused by infill urban development, the simulative modeling approach is best able to reflect the complexity of urban systems. The urban capitals concept is employed as a more specific form of application of the mathematical graph model.

2. Materials and Methods

Generic Space Syntax modelling was conducted in the following steps using ESRI ArcMAP and Depthmap [41] software:

- The road network data or so-called street central lines map in GIS format was obtained from Open Street Map (OSM);
- The central street lines were simplified as they had too many short segments, which would affect the precision of the model. The procedure involved merging of all segments, simplification of the map in order to make it less reflective of insignificant changes in the angles of street lines, and cutting the streets into segments at the crossroads, thus "informing" the Depthmap about the possibility of changing the direction of movement while running the simulation and making calculations.
- Additional specific processing of the two-level crossroads was made in order to reflect limitations of movement there.

The four mathematical graph centralities were calculated using Depthmap for the generic space syntax model as follows: integration or closeness centrality, choice or betweenness centrality, node count or simple density of street network, and metric reach or accessible length of a street network within a selected radius. Formulas for the calculated indexes are presented in the Results section. The indicators were calculated with 4 different radiuses: 1000 m as the pedestrian radius; 3000 and 5000 m as medium radiuses probably representing journeys based on public transport and bicycle; and radius n as the longest radius reflecting individual car journeys.

The final methodology for the investigation based on space syntax needed some adjustments for the following reasons:

- When investigating and modeling the effects of infill development, even a single building could be important because of its functions or a large number of living places. Traditional segment graphs, where each street segment is represented as a node, are not detailed enough for such tasks as the building can have many neighboring buildings, but centrality calculations are conducted for a segment only.
- In the areas with similar street network densities, the morphology of buildings could differ significantly, e.g., a longer perimeter of a street-building contact could facilitate street culture more [43] and increase the walkability indicators according to the World Bank Walkability report [44].
- Data for making the graph more precise by adding weights (the area or volume of a building, the above-mentioned perimeter, the exact location of functions, etc.) is quite often available for each building; thus, using a segment graph would not allow the use of all potential available data with high precision.

Because of the above-mentioned reasons, it was decided to use a graph with buildings as nodes and use the Urban Network Analysis Toolbox for that purpose [45].

As the main background for modeling urban capitals, the reach centrality of the graph was used based on the formula [46]:

$$Reach\ (i) = \sum_{G-i;d[i,j]} W\ (j)$$

where *Reach* (*i*) is reach centrality of building; $W(j)$ is a weight of any building in the graph; and $d[i, j]$ is the shortest path from the building to any other building which is reachable on the shortest distance from it within the selected radius.

Based on this, four urban capitals were modeled as following:

- Spatial capital was modeled as the reach centrality weighted by building perimeter based on the pattern by Alexander [43] and the World Bank Walkability report [44]. According to these sources, a longer contact perimeter between buildings and street space results in a more attractive environment for walking.
- Ecological capital was calculated as the reachability of green recreational areas weighted by a rank based on recreational infrastructure. The ranking was performed by an expert assigning values from 4 to 1, where 1 means no recreational infrastructure (1 was given to natural forest with just natural surface paths available) and 4 indicates the green recreation areas with the most developed infrastructure, such as paths, light-

ing, rest places, playgrounds, equipment for sports, etc. In order to have a graph of "points" similar to the one of buildings and reflect both the perimeter length and size of recreational areas, all green areas were divided into cells of 0.05 ha (the smallest area of green square), and each cell was represented as a node of the graph. The procedure was applied both to green areas with official recreational status (e.g., parks, recreational forests, protective greenery) and to green areas without official status but with some regular maintenance activities conducted by the municipality (e.g., green areas inside modernistic blocks maintained by the municipality).

- Economic capital was calculated as the reach centrality weighted by mean land price. Land price instead of building price was chosen as it is probably more objective and dependent on city configuration.
- Social capital employs the same reach centrality calculation while using the mean number of children per house within a radius of 1 km from the available census data as graph weight. We base this on the empirical observation that more children lead to more activities in public spaces, more communication between neighbors and a greater potential for social capital. Reach centrality was calculated within four radiuses:
  - 400 m as the smallest grid size for urban analysis;
  - 1000 m as a maximal pedestrian distance equal to 15 min walking time;
  - 3000 m as the interim radius between 1000 and 5200 m in Kaunas;
  - 5200 m as the mean radius of all journeys according to data from the sustainable mobility plan of Kaunas [47].

In addition to the above-described methodology. The artificial intelligence Neural Network module in MATLAB [48] was used for prediction of changes in land prices. It is described in more detail in the Results section.

3. Results

3.1. Validation of the Basic Model

Despite many scientific reports which present and validate space syntax models based on empirical data [49,50], it was decided to test if the model works well in Kaunas and some other cities. For this purpose, seven cities from the Baltic region were selected: Kaunas, Vilnius, Riga, Tallinn, Bialystok, Trojmiasto (Gdansk–Sopot–Gdynia), and Malmö. They all are comparable in size and, most importantly, were significantly affected by modernistic urbanism, which makes these cities more difficult and complicated for space syntax precise modeling because of separate pedestrian and car traffic in the areas of modernistic housing blocks. Examples of the maps of all seven cities are presented in Figure 2.

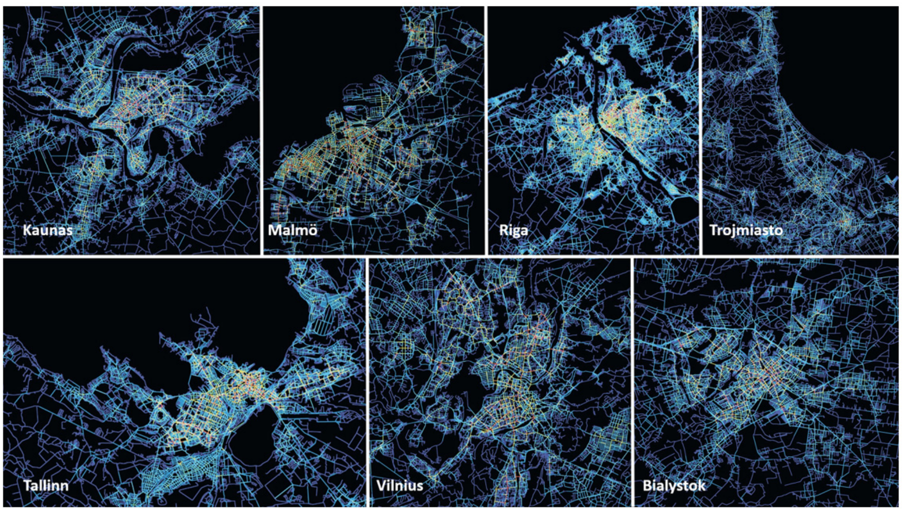

Figure 2. Space syntax maps of seven cities showing choice with 1000 m radius calculations. Red indicates higher numerical values.

Validation of the models was based on the earlier presented idea of movement economy, meaning that areas with higher concentration of the important objects (POIS or points of interest in Open Street Map) should demonstrate correlations with syntactic indicators if the models are working well. As a result, various syntactic indicators received in the models of the investigated test cities were checked for statistical correlations with density of POIS calculated as their number within 200 m from street segment. A distance of 200 m was chosen in order to reflect single points of POIS in GIS, which do not have any other spatial dimensions without x and y coordinates, on a more realistic urban scale where all objects have area and volume. Results of the statistical analysis are presented in Table 1.

Table 1. Spearman's Rho between syntactic indicator and density of POIS within radius 200 m. ** significant correlations at the level 0.01. Yellow indicates strong correlations. Green indicates moderate correlations.

	Ch_1000	Ch_3000	Ch_5000	Ch_n	In_1000	In_3000	In_5000	In_n	MR_1000	NC_1000	NC_3000	NC_5000
Kaunas	0.231 **	0.163 **	0.135 **	−0.018 **	0.601 **	0.610 **	0.592 **	0.318 **	0.624 **	0.654 **	0.620 **	0.601 **
Malmo	0.052 **	0.203 **	0.102 **	−0.028 **	0.483 **	0.439 **	0.354 **	0.144 **	0.548 **	0.564 **	0.465 **	0.365 **
Riga	0.260 **	0.157 **	0.118 **	−0.077 **	0.629 **	0.634 **	0.608 **	0.406 **	0.674 **	0.686 **	0.639 **	0.603 **
Tallinn	0.296 **	0.210 **	0.162 **	−0.051 **	0.659 **	0.673 **	0.642 **	0.463 **	0.682 **	0.705 **	0.686 **	0.649 **
Vilnius	0.181 **	0.111 **	0.090 **	−0.045 **	0.550 **	0.616 **	0.621 **	0.522 **	0.592 **	0.635 **	0.631 **	0.622 **
Bialystok	0.303 **	0.193 **	0.140 **	−0.048 **	0.709 **	0.719 **	0.690 **	0.458 **	0.749 **	0.778 **	0.745 **	0.721 **
Trojmiasto	0.213 **	0.092 **	0.051 **	−0.048 **	0.615 **	0.609 **	0.571 **	0.412 **	0.639 **	0.688 **	0.613 **	0.527 **

The following space syntax indicators were calculated for the purpose of validating the model:

- Choice with radiuses 1000, 3000, 5000 m and n (Ch_1000, Ch_3000, Ch_5000, Ch_n). Choice represents the simulated transit movement of people and transport and is calculated based on the following formula: Choice (x)=$\sum_y \sum_z g_{yz}$ (x), where choice of the node or street segment x is equal to the double sum of all the shortest journeys between the nodes y and z (g_{yz}) when both every y ($\sum_y$) and every z are modelled as the origin of journey ($\sum_z$). The additional condition $y \neq x \neq y$ means that x cannot be modeled either as an origin or destination when performing its calculation. All the other nodes in a network become y and z. Graphical representations of the results of calculations for Kaunas are presented in Appendix A. Choice in all cases demonstrated weak significant correlations, except in Bialystok. This result could be explained by the fact that all the investigated cities are relatively big and have well developed street networks which offer many equal alternative routes for every journey, thus assuring the functionality of logistics. An interesting point is that choice with radius n shows weak negative correlations with POIS density. This could be explained by that fact that radius n most probably simulates the longest journeys made by car by high-speed streets, including bypass roads, and it is logical to expect lower densities of POIS there. Integration with radiuses 1000, 3000, 5000 m and n (In_1000, In_3000, In_5000, In_n) shows the most reachable areas of the highest density of street networks, which potentially become the destination zones for most simulated movements in a city. It is calculated based on the following formula: Integration (x) = $NC^2/\sum_y d$ (x,y), where NC represents number of nodes within the calculated radius and $\sum_y$ is a sum of all the shortest distances d from x to every y. Graphical representations of the results of calculations for Kaunas are presented in Appendix A. In the majority of cases, we can see strong correlations between integration and POIS density at a lower radius and moderate correlations at radius n.
- The so-called metric reach within a radius 1000 m is calculated by the same formula as reach centrality described in the Materials and Methods section with one difference: it calculates not the number of buildings but the sum of street segment lengths. In such a case *W*(*j*), which is the mean weight of the building in the calculation or Reach centrality, as described earlier in the Materials and Methods section, means segment lengths when calculating metric reach. According to Peponis [51], clusters of street segments with the higher metric reach potentially identify zones of more active street

culture and more intensive social interaction in public spaces. It would be logical to expect a greater POIS concentration there as well. In all the investigated cities, we found strong correlations with POIS density, thus confirming the concept of Peponis. Graphical representations of the results of the calculations for Kaunas are presented in Appendix A.

- The node count or number of nodes as street segments within radiuses 1000, 3000, 5000 m and n (NC_1000, NC_3000, NC_5000) is calculated based on the formula: Node Count (x) = $\sum_y$ W(y), where $\sum_y$ is the sum of all nodes y (W(y)) within the radiuses used for calculation, and W is the weight which in the presented case is equal to 1, so the result represents just a simple sum of nodes reachable from x. In essence, it is a simpler version of metric reach as it considers just the number of street segments without calculating street length. We found a strong correlation in most cases. Graphical representations of the results of the calculations for Kaunas are presented in Appendix A.

Strong and moderate Spearman correlations were found for all the investigated cities. The results demonstrate monotonous dependency function between various syntactic indicators and space syntax modeling results and confirm that models are possibly "wrong, but useful".

