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Article

Energy-Saving Potential in Planning Urban Functional Areas: The Case of Bialystok (Poland)

Kęstutis Zaleckis [1] and Bartosz Czarnecki [2,*]

[1] Faculty of Civil Engineering and Architecture, Kaunas University of Technology, LT-51367 Kaunas, Lithuania
[2] Faculty of Architecture, Bialystok University of Technology, 15-893 Bialystok, Poland
* Correspondence: b.czarnecki@pb.edu.pl

Abstract: Mobility is one of the basic needs for modern people. The transport system is one of the largest consumers of energy. The largest dimension of mobility activity is concentrated in metropolitan areas, which also shows energy consumption by transport. The research looked at the potential for improving the energy efficiency of a functional and spatial structure, using the example of a medium-sized city and its functional area. The study refers to the idea of the pervasiveness of spatial structure and to the criteria of New Urbanism, as a multifunctional and sustainable urban form. The gravity fields concept was also used. This article presents simulation modeling that has made it possible to model the potential for optimizing an urbanized area towards a reduction in energy consumption in the mobility sphere and to compare the scale of the potential in this respect of its segments in relation to the movement relationships of the destinations (residence, services, workplaces, and leisure). Results show the greatest energy-saving potential located in the peripheral areas with longer distances from centers and the worst equipment of services and infrastructure. The analytic model presented in the article, based on the concept of pervasiveness, could be used for the evaluation of the multifunctionality and sustainability of urban structures.

Keywords: energy efficiency; spatial planning; functional structure; mobility; functional area; modeling

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1. Introduction

Energy efficiency is a key factor for most of the countries in the world, especially nowadays, during the post-pandemic crisis and war-time. The desire to achieve energy efficiency through space planning has been expressed since ancient times. Settlements have been located on elevated sites to limit contact with cold and humid air. A southern exposure was preferred in regions of low and medium temperatures, or a very dense urban fabric was created to provide shade and reduce the impact of daily temperature fluctuations in the Middle East. Nowadays, when efficiency in the use of energy to maintain thermal comfort is achieved primarily through the adequate insulation of buildings and efficient heating and ventilation systems and widespread mobility is recognized as an important component of the standard of living as well as a factor in the development of the economy [1], the influence of urban planning can be crucial in reducing the energy intensity of the transport system. Transport is responsible for ca. 25% of the global energy consumption; hence, it represents a significant potential for savings. This is all the more important given that in most countries, outside of major cities, the basis of mobility is the highly energy-inefficient mode of transport that is the individual car. Attempts are being made to address this by raising the cost of private car use in cities and by promoting public transport and developing alternative systems to provide mobility [2].

It remains within the sphere of spatial planning to adopt and develop an appropriate model for the functional–spatial structure in order to make it as efficient as possible. Optimization measures in this respect may address the following issues:

- Optimizing the technical structure of the links from the point of view of the routing of traffic routes, their permeability, degree of collision, and hierarchical structure;
- Optimization of the functional and spatial structure in terms of the location relationships of the individual functions and their distances.

The content of the article is the latter.

The most valuable content for the advanced methods of the structural analysis of urban forms during the last decades are Bill Hillier [3] introducing the space syntax methodology and Michael Batty [4] introducing the use of fractal-based models and the cellular automaton model for urban structural analysis.

1.1. Functional Area of the City

According to the openness theory of the urban system [5], cities are not isolated structures, but there are interactions with the functional environment through reception points. Although former cities had clear boundaries (walls, moats, or other fortifications), there were usually temporary, impermanent economic infrastructures outside, which were written off in the event of an armed invasion. Modern cities are structures with even more blurred boundaries. This is particularly true of medium-sized, large, and major cities. Firstly, they usually form close functional–spatial ties with surrounding cities (city–region theory [6]); secondly, there are processes of suburbanization, where a certain percentage of city dwellers and visitors, tying their future to the city, choose to live outside the city, in its surroundings, looking for cheaper land and the possibility of obtaining a plot of land to build a detached house. In this way, a suburban zone is being created. The increased mobility of the population has been fostered by technological advancements: whereas in the early days, the possibility to settle in the urban orbit was limited by walking distance, and later by the location of public transport stops. Today, the car is a common means of transport, which increases the possible range of mobility for daily needs up to several tens of kilometers. This has opened up the possibility of using areas that are often larger than the city itself for housing and business, but the price for this is time spent travelling and increased energy consumption many times over. On the one hand, this raises questions about how the transport system itself can be optimized in terms of permeability, capacity, and traffic flow. On the other hand, it raises the question of whether the functional and spatial structure of such an organism can be optimized so that the travel distances required to meet daily needs can be shortened, thus providing the opportunity to reduce average commuting times and thus energy consumption. The question also arises as to whether, when considering the problem on the scale of the entire functional area, this can be made easier by being able to use the infrastructure and services of the surrounding municipalities.

The territorial scope of the study covered the city of Bialystok and its functional area, which includes nine surrounding municipalities. The development of this area is co-ordinated by the Bialystok Functional Area Association, which brings together all of the 10 municipalities (https://bof.org.pl, accessed on 7 December 2022). The functional area covers 1728 km^2. In 2020, the area was inhabited by 422,000 people, with an increase rate of 2.1% compared to 2014 [7].

1.2. Study Objectives

1.2.1. Objective 1

The first objective of the research was to construct a simulative street network model. Based on the content of the Open Street Map, a street network model was created for the entire area and simulation modeling was carried out, using a mathematical graph model approach as the space syntax [3] and spatial design network analysis tool for ArcGIS [8]. The second part of the objective was to identify sources and targets of displacement based on Open Street Map data.

1.2.2. Objective 2

The second objective of the study was to model the operation of the complex urban system while using the simulative, space-syntax-based model which allows a better understanding of system functioning and its analysis.

1.2.3. Objective 3

The last objective was to identify correlations between the four simulated types of journeys within local neighborhoods (radius 1 km) and the metropolitan area (5 km) and to estimate the potential for energy saving in a precise perspective and multifunctionality of the urban areas in more generic view.