3.2. Results of the Modeling of Four Urban Capitals

The first part of the GIS database was created as a background for further modeling of the present situation and contains the following data:

- Street network, buildings, and green areas from OSM;
- Inhabitants' density data on 1000 × 1000 m grid from geoportal.lt [52];
- Mean land prices on 200 × 200 m grid purchased.

The second part of the database was created for modeling the changes in the four capitals. It had the same layers as the first part (streets, buildings, inhabitants, and land prices) with some changes added. Changes in the street network were reflected by adding new streets planned in the Kaunas city master plan [53]. Data on new buildings and inhabitants was collected from the open web portal https://citify.eu/, accessed on 10 October 2021 [54]. This portal collects and provides data about residential, commercial, public purpose and infrastructure projects that are either planned or under construction in cities (an example of the portal web page screen is presented in Figure 3). It provides such data as exact location, plans and visualizations, function, floor area if applicable, number of flats, etc. In the case of the presented modeling, citify data was used to add new buildings, functions and especially housing, predicted inhabitant number in the buildings, and changes in the infrastructure of green areas. The most problematic was identification of changes in land prices. Based on some successfully implemented analogs, it was decided to model future land prices based on changes in the configuration of street network as the essential and the most important factor. Such an approach in essence proved to be effective in various projects of Space Syntax Limited.ltd, London, UK, including *South East England, Urban Value* [55] and *Melbourne Urban Value Modeling* [56]. For modeling purposes, the earlier presented space syntax calculations on the Kaunas street network were taken and checked for correlations with the existing land prices intersected with buildings as the primary cell for graph creation. The results of the calculation are presented in Table 2.

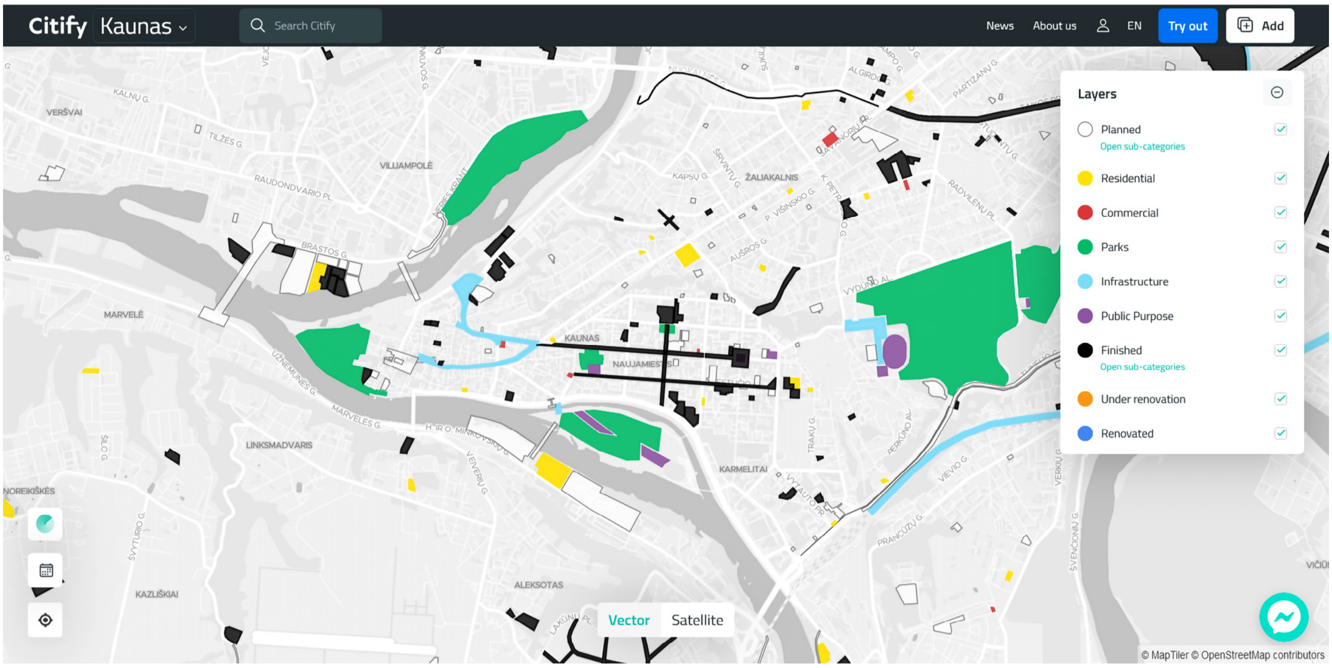

Figure 3. Citify portal web page with new developments in Kaunas center visible [54].

Four indexes from the different groups with the strongest correlations were chosen as the background for further modeling: node count with radius 5000 (NC_5000), integration with radiuses 3000 and 5000 (In_3000, In_5000), and choice with radius 5000 (Ch_5000). Two integrations were taken in order to reflect the concept of pervasive centrality by Hillier [57], which states that urban places are more alive which are well reachable within various radiuses. Strong correlations between land price values and Choice 5000 should be pointed out as evidence of the importance of logistics and transit to property values.

During the next step, the Neural Network tool by MATLAB was taught to predict the existing land prices based on space syntax and land price data in a part of Kaunas. The aim of the procedure was to use as small number of neurons as possible and, while experimenting with various predefined algorithms, to obtain as good a prediction as possible. The best result with practically 80 percent of the prediction based just on the spatial configuration of the street network and real land price coincidence was achieved with the hidden layer of 30 neurons and the Levenberg–Marquardt training algorithm [58]. The trained Neural Network was used on space syntax indicators calculated with new streets added to predict changes in land prices.

Regressions of the Neural Network modeling results with training, validation, test, and all data are presented in Figure 4.

Table 2. Spearman's Rho between mean land price and syntactic indicators. ** significant correlations at the level 0.01. Yellow indicates the strongest 4 correlations chosen for modeling.

	land price	Ch_1000	Ch_3000	Ch_5000	Ch_n	Connectivi	In_1000	In_3000	In_5000	In_n	MR_1000	NC_1000	NC_3000	NC_5000
Land price	1.000	0.503 **	0.538 **	0.545 **	0.240 **	00.006	0.502 **	0.558 **	0.571 **	0.370 **	0.472 **	0.524 **	0.573 **	0.592 **
Angular_Co	0.287 **	0.618 **	0.604 **	0.564 **	0.286 **	0.479 **	0.731 **	0.657 **	0.613 **	0.428 **	0.745 **	0.667 **	0.612 **	0.564 **
Ch_1000	0.503 **	1.000	0.929 **	0.858 **	0.402 **	0.188 **	0.963 **	0.876 **	0.838 **	0.482 **	0.947 **	0.983 **	0.884 **	0.830 **
Ch_3000	0.538 **	0.929 **	1.000	0.965 **	0.493 **	0.190 **	0.923 **	0.947 **	0.921 **	0.553 **	0.909 **	0.932 **	0.948 **	0.900 **
Ch_5000	0.545 **	0.858 **	0.965 **	1.000	0.575 **	0.170 **	0.859 **	0.909 **	0.922 **	0.568 **	0.835 **	0.861 **	0.911 **	0.911 **
Ch_n	0.240 **	0.402 **	0.493 **	0.575 **	1.000	0.121 **	0.425 **	0.421 **	0.412 **	0.562 **	0.395 **	0.391 **	0.357 **	0.335 **
Connectivi	00.006	0.188 **	0.190 **	0.170 **	0.121 **	1.000	0.260 **	0.226 **	0.199 **	0.150 **	0.282 **	0.222 **	0.201 **	0.171 **
In_1000	0.502 **	0.963 **	0.923 **	0.859 **	0.425 **	0.260 **	1.000	0.914 **	0.864 **	0.542 **	0.978 **	0.980 **	0.895 **	0.834 **
In_3000	0.558 **	0.876 **	0.947 **	0.909 **	0.421 **	0.226 **	0.914 **	1.000	0.972 **	0.609 **	0.907 **	0.914 **	0.982 **	0.931 **
In_5000	0.571 **	0.838 **	0.921 **	0.922 **	0.412 **	0.199 **	0.864 **	0.972 **	1.000	0.629 **	0.851 **	0.873 **	0.973 **	0.977 **
In_n	0.370 **	0.482 **	0.553 **	0.568 **	0.562 **	0.150 **	0.542 **	0.609 **	0.629 **	1.000	0.510 **	0.505 **	0.548 **	0.526 **
MR_1000	0.472 **	0.947 **	0.909 **	0.835 **	0.395 **	0.282 **	0.978 **	0.907 **	0.851 **	0.510 **	1.000	0.976 **	0.892 **	0.821 **
NC_1000	0.524 **	0.983 **	0.932 **	0.861 **	0.391 **	0.222 **	0.980 **	0.914 **	0.873 **	0.505 **	0.976 **	1.000	0.919 **	0.861 **
NC_3000	0.573 **	0.884 **	0.948 **	0.911 **	0.357 **	0.201 **	0.895 **	0.982 **	0.973 **	0.548 **	0.892 **	0.919 **	1.000	0.964 **
NC_5000	0.592 **	0.830 **	0.900 **	0.911 **	0.335 **	0.171 **	0.834 **	0.931 **	0.977 **	0.526 **	0.821 **	0.861 **	0.964 **	1.000

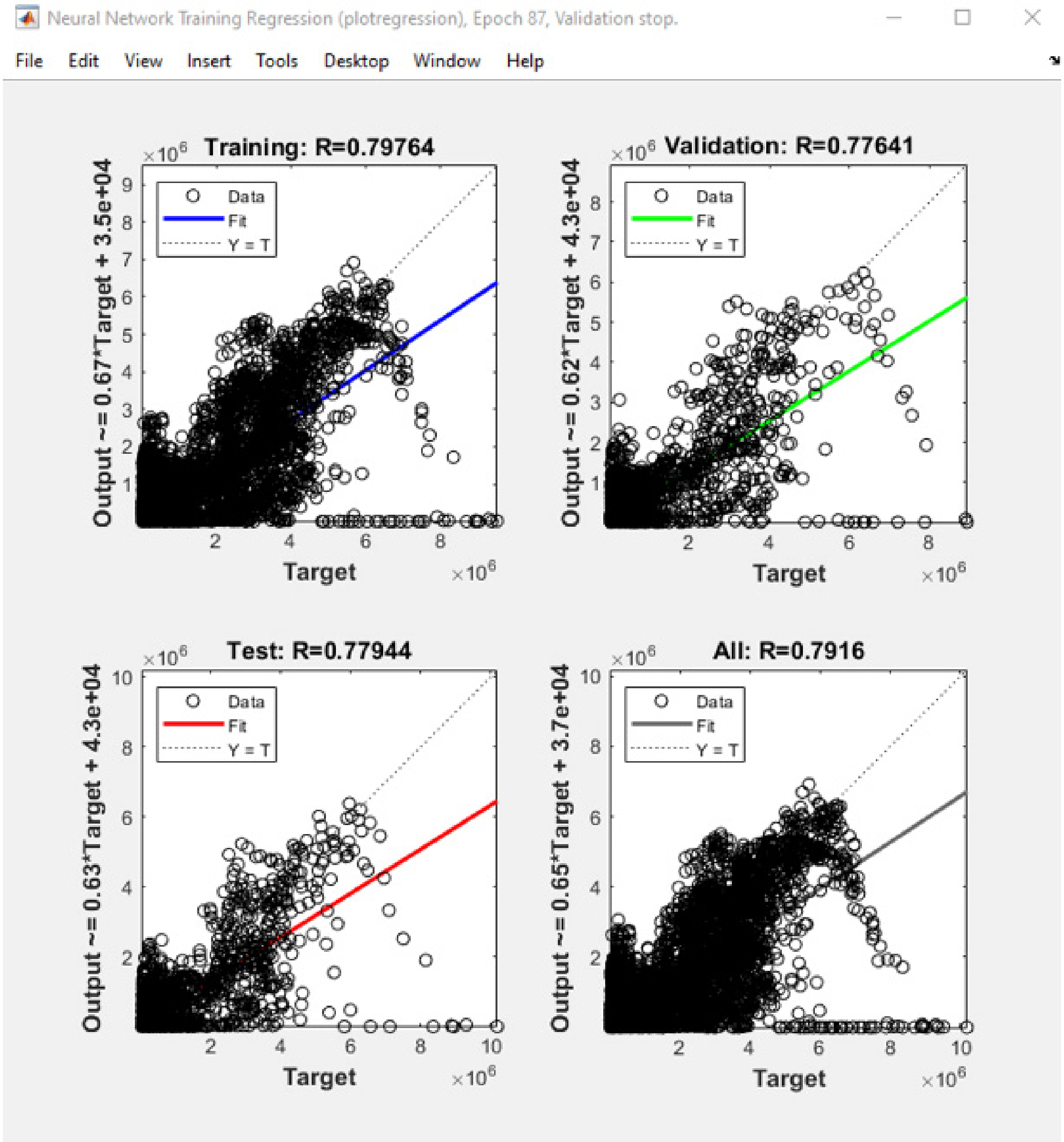

Figure 4. Regressions of the Neural Network modeling results with training, validation, test, and all data.

Visualized results of the modeling are presented in Figure 5. It is interesting to note in the top left image that land prices are affected by three factors:

- City configuration, e.g., higher prices in the urban center;
- Ecological conditions, e.g., land prices are higher closer to the forests or even inside them;
- Neighboring important objects which attract people and businesses, e.g., the airport.

Considering all three factors affecting land prices, it becomes interesting that the Neural Network was able to predict higher land price clusters around the airport effectively but it was less effective when considering ecological hedonistic aspects. An 80 percent coincidence in this case could be treated as a spatially influenced constituent of the land price and, because of that, it was used to predict land prices for modeling of both present and future economic capital.

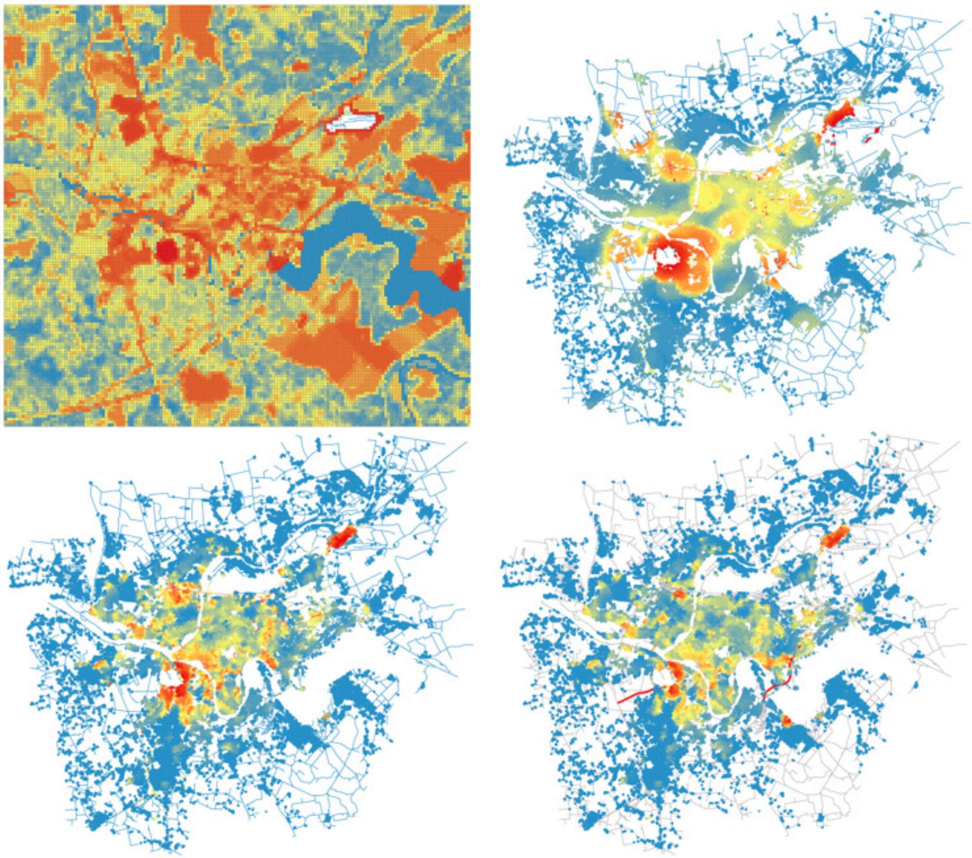

Figure 5. Modeling of land prices: **top left**—data on land prices; **top right**—land prices intersected with buildings; **bottom left**—predicted land price data for the present; **bottom right**—predicted land price data for the future. Red indicates higher prices.

The results for the four capitals modeling were obtained using the Urban Network Analysis Toolbox for ArcGIS [45]. Street network was used as a background of the mathematical graph with buildings added as nodes to the graph instead of street segments, as performed in traditional space syntax analysis.

The results of spatial capital modeling are presented in Figure 6. It can be seen in this graphical presentation that historically and organically developed urban areas demonstrate a greater potential for street culture. Zones of high spatial capital within different radiuses overlap just partially; it is especially visible at the historical city center and could be explained by relatively large housing blocks there and the relative isolation of the area by the slopes of Nemunas Valley, which has a limited number of streets crossing.

The results of the present social capital modeling (Figure 7) show that at the smaller and medium radius, the zone of high values is shifted to the side of the city center, thus reflecting the effects of depopulation of the downtown area during the Soviet period because of the application of the concept of monofunctional zoning according to the ideals of modernistic urbanism. Compared with the maps of spatial capital (Figure 6), it becomes quite easily visible that at the smallest radius, the highest values of social and spatial capital do not overlap much, thus identifying the problem: people and spaces of street culture do not meet in the city. The social capital of the city center is not increased very much, even with the largest radius or when mean journey distance in Kaunas is considered.

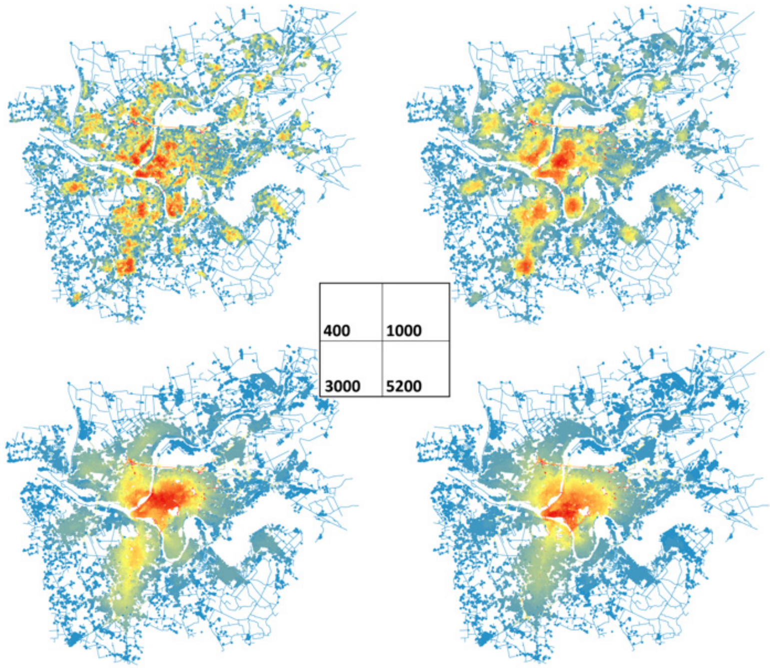

Figure 6. Present spatial capital modeled at four radiuses. Red indicates higher values.

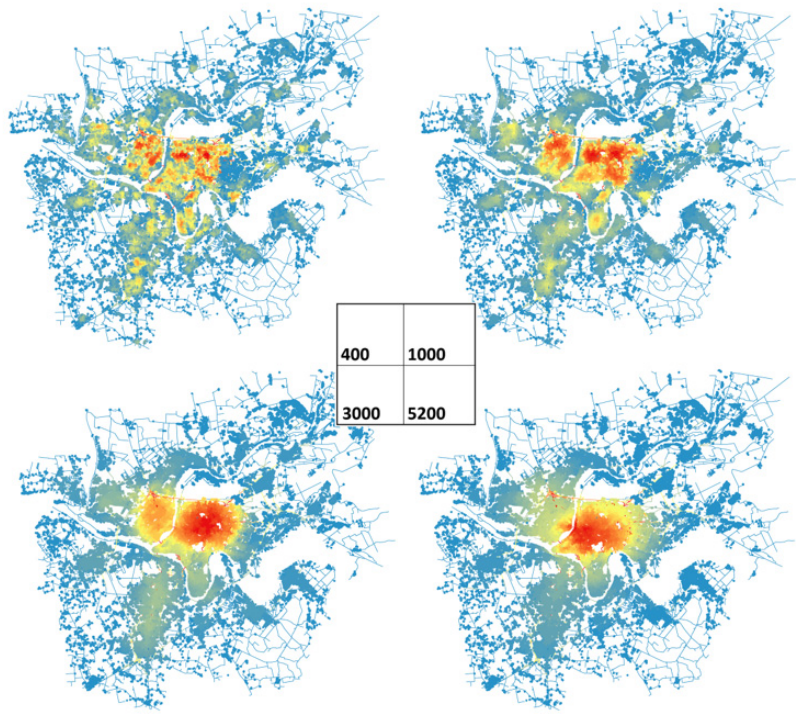

Figure 7. Present social capital modeled at four radiuses. Red indicates higher values.

As mentioned earlier, economic capital is affected not only by the spatial configuration of the street network but also by neighboring functions (e.g., airport, central hospital, etc.). Observing the visual results of calculations (Figure 8), it is also clear that with increases in the radius, the importance of the street network configurations increases and the influence of the neighboring objects is decreases. Comparing all three capitals, it can be seen that they overlap just partially at all radiuses, thus showing not so strong possible synergies between them.

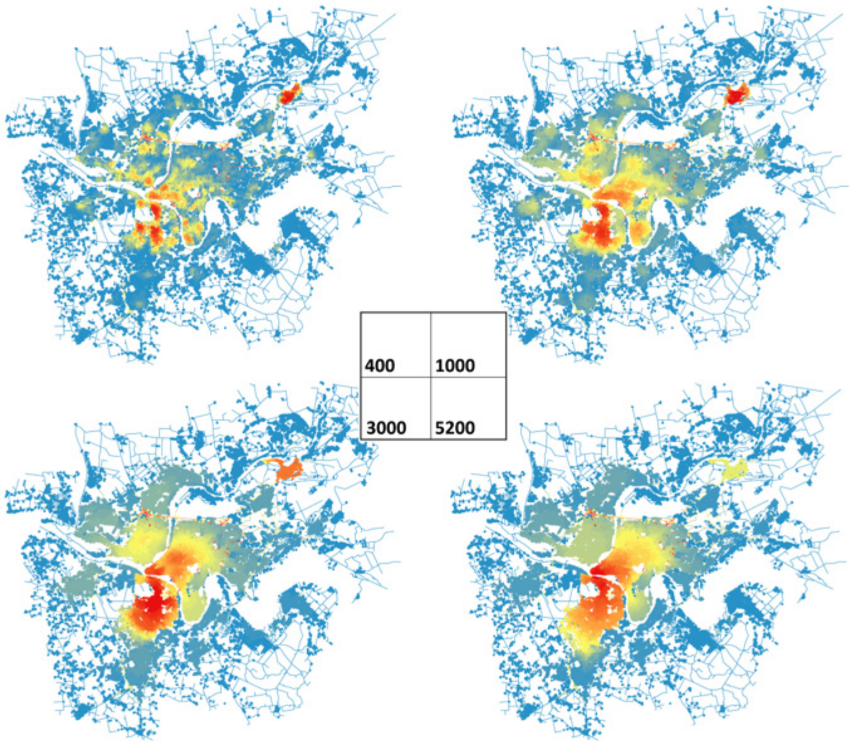

Figure 8. Present economic capital modeled at four radiuses. Red indicates higher values.

Although the previous capitals overlap with each other just partially, the ecological capital (Figure 9) does so even less as it depends on natural reachable territories which are very often located at the periphery of the city. At the same time, higher values could be seen in some more suburban and even some modernistic housing areas which were located close to the greenery, thus demonstrating certain valuable aspects of these territories.