The essence of the modeling is to simulate the movement of people using the shortest routes from each street segment to every other segment in order to identify the most achievable transit zones and streams based on a mathematical graph approach where every street segment is treated as a node of the graph. In the initial model, each street segment was treated as both the origin and destination of all trips and other data such as population density or the distribution of actual destinations (e.g., shops) were not assessed. The results of these simulations were used for the validation of the model based on the statistical analysis of correlations between the results of mathematical simulations and concentration of points of interests from the Open Street Map. The idea of validations was based on the concept of movement economy by Hillier. 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." [3] According to it, a concentration of points of interest could be seen as proof of the working simulative model. In the second part of the objective, the model was made more precise by adding information on exact locations for four types of trips to work, educations objects, shops, and recreational objects. Correlations between the four simulated types of journeys within local neighborhoods (radius 1 km) and the metropolitan area (5 km) were analyzed in order to understand synergies between different types of destinations, which, in turn, might mean more synergies between various forms of energy consumption.

1.3. Main Findings

Synergies between simulated gravity fields generated by various types of journeys within urban structures could be presented in graphical scatterplots which allow us to compare different neighborhoods in terms of degree of multifunctionality and pervasiveness as two aspects of the sustainability of urban form and potential optimality of energy consumption. Higher sustainability of urban form is represented by a more convex form of the scatterplot.

At the scatterplot of Bialystok, we can see that zones of attraction of trips of no weight (0.494 to 0.867 and 1.0) and perimeter (0.481 to 0.867 and 1), and also work (0.385 to 0.806 and 1), are quite regular and similar. Zones of population, but especially shopping (0.232 to 1), leisure (0.232 to 1), and education (0.344 to 1), show spiky parts, which means an irregular dispersion of journey and areas of concentration, and more expressed features of mono-functional zoning.

Much more irregular they are also almost in all peripheral communities with the exception of Lapy: the community with the biggest capital town and directly connected to Bialystok by train on the Warsaw–Bialystok line. Other ones show differences in parallel functional spheres like Bialystok, but with the addition of work (except Choroszcz, Czarna Białostocka, and Supraśl).

The functional spheres showing irregularities in distribution are: education, shopping, and leisure. In all probability, this means both inadequacy of the location of some of the destinations from these spheres in relation to the distribution of the population, but also variation in the preferences of the customers of the functions from this sphere and their exercise of freedom of choice. However, apart from education, these are functions that are not used intensively on a daily basis. However, for about half of the surrounding municipalities, one can also see the uneven distribution of travel to work, which is a daily and obligatory activity. Thus, it is in the location of workplaces in relation to residences that the greatest potential for energy savings lies by optimizing the functional and spatial structure. However, this is not easy, because in many cases, on the scale of a rather small structure, where a number of higher-ranking institutions occur one at a time, it can be difficult for many people to optimize their choice of workplace from the point of view of shortening their commute and saving time and cost. The location of the place of residence, on the other hand, can often be optimized because of the location of the spouse/partner's workplace, so there is little potential for this.

2. Materials and Methods

In accordance with the objectives of the study, the Bialystok Functional Area located in north-eastern Poland was selected. It consists of the City of Bialystok, a capital city of 300,000 inhabitants with all the functions and institutions typical of such cities. In addition, the area includes 9 urban and rural municipalities, which are included within the boundaries of a formally separate functional area. For this area, data is available and strategic documents are produced. This area also forms a zone within which there are strong and close functional, social and economic relations. It is an area of strategic planning and co-operation between municipalities in terms of public transport services, the creation of social infrastructure, the creation of support for residents' initiatives, and the creation of energy partnerships.

The Open Street Map data and Space Syntax and Spatial Design Network analysis software for ArcGIS analysis software were used to conduct the study.

A street network model was created for the entire area and simulation modeling was performed, while using a mathematical graph model approach as the space syntax. All possible origins and destinations for the simulative model were identified (Figure 1). Next step: trips within two radiuses (1 km and 5 km) between origins and destinations were modeled based on the shortest route principle. The modeling allowed us to see the highest potential concentration of people travelling with four different purposes and compare the concentrations between them. The concentration of people while performing different journeys could be seen as an indicator of multifunctionality in either neighborhood or the whole investigated area level. Multifunctionality on its own is named as one of the important aspects of New Urbanism [9] or a sustainable urban form [10] of higher energy consumption; then, either positive or negative synergy between the concentrations could show entropy of energy consumption during the day as well, at least indirectly.

The essence of modeling—simulating the movement of people by taking the shortest routes from each street segment to every other segment to determine the most achievable zones and transit flows—was used. In the initial model, every street segment was seen as both origin and destination of all trips and there is no other data, as density of inhabitants or allocation of real destinations of trips (e.g., shops) was not evaluated.

The model was used for validation of simulative approach—if model is working, it was tested while calculating correlations (Spearman's rho) between results of simulative calculation and density of points of the interest from Open Street Map (OSM) and density of populations within 1×1 km grid (Table 1). As described earlier, based on the concept of the movement economy [3], correlations between spatial configurations of the road network, described by the results of simulative modeling and both density of POIs and inhabitants, could be seen as proof of working model.