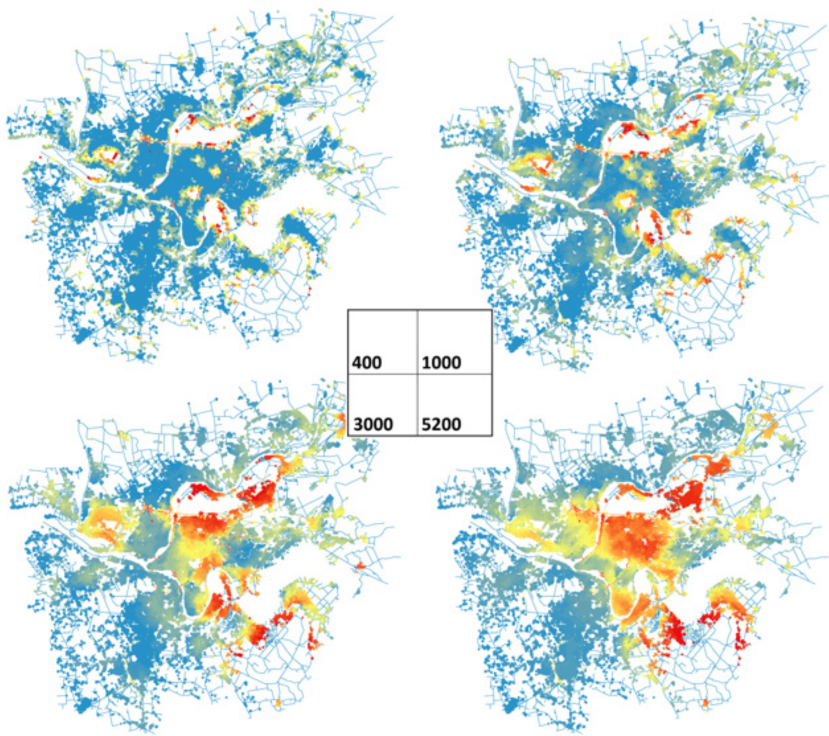

Figure 9. Present ecological capital modeled at four radiuses. Red indicates higher values.

3.3. Validation of the Present Capitals

Additional validation of the capitals models was performed based on the same idea of movement economy as in the validation of the generic space syntax indicators, as described earlier. The indicators of the working model were chosen POIS or points of interest combined with public transport stops and data on established housing communities obtained from the "Mano bendrijos" webpage [59]. The idea to add the latest data was based on the premise that stronger social capital can result in more collaboration between inhabitants, which could be represented formally by the number of housing communities. Correlations between the four capitals within different radiuses and the above-mentioned validation data density are presented in Table 3.

Statistical analysis revealed that the spatial, economic, and social capital models work reasonably well at all radiuses, while the strength of Spearman's Rho varies from radius to radius. The majority of correlations with these three capitals are strong, except for spatial capital at radius 400 m, which could be seen as evidence of high heterogeneity of urban morphotypes of buildings at lower scale caused by modernistic interventions. The situation is different with ecological capital as at the shortest radius of 400 m, it demonstrates significant weak negative correlations. This result looks quite logical if the "traditional" model of urban development, based on the movement economy concept, is considered. In such models, the most reachable location attracts more people, and over time, people attract more functions, thus causing an increase in the densities, etc. In such a case, green areas represent just a part of the urban functions and needs of the inhabitants, and these are most often in some conflict with other needs, e.g., recreational areas which offer open spaces and low use intensity are under pressure from high intensity development in a city center where land prices are high and can generate high short term income if used for other purposes. The shift of the urban paradigm and complex view of a city can change such a situation and was demonstrated in other cities. However, according to the presented results, Kaunas demonstrates the "traditional" form of development, which was demonstyrated by the recent use of various green areas for urbanization, including the construction of commercial and public buildings in the green island in the city center and transformation of a former green area of a water supply protection zone into housing zones.

3.4. Synergy between Capitals

The differences between the validation data and the values of the four capitals raised the idea to investigate the synergy between the capitals themselves. The actuality of the idea is grounded on the fact that each city has certain limits to increases in the capitals because of a limited number of inhabitants, limited availability of recreational areas, the size of property market, and limited possibilities to increase the density of buildings. Therefore, it is important not only to see if one or another capital is increasing but also if a positive or negative synergy between them is increasing or declining. The potential usefulness of this idea is supported by earlier noted differences between the allocation of the highest values of capitals when comparing the visual results of the modeling. A comparison of the synergies could be useful when comparing present and future situations or when visually identifiable differences are be not precise enough. The synergy between capitals was calculated as Spearman's Rho between all of them, and the results are presented in Table 4.

Table 3. Spearman's rRho between mean land price and syntactic indicators. ** significant correlations at the level 0.01. Yellow indicates strong correlations and green, medium correlations. Abbreviations: spat—spatial capital; socc—social capital; ecol—ecological capital; econ—economic capital; p—density of pois; s—density of public transport stops; b—density of housing communities. When several symbols are written beside each other, the value refers to their combined density, e.g., psb—density of POIS, stops and communities together.

	Spat5200	Spat3000	Spat1000	Spat400	Socc5200	Soc3000	Soc1000	Soc400	Ecol400	Ecol1000	Ecol3000	Ecol5200	Econ5200	Econ3000	Econ1000	Econ400
psb	0.673 **	0.654 **	0.606 **	0.463 **	0.674 **	0.680 **	0.696 **	0.611 **	−0.146 **	0.014 **	0.278 **	0.388 **	0.650 **	0.672 **	0.711 **	0.668 **
pb	0.617 **	0.612 **	0.556 **	0.420 **	0.614 **	0.634 **	0.649 **	0.567 **	−0.147 **	−0.020 **	0.253 **	0.354 **	0.595 **	0.622 **	0.648 **	0.606 **
ps	0.657 **	0.640 **	0.604 **	0.465 **	0.654 **	0.657 **	0.675 **	0.592 **	−0.145 **	0.014 **	0.270 **	0.374 **	0.639 **	0.661 **	0.705 **	0.662 **
b	0.609 **	0.556 **	0.406 **	0.292 **	0.638 **	0.623 **	0.604 **	0.540 **	−0.107 **	−00.003	0.245 **	0.355 **	0.542 **	0.535 **	0.508 **	0.479 **
p	0.589 **	0.591 **	0.549 **	0.418 **	0.581 **	0.600 **	0.616 **	0.535 **	−0.148 **	−0.021 **	0.245 **	0.333 **	0.578 **	0.603 **	0.635 **	0.593 **

Table 4. Spearman's Rho between capitals. ** significant correlations at the level 0.01. Yellow indicates a strong correlation and green a medium correlation. Abbreviations: spat—spatial capital; socc—social capital; ecol—ecological capital; econ—economic capital.

	Spat5200	Spat3000	Spat1000	Spat400	Socc5200	Socc3000	Socc1000	Socc400	Ecol400	Ecol1000	Ecol3000	Ecol5200	Econ5200	Econ3000	Econ1000	Econ400
spat5200	1	0.935 **	0.693 **	0.527 **	0.965 **	0.938 **	0.802 **	0.707 **	−0.231 **	−0.185 **	−0.025 **	0.138 **	0.895 **	0.875 **	0.782 **	0.720 **
spat3000	0.935 **	1	0.807 **	0.605 **	0.883 **	0.944 **	0.848 **	0.724 **	−0.316 **	−0.242 **	−0.009 **	0.147 **	0.894 **	0.904 **	0.814 **	0.728 **
spat1000	0.693 **	0.807 **	1	0.841 **	0.644 **	0.730 **	0.880 **	0.775 **	−0.399 **	−0.251 **	0.034 **	0.185 **	0.720 **	0.781 **	0.856 **	0.767 **
spat400	0.527 **	0.605 **	0.841 **	1	0.477 **	0.537 **	0.707 **	0.820 **	−0.268 **	−0.125 **	0.040 **	0.145 **	0.550 **	0.600 **	0.708 **	0.775 **
socc5200	0.965 **	0.883 **	0.644 **	0.477 **	1	0.947 **	0.801 **	0.705 **	−0.228 **	−0.184 **	0.030 **	0.221 **	0.853 **	0.832 **	0.751 **	0.700 **
socc3000	0.938 **	0.944 **	0.730 **	0.537 **	0.947 **	1	0.880 **	0.764 **	−0.295 **	−0.224 **	0.053 **	0.236 **	0.857 **	0.857 **	0.782 **	0.717 **
socc1000	0.802 **	0.848 **	0.880 **	0.707 **	0.801 **	0.880 **	1	0.899 **	−0.345 **	−0.213 **	0.099 **	0.265 **	0.772 **	0.810 **	0.830 **	0.754 **
socc400	0.707 **	0.724 **	0.775 **	0.820 **	0.705 **	0.764 **	0.899 **	1	−0.262 **	−0.131 **	0.095 **	0.232 **	0.671 **	0.700 **	0.742 **	0.773 **
ecol400	−0.231 **	−0.316 **	−0.399 **	−0.268 **	−0.228 **	−0.295 **	−0.345 **	−0.262 **	1	0.662 **	0.228 **	0.059 **	−0.227 **	−0.258 **	−0.279 **	−0.206 **
ecol1000	−0.185 **	−0.242 **	−0.251 **	−0.125 **	−0.184 **	−0.224 **	−0.213 **	−0.131 **	0.662 **	1	0.536 **	0.321 **	−0.174 **	−0.183 **	−0.140 **	−0.083 **
ecol3000	−0.025 **	−0.009 **	0.034 **	0.040 **	0.030 **	0.053 **	0.099 **	0.095 **	0.228 **	0.536 **	1	0.804 **	0.004	0.031 **	0.118 **	0.129 **
ecol5200	0.138 **	0.147 **	0.185 **	0.145 **	0.221 **	0.236 **	0.265 **	0.232 **	0.059 **	0.321 **	0.804 **	1	0.133 **	0.174 **	0.263 **	0.263 **
econ5200	0.895 **	0.894 **	0.720 **	0.550 **	0.853 **	0.857 **	0.772 **	0.671 **	−0.227 **	−0.174 **	0.004	0.133 **	1	0.972 **	0.842 **	0.741 **
econ3000	0.875 **	0.904 **	0.781 **	0.600 **	0.832 **	0.857 **	0.810 **	0.700 **	−0.258 **	−0.183 **	0.031 **	0.174 **	0.972 **	1	0.896 **	0.784 **
econ1000	0.782 **	0.814 **	0.856 **	0.708 **	0.751 **	0.782 **	0.830 **	0.742 **	−0.279 **	−0.140 **	0.118 **	0.263 **	0.842 **	0.896 **	1	0.912 **
econ400	0.720 **	0.728 **	0.767 **	0.775 **	0.700 **	0.717 **	0.754 **	0.773 **	−0.206 **	−0.083 **	0.129 **	0.263 **	0.741 **	0.784 **	0.912 **	1

An analysis of the correlations presented in Table 4 reveals that ecological capital has a negative synergy with the other capitals, whereas there are various positive strong correlations between economic, social and spatial capital. In order to generalize the results and make them more intelligible, the values of each capital within different radiuses were multiplied with each other in order to express the largest synergies between layers of each capital as one number (Figure 10 and Table 5). The combined results demonstrate both visually and statistically that the strongest synergy is between spatial and social capital, and economic capital demonstrates a slightly weaker correlation with both of them. Additional validation of the combined results (Table 5) demonstrates similar results to those presented in Table 3.

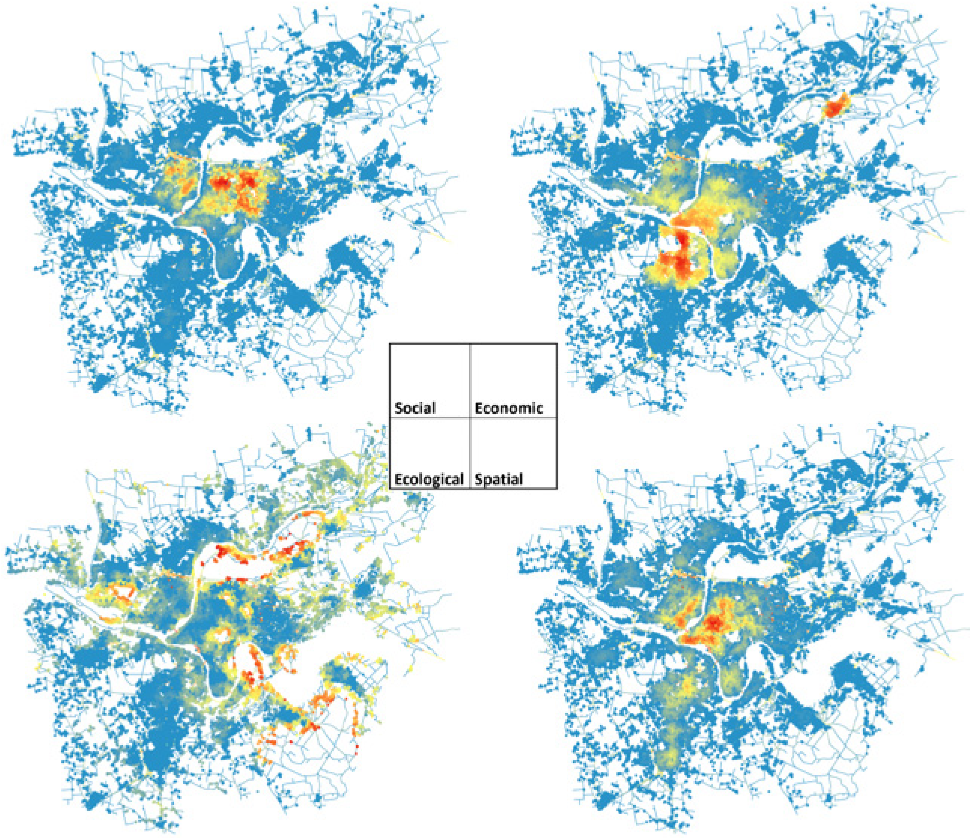

Figure 10. Present capitals combined by multiplication of the mathematical values. Orange indicates higher values. Red indicates the highest numerical values.