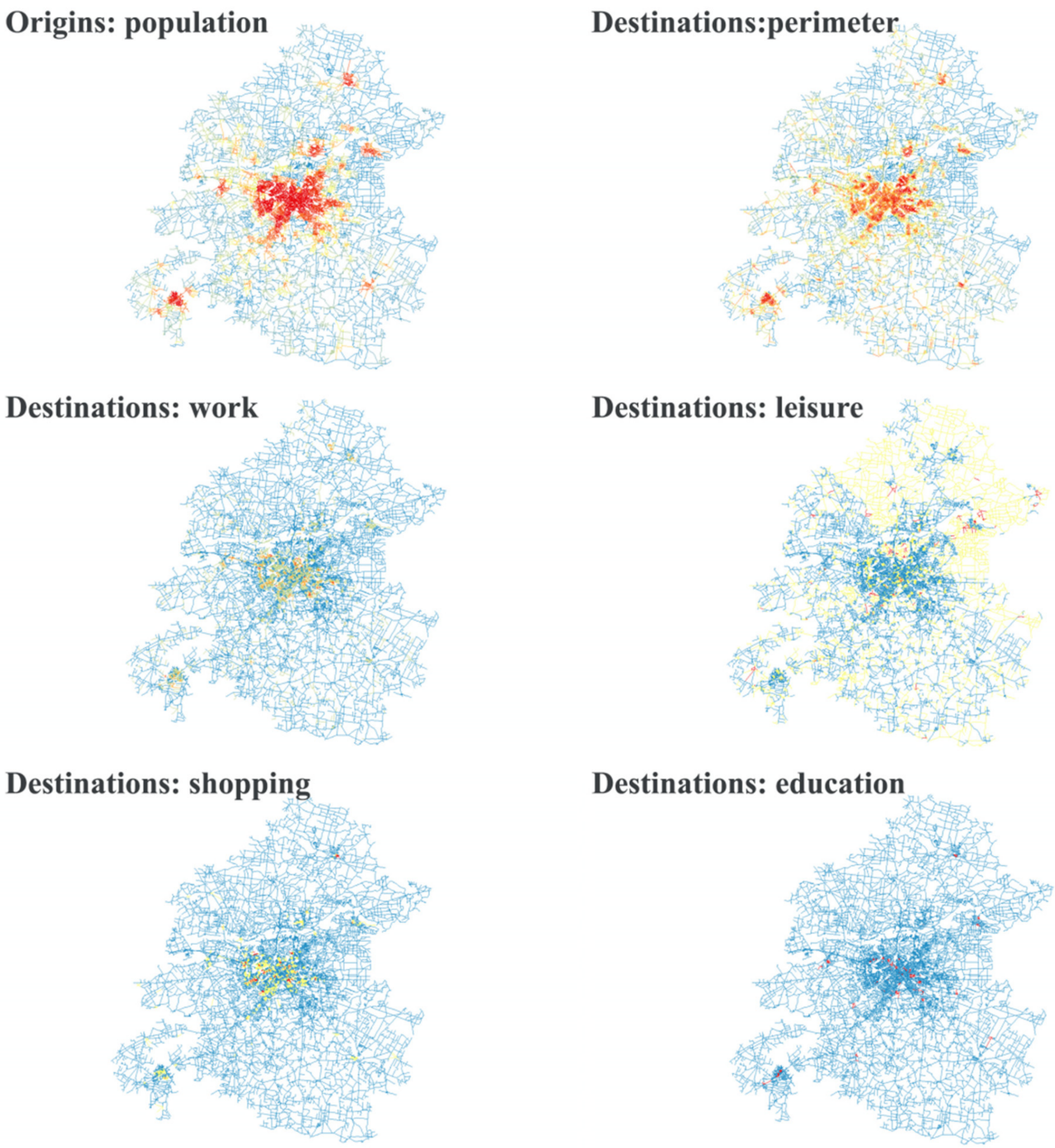

Figure 1. Location of origins and destinations of trips within Bialystok Functional Area. Red color shows the biggest while blue showed the lowest numerical values.

Next step was identification of more precise origins and destinations of simulated journeys. As origins were considered places where people live, data of inhabitants' density were used.

Table 1. Level of functional correlations of Bialystok Functional Area. Green color marks moderate correlations, orange marks strong correlation. All correlations have 0.01 significance—it means chance that they are accidental is just 1 percent.

	Transit (Choice) 1000	**Transit (Choice) 15,000**	**Transit (Choice) 5000**	**Closeness (Integration) 1000**	**Closeness (Integration) 15,000**	**Closeness (Integration) 5000**	**Density of Street Segments (Node Count) 1000**	**Density of Street Segments (Node Count) 15,000**	**Density of Street Segments (Node Count) 5000**
Density of POIs	0.382	0.033	0.208	0.788	0.623	0.764	0.838	0.689	0.773
Density of populations	0.389	0.046	0.213	0.796	0.676	0.791	0.856	0.729	0.799

For destinations, the following data from OSM were used:

For work journeys (names taken from the OSM attribute list): 'archaeological', 'arts_centre', 'bakery', 'bank', 'bar', 'beauty_shop', 'beverages', 'bicycle_rental', 'bicycle_shop', 'biergarten', 'bookshop', 'butcher', 'cafe', 'car_dealership', 'car_rental', 'car_wash', 'castle', 'chemist', 'cinema', 'clinic', 'clothes', 'college', 'community_centre', 'computer_shop', 'convenience', 'dentist', 'department_store', 'doctors', 'doityourself', 'embassy', 'fast_food', 'fire_station', 'florist', 'food_court', 'furniture_shop', 'garden_centre', 'general', 'gift_shop', 'greengrocer', 'guesthouse', 'hairdresser', 'hospital', 'hostel', 'hotel', 'jeweller', 'kindergarten', 'kiosk', 'laundry', 'library', 'mall', 'market_place', 'mobile_phone_shop', 'museum', 'nightclub', 'optician', 'outdoor_shop', 'pharmacy', 'police', 'post_office', 'pub', 'restaurant', 'school', 'shoe_shop', 'sports_centre', 'sports_shop', 'stationery', 'supermarket', 'swimming_pool', 'theatre', 'toilet', 'tourist_info', 'town_hall', 'toy_shop', 'travel_agent', 'university', 'veterinary', 'video_shop'.

For leisure journeys: 'alpine_hut', 'archaeological', 'arts_centre', 'artwork', 'attraction', 'bar', 'bench', 'bicycle_rental', 'biergarten', 'cafe', 'camp_site', 'car_rental', 'caravan_site', 'castle', 'cinema', 'community_centre', 'drinking_water', 'fast_food', 'food_court', 'fountain', 'guesthouse', 'hostel', 'hotel', 'monument', 'museum', 'nightclub', 'observation_tower', 'park', 'picnic_site', 'pitch', 'playground', 'pub', 'restaurant', 'ruins', 'sports_centre', 'stadium', 'swimming_pool', 'theatre', 'tourist_info', 'viewpoint', 'wayside_shrine'.

For shopping journeys: 'atm', 'bakery', 'beauty_shop', 'beverages', 'bicycle_shop', 'bookshop', 'butcher', 'chemist', 'clothes', 'computer_shop', 'convenience', 'department_store', 'doityourself', 'florist', 'furniture_shop', 'garden_centre', 'general', 'gift_shop', 'greengrocer', 'jeweller', 'kiosk', 'mall', 'market_place', 'mobile_phone_shop', 'optician', 'outdoor_shop', 'pharmacy', 'shoe_shop', 'sports_shop', 'stationery', 'supermarket', 'toy_shop', 'video_shop'.

For education journeys: 'college', 'kindergarten', 'library', 'mall', 'museum', 'school', 'swimming_pool', 'university'.

The movement from origins to destinations was simulated within 1000 m and 5000 m in order to see where majority of people are attracted during the day within own neighborhood or at the whole investigated area scale. The results for various types of trips were compared between themselves as well as to location of living places. Synergy was measured as correlations between calculation results within radius 1000 (higher correlations: more multifunctional neighborhood) and between radius 1000 and 5000 (higher correlations: more synergy between local and global) or whole area structure or pervasiveness which shows sustainability of urban form according to Hillier [11].

Correlations were obtained in an Excel spreadsheet. As the main and only indicator, we used so-called gravity or network quantity penalized by distance (*Integration* in Space Syntax).

The formula was following [12]:

$$\mathbf{NQPD}(x) = \sum_{y \in Rx} W(y)/d(x,y) \quad (1)$$

where:

$\mathbf{NQPD}(x)$—indicator calculated for the node x (segment street) of the graph-network of the streets;

x—origin of every simulated journey and only segments where people live nearby were used for calculation;

$\sum_{y \in Rx}$—sum of the values of all destinations y which could be reached from x within radius R

$W(y)$—weight of destination (if there is an object to travel to, weight is 1; if not, 0)

$d(x,y)$—distance between x and every y in meters (for 1000 radius) and in angles of road network (for 5000 radius)

Finally, the pervasiveness evaluation was performed. The idea was that urban structure by itself and allocation of people and working/leisure/shopping/education places create a kind of "gravity fields" which attract people during the day. Fluctuations of differences between those "gravity fields" demonstrate either multifunctionality (smaller fluctuations) or mono-functionality (bigger fluctuations) of the investigated urban structure. Smaller fluctuations, as it was argued earlier, demonstrate higher correspondence to the New Urbanism neighborhood idea at the local level or radius 1000 m. Smaller fluctuations between the simulations results with radius 1000 m and 5000 m demonstrated higher pervasiveness of urban structure. Both models—New Urbanism and pervasiveness—demonstrate sustainability of urban form and, at least indirectly, could demonstrate entropy of energy consumptions. Synergy between these gravity fields was counted as Spearman's correlations between space syntax values, while allocation of destinations (work, leisure, shopping, education) as weight for destination. Weak correlations of low synergy mean entropy of both functions and energy consumption in the area.

3. Results

The simulated journeys on the base space syntax model within selected radiuses in the investigated area allowed us to identify the probable zones of the highest concentration of people or so-called human load while travelling to shops, educational facilities, for leisure purposes, and work. The overlap of these zones was evaluated by means of the statistical analysis—the identified Spearman's correlation coefficients could be seen not only as a mathematical indicator of the degree of overlap between the allocation of the four types of the objects (work, leisure, education, and commerce) but as a synergy between a kind of field of gravity generated by various objects within the urban network. In terms of energy consumption and load on the urban infrastructure, the higher synergies and bigger correlations mean the lower fluctuation of human load and therefore, more stable and predictable patterns of energy consumption. The usage of correlation between various zones of gravity works as a kind of normalization, thus allowing us to perform a comparison between different neighborhoods in the investigated area or even smaller pieces of territory if needed. It is important to point out that, because of the simulative nature, the space syntax modeling could be conducted not only for the present, but for the past and future situations as well. In the first case, the modeling results can help us to see and understand the evolution of the area and, if applicable, learn from the past. In the second case, the presented model could serve as a part of the decision support system or even background for parametric modeling for future solutions.

Despite the fact that the presented research was focused primarily on the analysis and comparison of fluctuations of human load on urban energy infrastructure, it should be pointed out the identified synergy between different gravity fields generated by four types of travel destinations within three different radiuses in the urban network demonstrated a degree of multifunctionality of the areas. As such, it could be related to the concept of pervasiveness as an indicator of the sustainability of the urban structure, offered by Hillier. According to him, "pervasive centrality refers to the function of centrality in cities that pervades the urban grid in a more intricate way than has been thought, and that multi-scale centrality should be seen as a pervasive function in cities, with clear spatial correlates, and not simply as a hierarchy of locations." [11]. In this case, the results of the presented investigation could be used for the analysis and comparison of urban sustainability in a similar way or besides such tools as urban sustainability compass [13].

The validation of the modeling results demonstrated that a generic space syntax model both at the level of the neighborhood (radius 1000) and the whole area (radiuses 5000 and 15000) work very well. Results of the statistical analysis of correlations between the density of POIs, inhabitants, and four space syntax indicators are presented in Table 1. The weakest correlations are between the simulated transit flows (Choice in Space Syntax) and POIs density with inhabitant density. Even if moderate correlations were observed at the local level (radius 1000) and it could be considered as not very strong, but sufficient for validation of the model, the absence of better results with global transit (radius 5000 m) could be explained by a very well developed road network in the area, thus creating a lot of alternative routes for journeys inside the region. Strong correlations were observed with so-called closeness centrality represented by Integration in the space syntax or Gravity in the presented investigation and density of street segment nodes in the network. In both cases, correlations demonstrated high values with a slightly higher result for street segment node density (node count). Based on these results, the simulative model was considered as valid and the integration of gravity chosen for the modeling and node count do not represent a simulation of the movement of people.