Table 5. Spearman's Rho between combined capitals and validation data. ** significant correlations at the level 0.01. Yellow indicates a strong correlation and green a medium correlation. Abbreviations: spat—spatial capital; socc—social capital; ecol—ecological capital; econ—economic capital; p—density of POIS; s—density of public transport stops; b—density of housing communities. When several symbols are written beside each other, the value refers to their combined density, e.g., psb—density of POIS, stops and communities together.

	Econ1	Ecol1	Spat1	Social1	Psb	Pb	Ps	B	P
econ1	1	−0.144 **	0.865 **	0.824 **	0.661 **	0.587 **	0.653 **	0.477 **	0.572 **
ecol1	−0.144 **	1	−0.271 **	−0.213 **	−0.020 **	−0.039 **	−0.022 **	−0.013 **	−0.044 **
spat1	0.865 **	−0.271 **	1	0.930 **	0.667 **	0.612 **	0.659 **	0.517 **	0.595 **
social1	0.824 **	−0.213 **	0.930 **	1	0.705 **	0.653 **	0.683 **	0.638 **	0.617 **

3.5. Results of Comparison of the Present and Future Urban Capitals

The same procedure as conducted during modeling of the four present capitals was repeated for modeling of future changes. The earlier mentioned GIS data on new buildings, number of inhabitants according to the projects, planned streets and predicted land values was used for the modeling. Layers of each capital were combined into one based on multiplication of the numerical values. Changes in the capitals were compared visually using scatterplots and by changes in synergies between them.

Despite the fact that Kaunas is developing in an infill manner with only short segments of streets or small groups of the buildings being added in the city, visualization of the results demonstrated some notable differences between the present and future situations. An example of the comparison of economic capital is presented in Figure 11. It is possible to see some differences between present and future situations despite the above-mentioned infill development, but this comparison is only suitable for a preliminary check that the model is working and is not suitable for precise comparisons. On the other hand, it is more interesting from the point of urban planning how capitals are changing at the neighborhood scale and when comparing different parts within a city. The results of this comparison are presented in Figure 12.

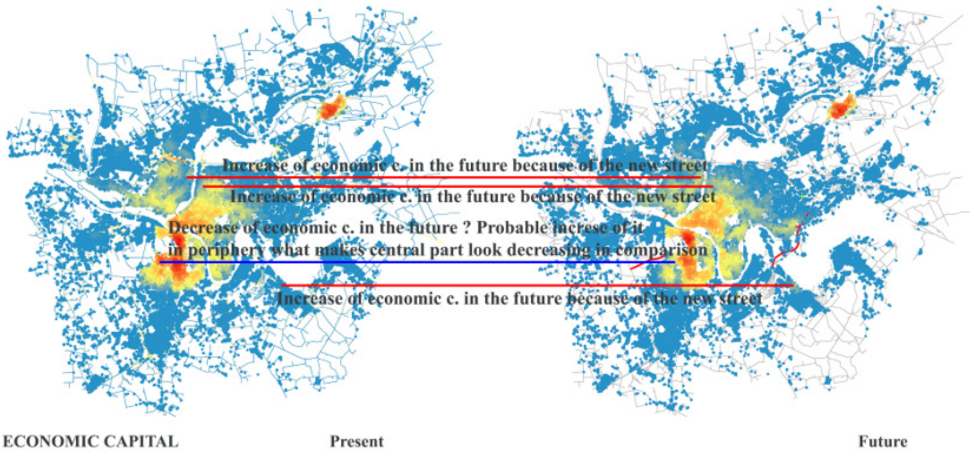

Figure 11. Comparison of present and predicted future economic capital. Orange indicates higher values. Red indicates the highest numerical values.

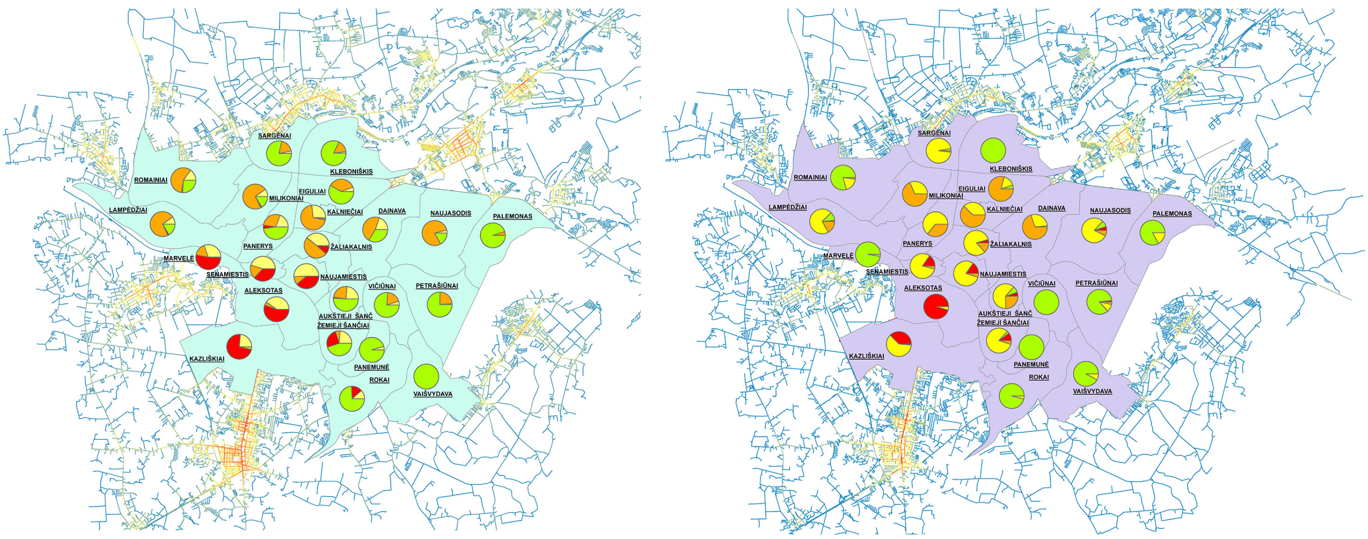

Figure 12. Four capitals now (**left**) and in the predicted future (**right**). Economic capital is indicated by red, spatial capital by yellow, social capital by orange and ecological capital by green.

To make numerical values more comparable between capitals, they were divided by the standard deviation values of the data. In this way, large differences between the scales of different capitals were at least minimized, thus making them presentable on a scatterplot. The results represented in circular scatterplots show quite noticeable changes in some situations. For example, in the central historical part of Kaunas, a significant increase in spatial capital can be noted which corresponds to the construction of a large number of commercial or public buildings there. There is an increase in economic capital in Aleksotas where land prices are already high; however, there is a relatively limited number of inhabitants and low densities of buildings, which could be explained by the creation of new connections between the area and the Via Baltica international road which might make the territory even more attractive for businesses. The same scatterplot-based comparison could be used at the level of a single building if needed (Figure 13) as even within the same neighborhood, notable differences in the capitals were demonstrated. In Figure 13, a part of Žaliakalnis neighborhood is presented where differences in the ecological capital of single buildings are notable. Such differences are caused by closer placement of some buildings to žuolynas park.

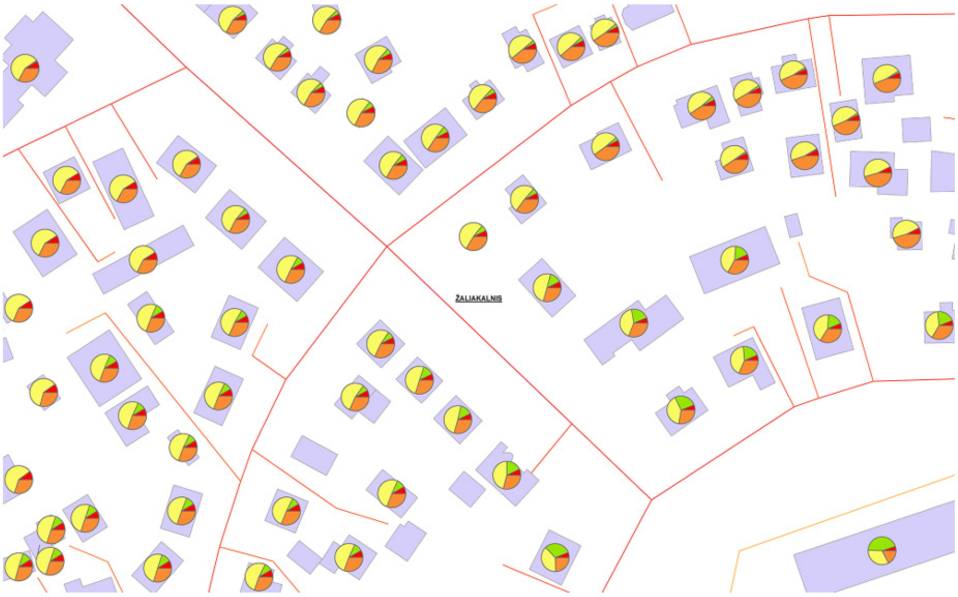

Figure 13. Comparison of four capitals at the level of a single building. Economic capital is indicated by red, spatial capital by yellow, social capital by orange and ecological capital by green.

Although a visual comparison of the changes in the capitals could be useful at least in some cases, the final and the most precise comparison was conducted based on identified changes in the synergies of correlations of the capitals. For this purpose, the Spearman's Rho between capitals was calculated and analyzed (Table 6). The idea was to identify both positive and negative correlations from medium to strong, sum them up and compare changes between the present and the future situations. As the visualization in Figure 14 shows, positive synergy between capitals is increasing in the city center and partially around it in Naujamiestis, Žaliakalnis and Dainava. This means that various infill developments in these areas, despite uncontrolled results due to high flexibility and the too general zoning of the Kaunas master plan, make interaction between capitals in these areas stronger. The suburban "recreational" neighborhoods demonstrate increased synergy, which means that despite scarce urbanization, some new developments are planned in the optimal locations to increase synergies between capitals. This demonstrates that high densities of buildings and people are not necessary preconditions for positive interaction of capitals and thus offers possible insights for sustainability of suburban areas when "compact city" models are not the only alternative.

Table 6. Spearman's Rho between combined capitals and validation data. All correlations are significant at the level 0.01. Orange indicates the medium and strong positive correlations; blue indicates medium and strong negative correlations. Total changes in values correlation are indicated by orange and blue. Comparisons of the present and future situations of Kaunas are shown at the bottom of the table where red indicates increased synergy and green decreased synergy.