Calculated zones of attraction (Table 2, Figures 2–4) when people move to work, recreation, shopping, and education, and the most intensive zones of spatial urban structure within 1000 m could be related to the optimality of 15 min city or New Urbanism neighborhood concepts. A scatterplot of the zones of attraction according to the functional spheres for Bialystok city is presented in Figure 2. It shows synergies or correlations (Table 2) between gravity fields generated by four types of journeys (work, leisure, shopping, ajd education) within radius 1000 m and two additional calculations: gravity with no specific destinations considered as affected just by the configuration of the street network (no weight) and as destination-marked zones with a higher building and street contact perimeter. The last indicator is based on the World Bank report on walkability [14] and could reveal public space to be more attractive for street culture. The "no weight" calculation could be useful for urban planners focussing just on spatial form while evaluating its effects on sustainability. Gravity fields of each type of journey are represented by the accordingly named line in the scatterplot while its correlations are reflected by the position of the line of the seven axes. Because correlations between the same innovators are always one, each line reaches the maximal position at least on one axe which marks itself. A more "spiky" and "star shape" scatterplot means less synergy between the gravity fields generated by different journeys. Based on the comparison of the correlations vs. scatterplots, the following neighborhoods could be named as the least multifunctional: Dobrzyniewo Duże, Choroszcz, Juchnowiec_Kościelny, Turośń_Kościelna, and Wasilków. Zabłudów, Łapy, Czarna_Białostocka, Supraśl, and Bialystok city could be named as more multifunctional neighborhoods.

Table 2. Calculation of zones of attraction in accordance to the functional spheres. Example for Bialystok city.

	No Weight	Work	Leisure	Shopping	Education	Perimeter	Populations
no weight	1.000	0.806	0.5	0.723	0.494	0.867	0.559
work	0.806	1.000	0.385	0.791	0.443	0.641	0.422
leisure	0.5	0.385	1.000	0.232	0.409	0.481	0.392
shopping	0.723	0.791	0.232	1.000	0.344	0.633	0.543
educations	0.494	0.443	0.409	0.344	1.000	0.539	0.487
perimeter	0.867	0.641	0.481	0.633	0.539	1.000	0.647
populations	0.559	0.422	0.392	0.543	0.487	0.647	1.000

At the scatterplot of Bialystok, we can see that zones of attraction of journeys of no weight and perimeter and also work are quite regular and similar. Zones of population, but especially shopping, leisure, and education, show spiky parts which means an irregular dispersion of journey and areas of concentration.

Much more irregular is that they are also almost in all peripheral communities with the exception of Lapy: the community with the biggest capital town and directly connected to Bialystok by train on the Warsaw–Bialystok line. Others show differences in parallel functional spheres like Bialystok, but with the addition of work (except Choroszcz, Czarna Bialostocka, and Supraśl).

In Figure 5, colors represent numerical values of gravity or NQPD when people travel from where they live to work places. Red color means higher values, while blue means the lowest values. The red color shows patterns of concentration of NQPD high values and how they overlap with the other values could even be visually compared.

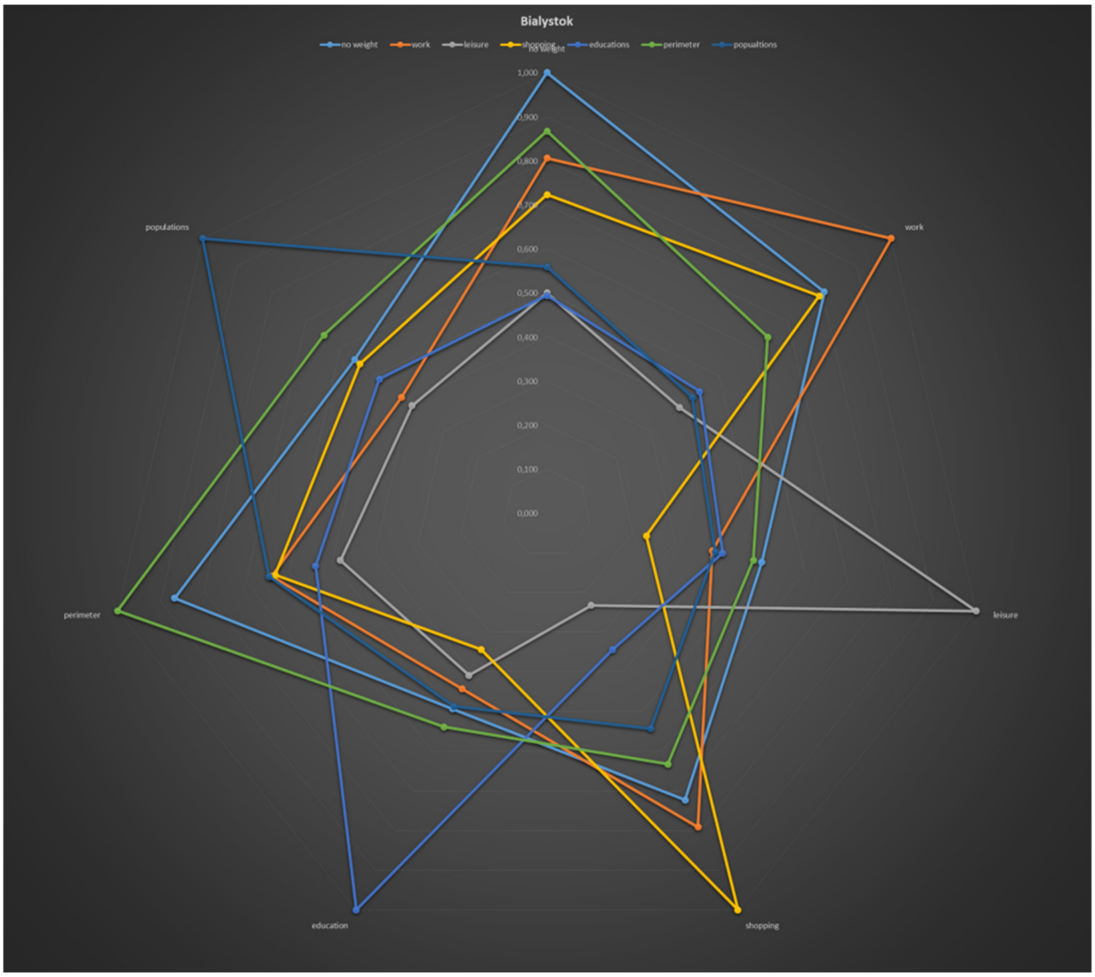

Figure 2. Zones of attraction according to functional spheres for Bialystok city.