	PRESENT								FUTURE					
	econ-ecol	econ-spat	econ-soc	ecol-spat	ecol-soc	spat-soc	total positive correlations	total negative correlations	econ-ecol	econ-spat	econ-soc	ecol-spat	ecol-soc	spat-soc
All Area	−0.144	0.865	0.824	−0.271	−0.213	0.93	2.619		−0.09	0.851	0.836	−0.264	−0.209	0.939
Kaunas	−0.22	0.798	0.559	−0.309	−0.212	0.831	2.188		−0.165	0.796	0.611	−0.3	−0.211	0.859
Alesotas	0.028	0.602	0.582	0.421	0.472	0.86	2.937		0.065	0.605	0.568	0.381	0.443	0.887
A. Šančiai	−0.089	0.799	0.572	−0.062	−0.361	0.594	1.965	−0.361	−0.256	0.541	0.679	−0.011	−0.314	0.564
Dainava	0.025	0.815	0.182	−0.051	−0.091	0.632	1.447		0.005	0.842	0.306	−0.076	−0.1	0.671
Eiguliai	−0.126	0.771	0.693	−0.322	−0.325	0.947	2.411	−0.647	−0.095	0.775	0.65	−0.322	−0.357	0.941
Kalniečiai	−0.324	0.894	0.793	−0.204	−0.444	0.649	2.336	−0.768	0.04	0.347	0.163	−0.218	−0.409	0.724
Kazliškiai	−0.062	0.595	0.501	−0.068	0.009	0.934	2.03		0.078	0.557	0.369	−0.159	−0.197	0.854
Kleboniškis	−0.177	0.499	0.464	0.013	0.074	0.979	1.942		−0.178	0.787	0.776	−0.221	−0.064	0.919
Lampėdžiai	−0.677	0.937	0.849	−0.728	−0.62	0.905	2.691	−2.025	−0.534	0.844	0.752	−0.721	−0.625	0.912
Marvelė	0.091	0.872	0.836	0.381	0.418	0.994	3.501		−0.158	0.352	0.441	−0.106	−0.149	0.987
Milikoniai	−0.064	0.24	0.421	−0.014	−0.29	0.686	1.107		0.556	0.293	−0.041	0.073	−0.263	0.684
Naujamiestis	−0.072	0.903	0.73	−0.136	−0.175	0.864	1.767		0.117	0.854	0.592	0.117	0.141	0.809
Naujasodis	−0.362	0.839	0.835	−0.39	−0.312	0.831	2.505	−0.674	−0.247	0.879	0.859	−0.346	−0.236	0.87
Palemonas	0.307	0.827	0.516	0.358	0.455	0.646	3.109		0.228	0.884	0.507	0.223	0.316	0.728
Panemunė	−0.045	0.928	0.791	−0.145	−0.343	0.885	2.604	−0.343	−0.037	0.926	0.827	0.133	−0.191	0.818
Panerys	−0.167	0.692	−0.25	−0.333	−0.295	0.424	1.116	−0.333	−0.249	0.519	0.04	−0.388	−0.229	0.801
Petrašiūnai	−0.446	0.882	0.612	−0.282	−0.009	0.843	2.337		−0.203	0.882	0.793	−0.028	0.106	0.94
Rokai	0.153	0.746	0.676	0.09	0.241	0.784	2.206		−0.028	0.857	0.521	0.071	0.424	0.668
Romainiai	0.176	0.348	0.504	−0.05	−0.107	0.858	1.71		0.172	0.321	0.426	−0.165	−0.242	0.821
Sargėnai	−0.407	0.8	0.87	−0.621	−0.497	0.899	2.569	−1.525	−0.03	0.426	0.536	−0.59	−0.531	0.94
Senamiestis	−0.206	0.937	0.859	−0.113	−0.162	0.95	2.746		−0.124	0.881	0.941	−0.143	−0.22	0.934
Vaišvydava	−0.323	0.988	0.911	−0.302	−0.244	0.944	2.843	−0.625	−0.061	0.568	0.632	−0.368	−0.414	0.925
Vičiūnai	0.071	0.518	0.395	0.557	0.731	0.838	3.039		0.049	0.392	0.575	−0.216	0.096	0.869
Žaliakalnis	−0.106	0.346	0.275	−0.433	−0.161	0.767	1.113	−0.433	−0.22	0.493	0.412	−0.339	−0.068	0.813
Žemieji Šančiai	−0.267	0.728	0.768	−0.288	−0.439	0.927	2.423	−0.439	−0.235	0.751	0.775	−0.362	−0.45	0.949

Table 6. *Cont.*

Change of negative correlations	Change of positive correlations	total negative correlations	total positive correlations
	0.007		2.626
	0.078		2.266
	0.012		2.949
0.047	−0.181	−0.314	1.784
	0.372		1.819
−0.032	−0.045	−0.679	2.366
0.359	−1.265	−0.409	1.071
	−0.25		1.78
	0.54		2.482
0.145	−0.183	−1.88	2.508
	−1.721		1.78
	0.133		1.24
	0.488		2.255
0.328	0.103	−0.346	2.608
	−0.674		2.435
0.343	−0.033		2.571
−0.055	0.204	−0.388	1.32
	0.278		2.615
	0.264		2.47
	−0.142		1.568
0.404	−0.667	−1.121	1.902
	0.01		2.756
−0.157	−0.718	−0.782	1.2
	−1.203		1.836
0.094	0.605	−0.339	1.718
0.077	0.052	−0.362	2.475

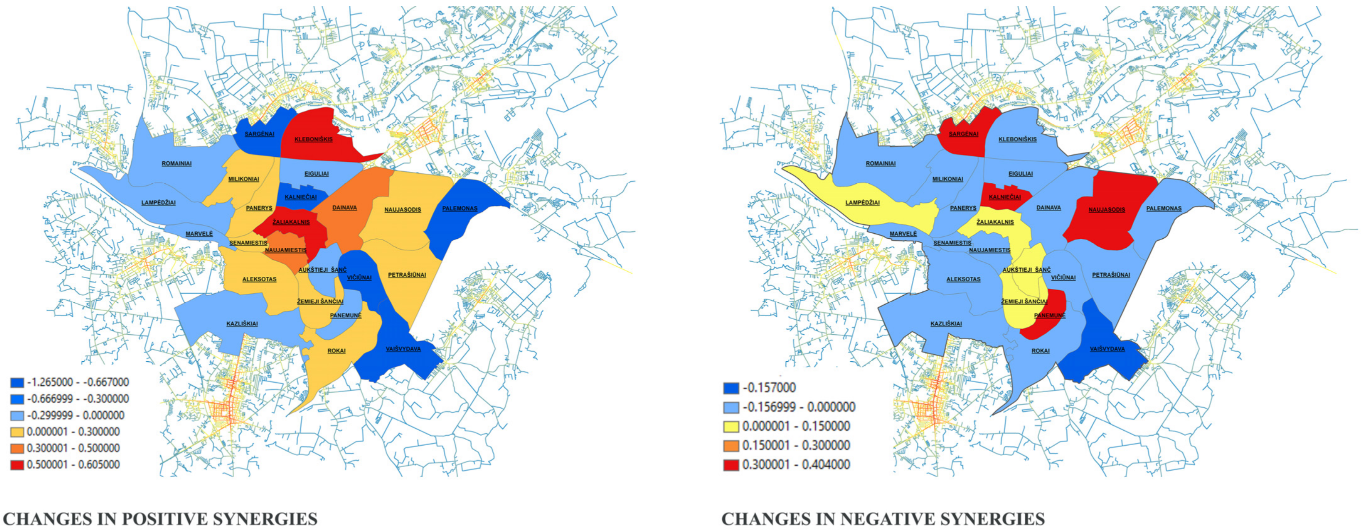

Figure 14. Changes of the synergies between capitals as a sum of medium and strong correlations. Changes in positive synergies (**left)** and negative synergies (**right**). Visualization based on the standard deviation of the numerical values. Colors and standard deviation values are represented beside the maps.

Changes in negative correlations demonstrate that they are increasing in many areas of Kaunas (Figure 14), thus giving an alarm signal for the city administration and demonstrating that only a few seemingly insignificant infill developments can change the synergy between the four urban capitals in a negative way.

4. Discussion

A city masterplan is often focused on large-scale zoning, infrastructure planning, heritage protection, etc. In reality, a master plan makes a general framework for relatively small-scale infill development which is initiated in a bottom-up way by various businesses and other stakeholders. A problem is created by the fact that such bottom-up initiatives may implement the vision of the master plan just in a fragmented way because of limiting factors, such as the number of inhabitants, speed of economic growth and other peculiarities of a specific city. If not understood, predicted, and catalyzed properly in a top-down way, such infill actions can create imbalances between social, economic, ecological and even cultural aspects of sustainable urban development. The main research question of the present study was formulated as follows: would it be possible based on the open data to analyze and predict the effect of various infill developments on sustainability of a city at the city level or at the level of the neighborhoods? Sustainability based on the concept of New Urbanism [60], which supports multi-functionality, diversity, walkability, proximity of housing and commerce, etc., was addressed as a synergy between four urban capitals by Marcus [42]: spatial, social, ecological, and economic.

Kaunas city was chosen for study due to its low top-down control of urban processes and strong dominance of private business interests in bottom-up development initiatives. A simulative modeling approach was chosen as it can reflect the complexity of urban functioning based on its configuration (e.g., street network, allocation of buildings, allocation of green areas). Several mathematical graph-based models have been used for this purpose, including space syntax [35] and graph of buildings [45]. Despite the availability of numerous tests of workability of mathematical graph models in urban settings, the models were additionally tested a few times during the current research. Various data from the open sources, such as the perimeter of buildings, density of inhabitants, and area of green recreational zones, were used as weightings in the model in order to reflect the ecological, economic, social, and spatial capitals.

The key findings of the study can be summarized as follows:

- Simulative mathematical graph-based modeling was used successfully for the analysis of the potential transformations of the synergies between capitals, thus revealing that the chaotic infill development in Kaunas in some neighborhoods could be seen as a positive in terms of sustainability, but negative in the other ways. Despite the positive synergies in some neighborhoods, in general, the study reveals the quite accidental character of interaction of the capitals under the present planning situation in Kaunas and reveals a need for predictive, catalyzing top-down approach in the city master plan.
- All the simulative models involved in the presented research were validated positively using independent open GIS data as density of points of interest based on the movement economy approach [35].
- The modeling results could be used at various scales of urban planning: at a level of the whole city, at a level of the neighborhood, and at a level of the single house. Such flexibility reveals the potential of the presented modeling approach as a decision support system for various stakeholders involved in urban development and planning.

The presented research, besides "traditional" space syntax analysis which focuses primarily on modeling and simulation of the movement of people, most often, just on a street network without consideration of the other urban factors as inhabitants' density, morphology of buildings, allocation of recreational areas, etc., could be compared to some more complex views and studies of functioning of urban structures based on analysis of spatial characteristics.

Firstly, Urban Mixed-use Index (MXI) could be mentioned. It calculates the floor space of buildings with residential use as percentage of the total amount of floor space in the investigated area. It is argued by some authors that MXI " ... in a dimensionless quantity that expresses a proportion analog to density, building percentage and open space ratio using physical parameters like floor space and plot size in a same manner." [61]. MXI, in this case, is seen as a neutral definition of multifunctionality of land use, which might differ significantly between different stakeholders of urban development and as a methodological tool for implementation of various models of New Urbanism. While agreeing with the importance of the proposed index and its potential usefulness in urban planning, the absence of the logistic dimension in the model should be noted. It is important to note that, even within the scope of New Urbanism concept, modelling of transit flows should be considered as an important aspect of urban corridors, which depending on their significance, can call for different MXI. The proposed model addresses aspects of logistics by using a mathematical graph model and adds an economic–ecological–social dimension to the analysis. On the other hand, it is possible to look for a way to use MXI as a part of weighting procedure in the calculations of centralities, thus making the model of spatial capital even more precise and more sensitive to specific functional mixes identified by the index.

The Space Matrix index is another concept which allows the quantification of such variables of urban structure as intensity, compactness, non-built space, and building height, and thereby differentiates urban form efficiently [62]. The differentiation of the efficiency of urban form is classified based on statistical cluster analysis. The method utilizes possibilities for data analysis offered by GIS technologies in a similar way to the research presented in this article, but as in MXI case, the aspect of urban logistics is missing. At the same time, it should be noted that the application of cluster analysis in the identification of synergies between four urban capitals instead of calculations of correlations is a potential alternative which should be tested in future.

Van Ness [63] addresses the common "weak point" of both the above-mentioned concepts by combining Space Syntax, MXI and Spacematrix in a GIS environment. This model differs from the proposed one as it is not assessing economic, social and ecological data directly, but its employment of GIS and a combination of Space Syntax models makes it similar to the research presented in the article, even if the syntactic modelling is constructed at the level of street segment but not building.

Within this theoretical context, the presented research on four urban capitals is an alternative or supplementary addition focused on practical implementation that further develops and tests the ideas of Marcus while applying the same mathematical graph model to all four capitals: spatial, ecological, economic and social.

Within the wider context, the capitals model could be seen as creating potential synergies with various GIS based visualized analysis, e.g., analysis of groundwater quality [64], which could be related to ecological capital, or analysis of seismic risk in a specific geographical area [65], which could be related to economic capital. The data for the presented research was obtained from OSM but it could be based on the other methods which allow the creation of vector data from orthophoto or photogrammetry [66], thus expanding list of potential components of the four capitals in the model.

The results obtained first of all allow us to address various issues of urban planning related to changes in spatial configurations of the street network, changes in building density and allocation of new buildings from the perspective of sustainable urban development. Moreover, the presented methodology allows the use the obtained results as an expansion to various sustainability compass methodologies [67] or could be used on their own as evidence in discussions between various stakeholders or even as a background for parametric urban design.

The proposed model may be limited by the availability of suitable open data for the modeling of economic capital. In the case of Kaunas, the necessary information was purchased from the state agency "Registrų centras". At the moment, the model is limited just to validation in Kaunas, and its feasibility should be tested in other cities. In the Kaunas case, the positive synergies between spatial, economic, and social capital were revealed, whereas ecological capital produced negative correlations with the other three capitals. This result is quite logical when considering the traditional form of urban development when nature and urban zones of higher density do not overlap with each other, but in a wider context, possible positive synergies between all four capitals may show the way for a new paradigm of urban planning.

The presented research should be tested in more cities, and more options for normalization of the values of the four urban capitals should be tested as well as the synergy between them.

5. Conclusions

- The proposed mathematical graph-based model of four capitals works effectively and could be used for complex evaluation and prediction of changes in the four capitals in cases of urban regeneration initiated by both top-down and bottom-up initiatives.
- Using the proposed method, impacts of various types of urban objects on the changes in capitals could be modelled, e.g., new streets, increased rank of green infrastructure, new or renovated buildings, new public spaces as attraction points, etc.
- It was discovered in the case of Kaunas, that, infill development, even when "chaotic" and small in number, can create a "butterfly effect" on a bigger part of the whole urban structure.
- The created model could be used at various scales: regional, whole city, neighborhood, block, or single buildings.
- Preliminary insights into the regularities of synergies between capitals in a city were obtained based on Kaunas, but such synergies should be further investigated in other cities and the research should be continued.
- If not synergies but capital sizes are compared, then a normalization procedure is necessary.

Author Contributions: K.Z.: the concept of the research, creation of complex GIS database, simulative and Neural Network modeling; writing—introduction, methods, results, discussion, conclusions. J.K.: collection of data on ecological capital and adding it to the GIS database; writing—introduction, references; final text editing. A.M.: collection of data on economic capital and adding it to GIS database; writing—introduction, references; editing and formatting of the text; final text editing. L.J.-J.: collection of data on spatial and social capitals and adding it to GIS database; final text editing. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the Research Council of Lithuania (LMTLT), agreement No S-LLT-20-3 and has been performed in a cooperation with State Education Development Agency of the Republic of Latvia, the Taipei Mission in the Republic of Latvia and Lithuania.

Institutional Review Board Statement: Ethical review and approval were waived not applicable.

Informed Consent Statement: Requirement for subjects consent was not applicable as no personal data was collected.

Data Availability Statement: Data used for modelling is available at https://www.openstreetmap.org/, accessed on 13 December 2022. Data on planned infill development at Kaunas is available at https://citify.eu/en/kaunas/, accessed on 13 December 2022. Data on the present mean land prices available on request due to restrictions of privacy and was obtained from State Enterprise Centre of Registers (https://www.registrucentras.lt/en/, accessed on 13 December 2022).

Acknowledgments: This research is conducted within the framework of Taiwan-Latvia-Lithuania Cooperation Project "Up-to-date Information systems in Urban Regeneration" and is supported by Ministry of Education, Science and Sport of the Republic of Lithuania, and the Taipei Mission in the Republic of Latvia and Lithuania.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. The Results of the Space Syntax Calculations for Kaunas

Figure A1. Kaunas, Choice within radius 1000 m. Red indicates high and blue low numerical values.

Figure A2. Kaunas, Choice within radius 3000 m. Red indicates high and blue low numerical values.

Figure A3. Kaunas, Choice within radius 5000 m. Red indicates high and blue low numerical values.

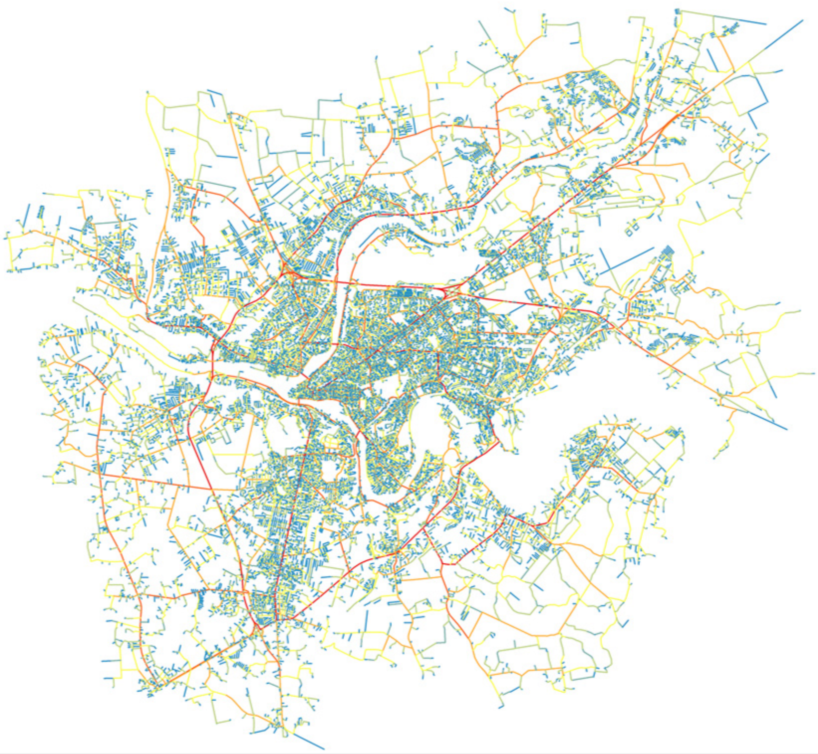

Figure A4. Kaunas, Choice within radius n. Red indicates high and blue low numerical values.

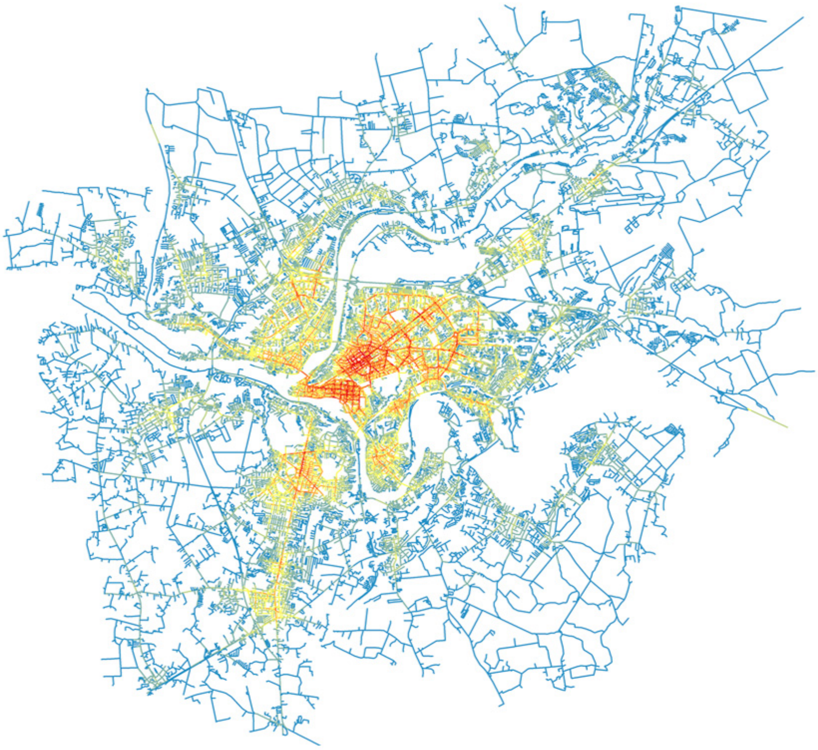

Figure A5. Kaunas, Integration within radius 1000 m. Red indicates high and blue low numerical values.

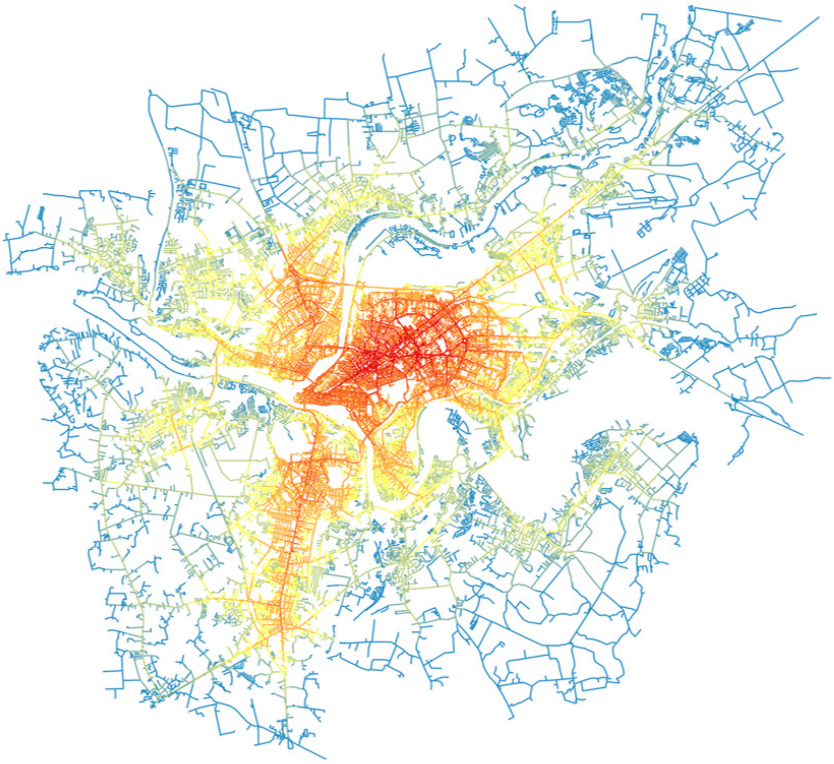

Figure A6. Kaunas, Integration within radius 3000 m. Red indicates high and blue low numerical values.

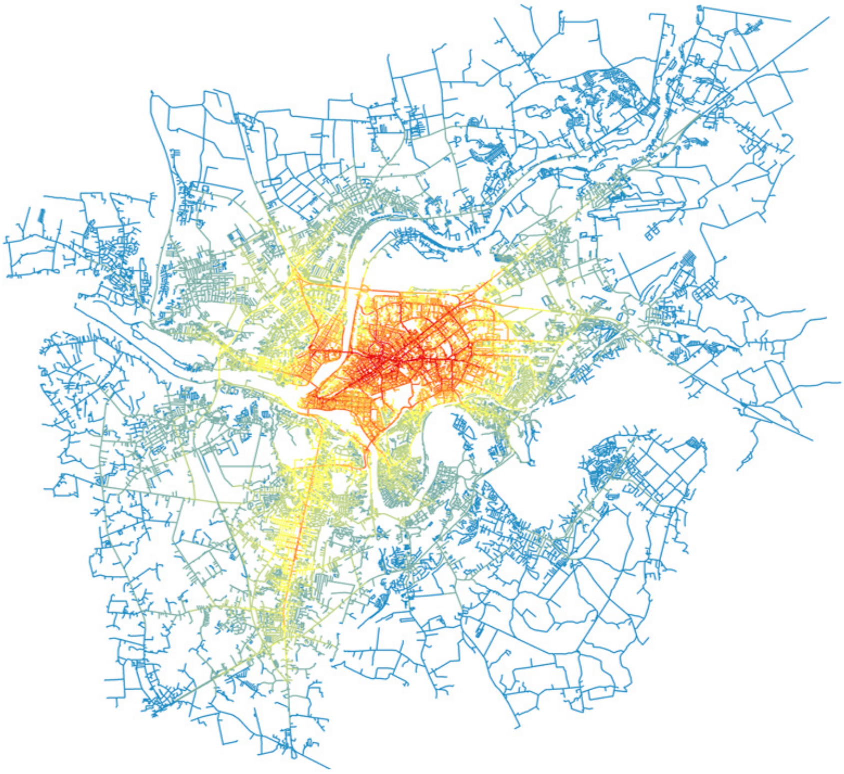

Figure A7. Kaunas, Integration within radius 5000 m. Red indicates high and blue low numerical values.