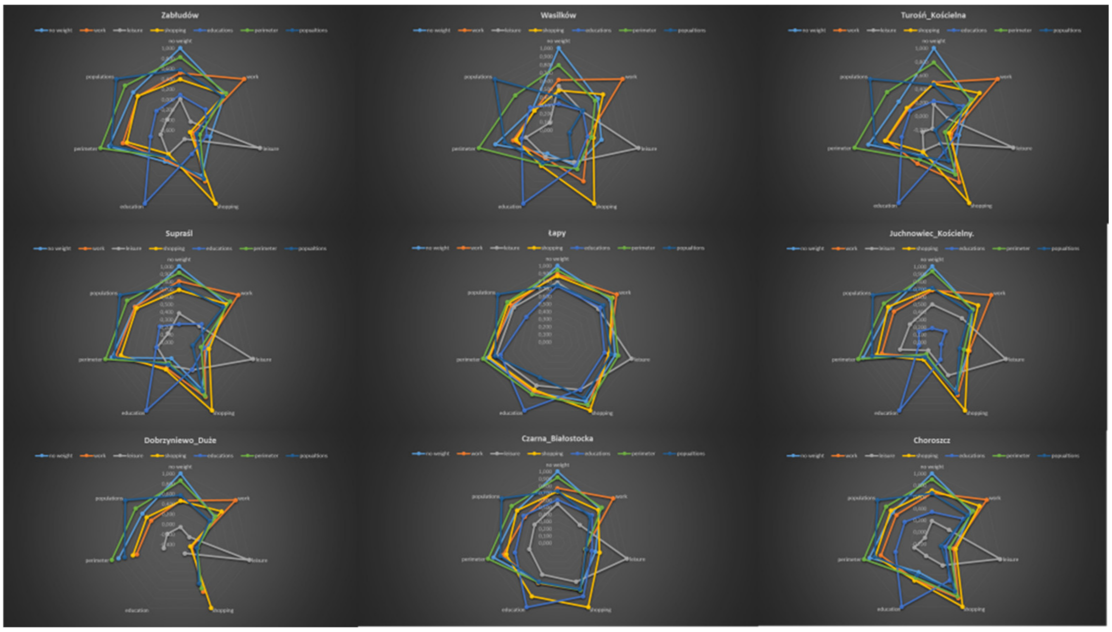

Figure 3. Zones of attraction according to functional spheres for 9 municipalities in outskirt of Bialystok, from top left: Zabludow, Wasilkow, Turosn Koscielna, Suprasl, Lapy, Juchnowiec Koscielny, Dobrzyniewo Duze, Czarna Bialostocka, Choroszcz.

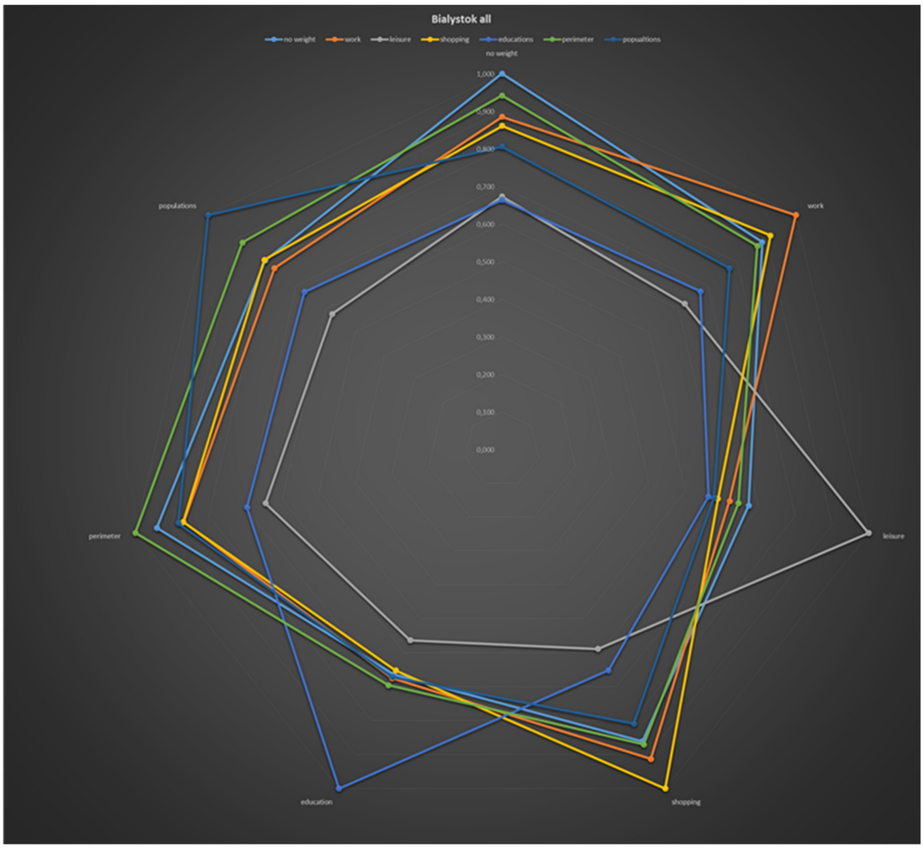

Figure 4. Zones of attraction according to functional spheres for Bialystok Functional Area (city Bialystok + 9 communities).

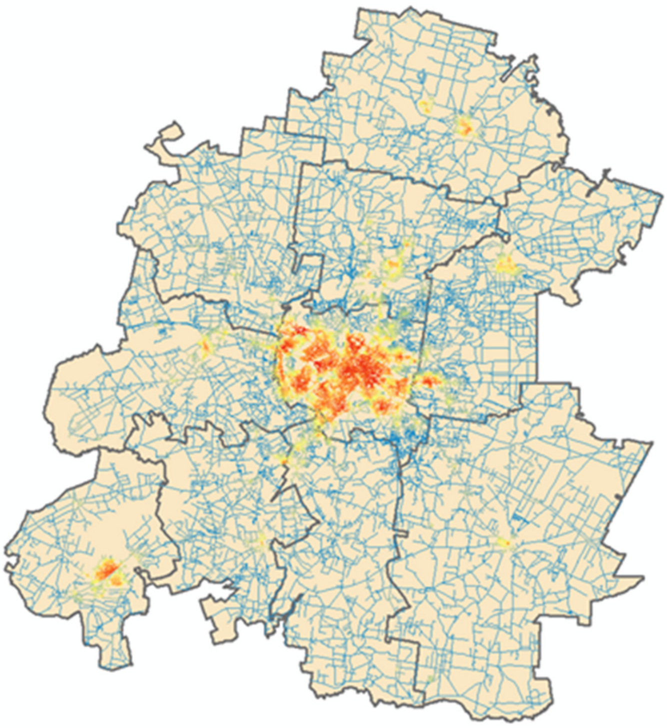

Figure 5. Trips to work r1000 m.

The meaning of the colors is the same as before in the Trips to education NQPD (Figure 6), and red-color-based patterns show quite noticeable differences if compared with the previous trips to work.

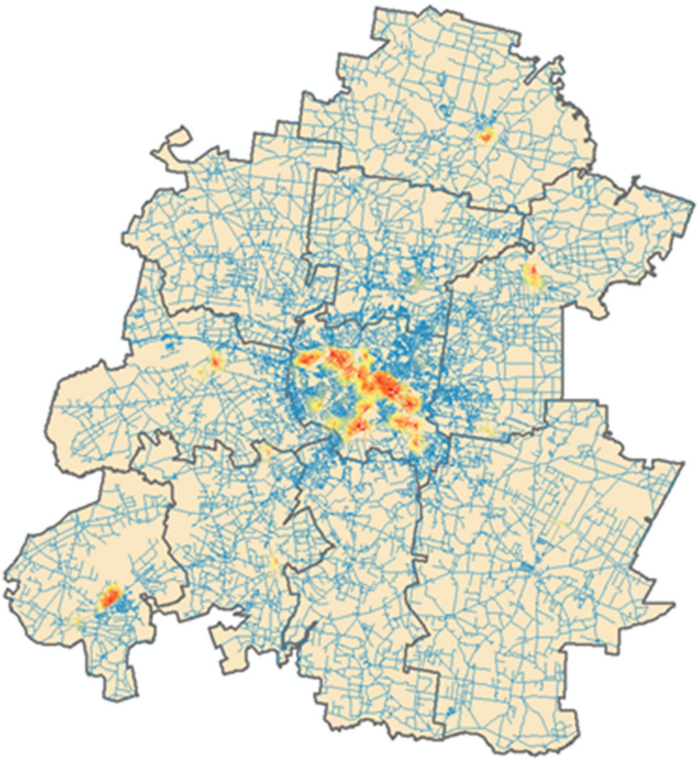

Figure 6. NQPD based on trips to schools and universities r1000.

For the Trips to work NQPD (Figure 7) (color again shows high/low values of NQPD), if compared visually to the first picture (work r1000), we can see that in some cases, red colors overlap very much (Bialystok itself); in some neighborhoods overlap is visible as well (bottom left corner, etc.).

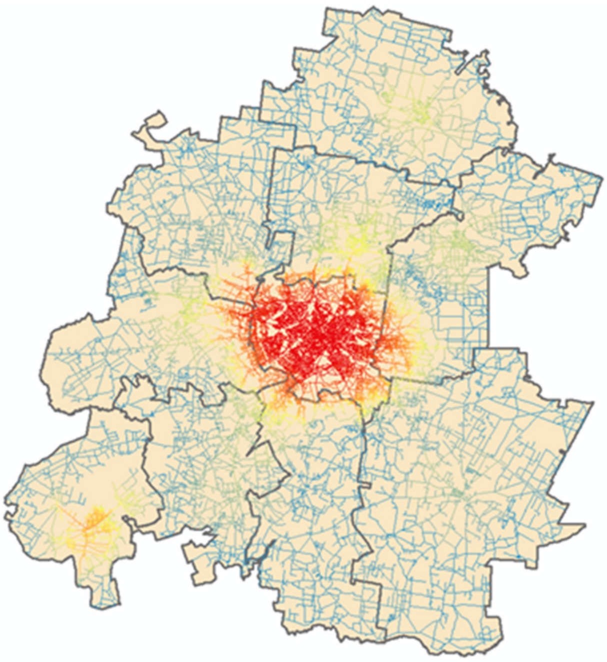

Figure 7. Trips to work within a whole metropolitan area while using cars or public transport.

They differ (Figure 8) quite significantly from work r5000 and reflect scattered locations of potentially recreational areas thus increasing the pervasiveness of some peripheral neighborhoods.

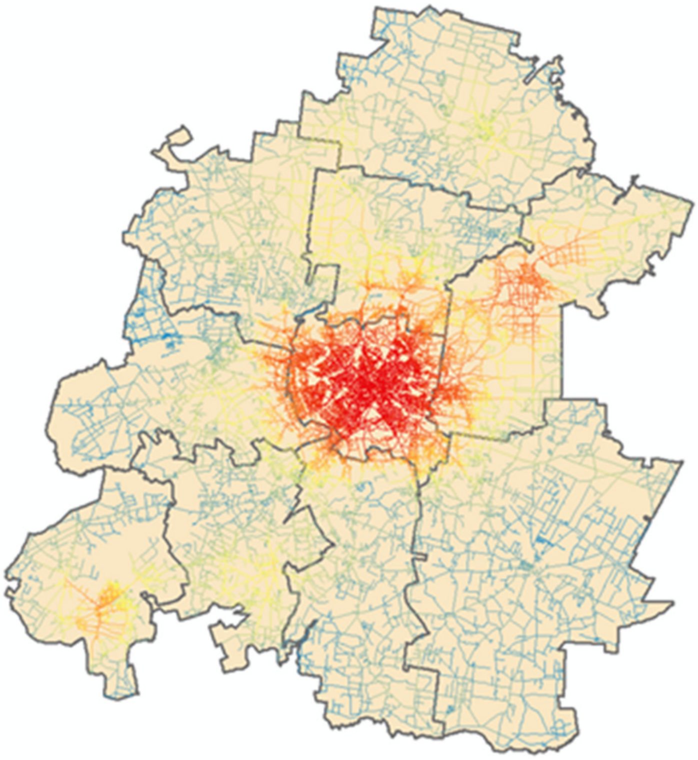

Figure 8. Leisure trips r5000.