Figure A8. Kaunas, Integration within radius n. Red indicates high and blue low numerical values.

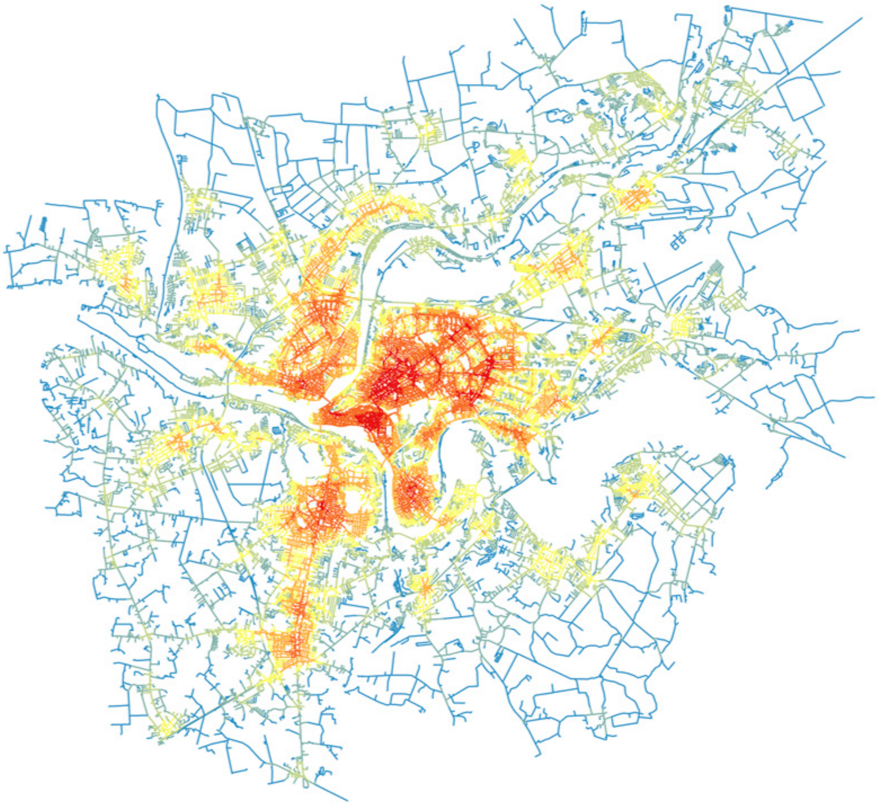

Figure A9. Kaunas, Metric reach within radius 3000 m. Red indicates high and blue low numerical values.

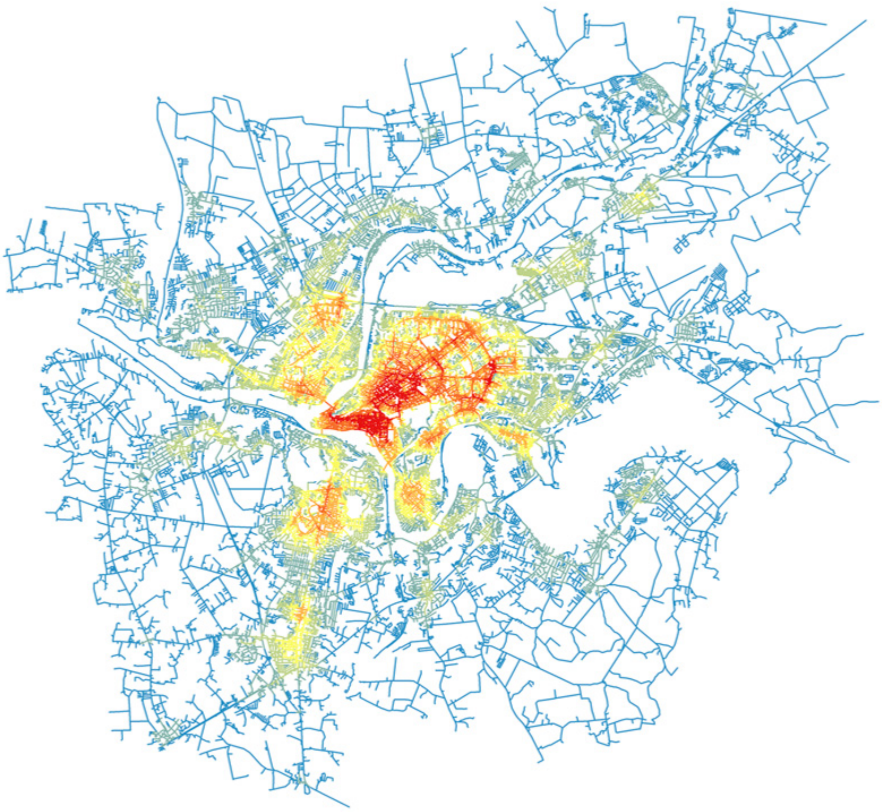

Figure A10. Kaunas, Node count within radius 1000 m. Red indicates high and blue low numerical values.

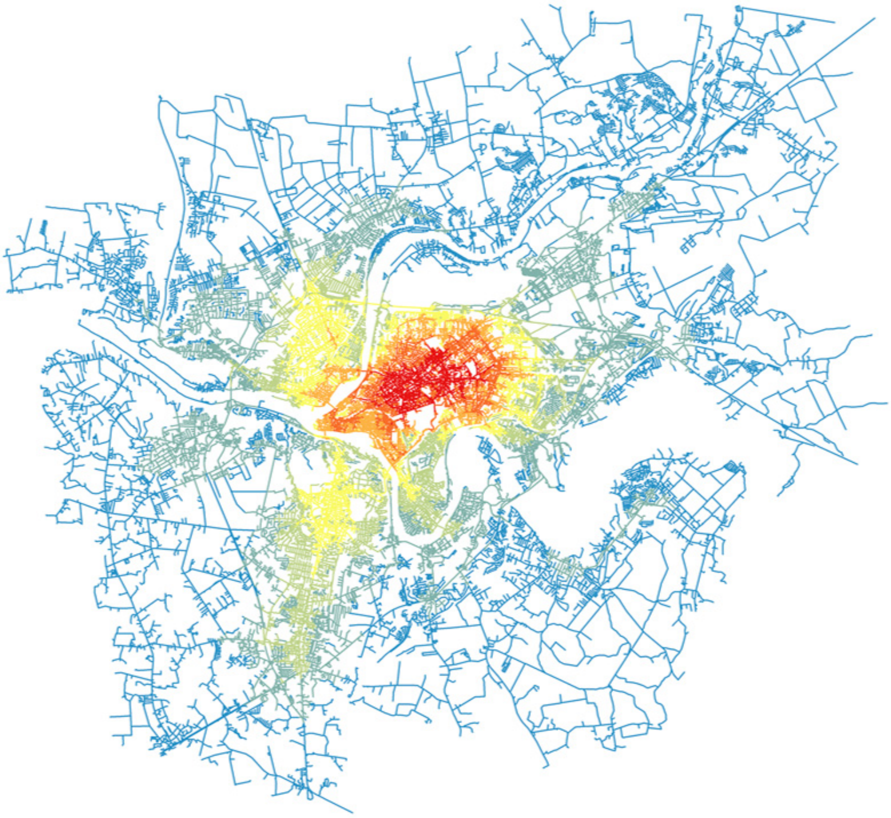

Figure A11. Kaunas, Node count within radius 3000 m. Red indicates high and blue low numerical values.

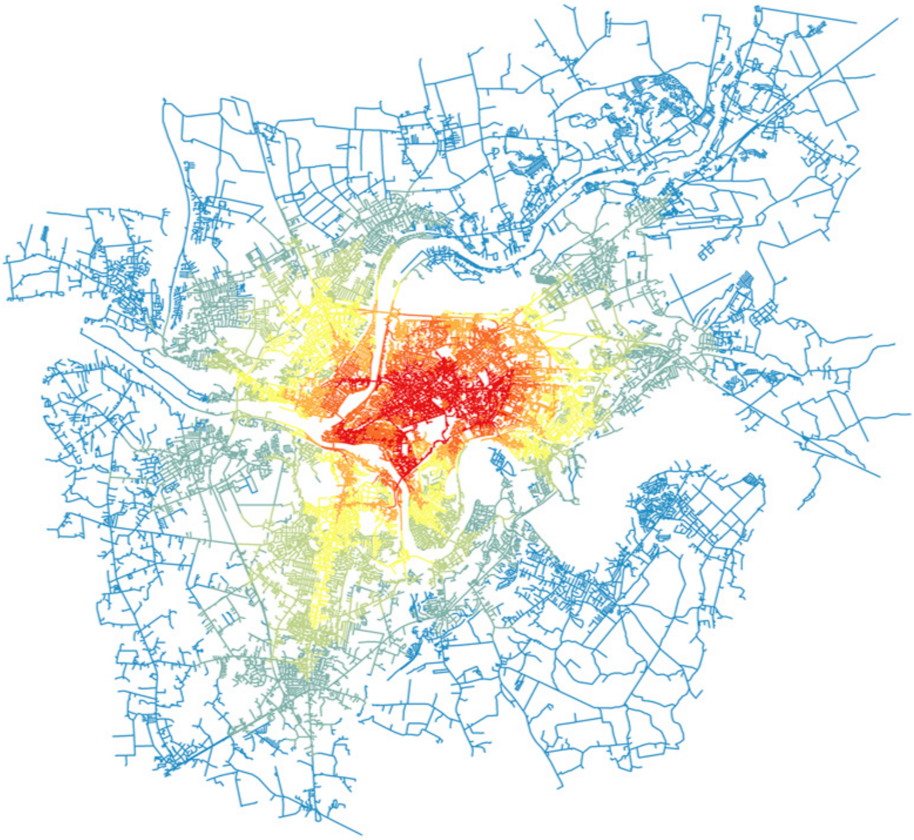

Figure A12. Kaunas, Node count within radius 5000 m. Red indicates high and blue low numerical values.

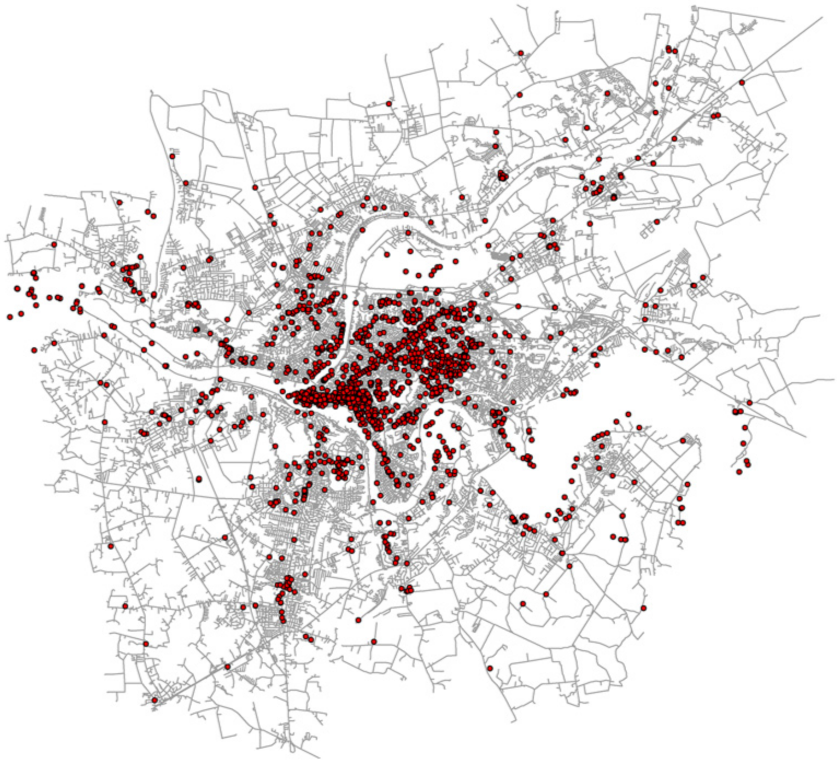

Figure A13. Kaunas, allocation of the points of interest (POIS) (marked by red dots) which were used for validation of the syntactic model.

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