Education r5000 (Figure 9) shows results that are not bad, as not all journeys are focused just on Bialystok, and it means that the network of educational objects is more evenly spread if compared to the allocation of working places.

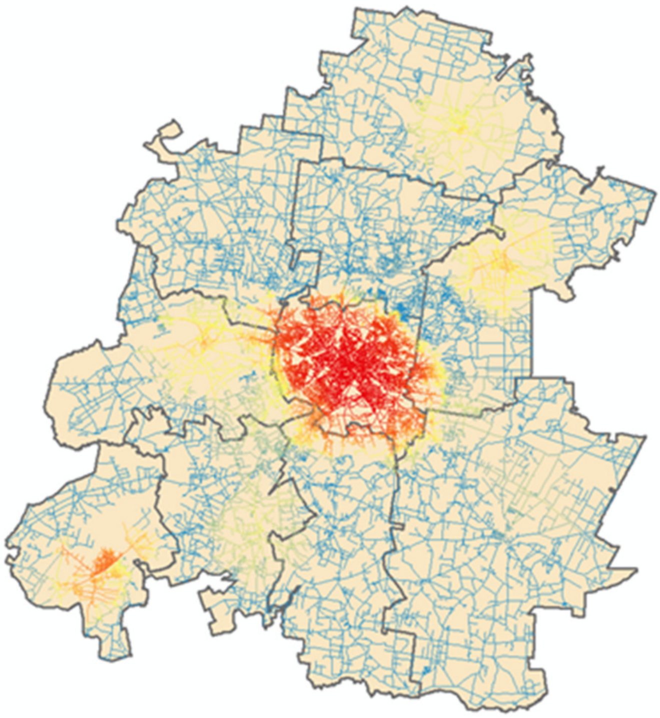

Figure 9. Education r5000.

According to some of Alexander's patterns, and the World Bank report/study on walkability [15], more contact between street and building creates a space that is more attractive from a street culture perspective, so it was interesting to see (Figure 10) how, at r1000 level, these zones overlap with other trips: more overlap means more trips end up in an environment that catalyzes street culture.

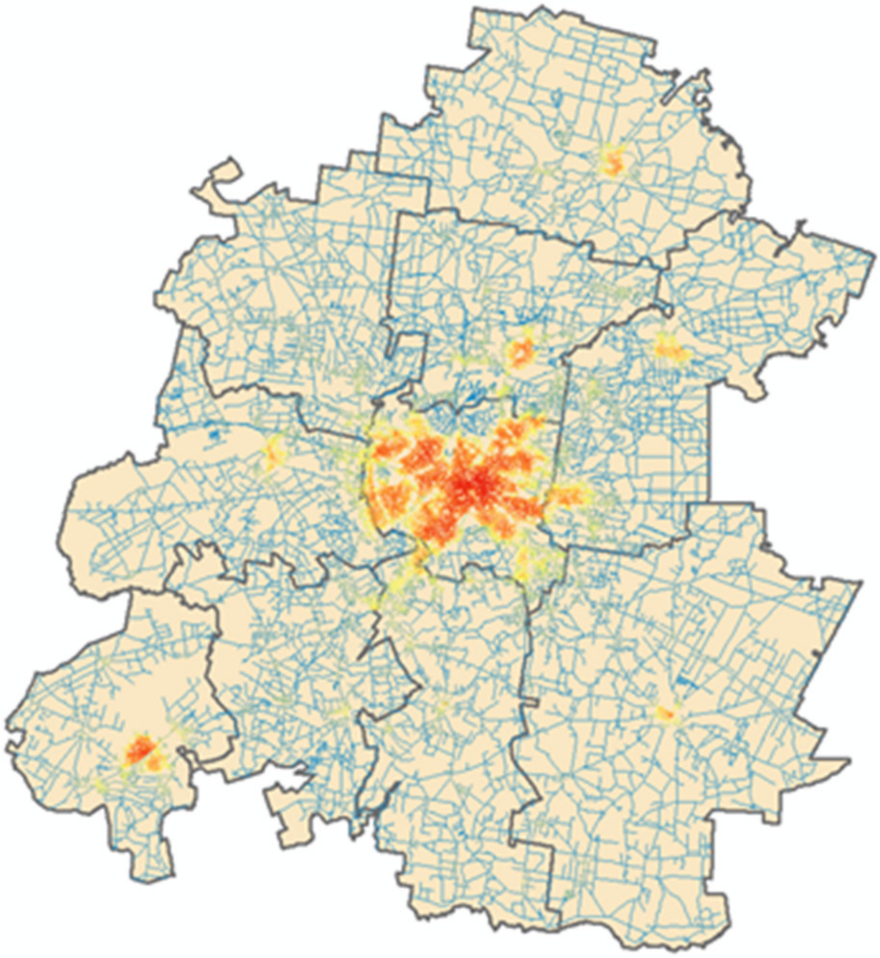

Figure 10. An additional calculation is for trips to street sections with more intense development around them, measured as accessible from the street at the perimeter of the buildings.

We can see (in Figure 11) that in five communities there are differences especially in accordance to spheres of leisure and education. Other ones and other communities and also all of the functional area generally show sustainability in connection dispersion.

Figure 11 represents the pervasiveness evaluation results. The correlations between gravity fields of different trips within radius 1000 m and radius 5000 m were calculated. A higher correlation means higher pervasiveness in Hillier's terms or higher multi-functionality at both the local and regional level as well as a higher mix of various types of short and long journeys. A more "spiky" scatterplot represents a less sustainable and less pervasive neighborhood within the region.

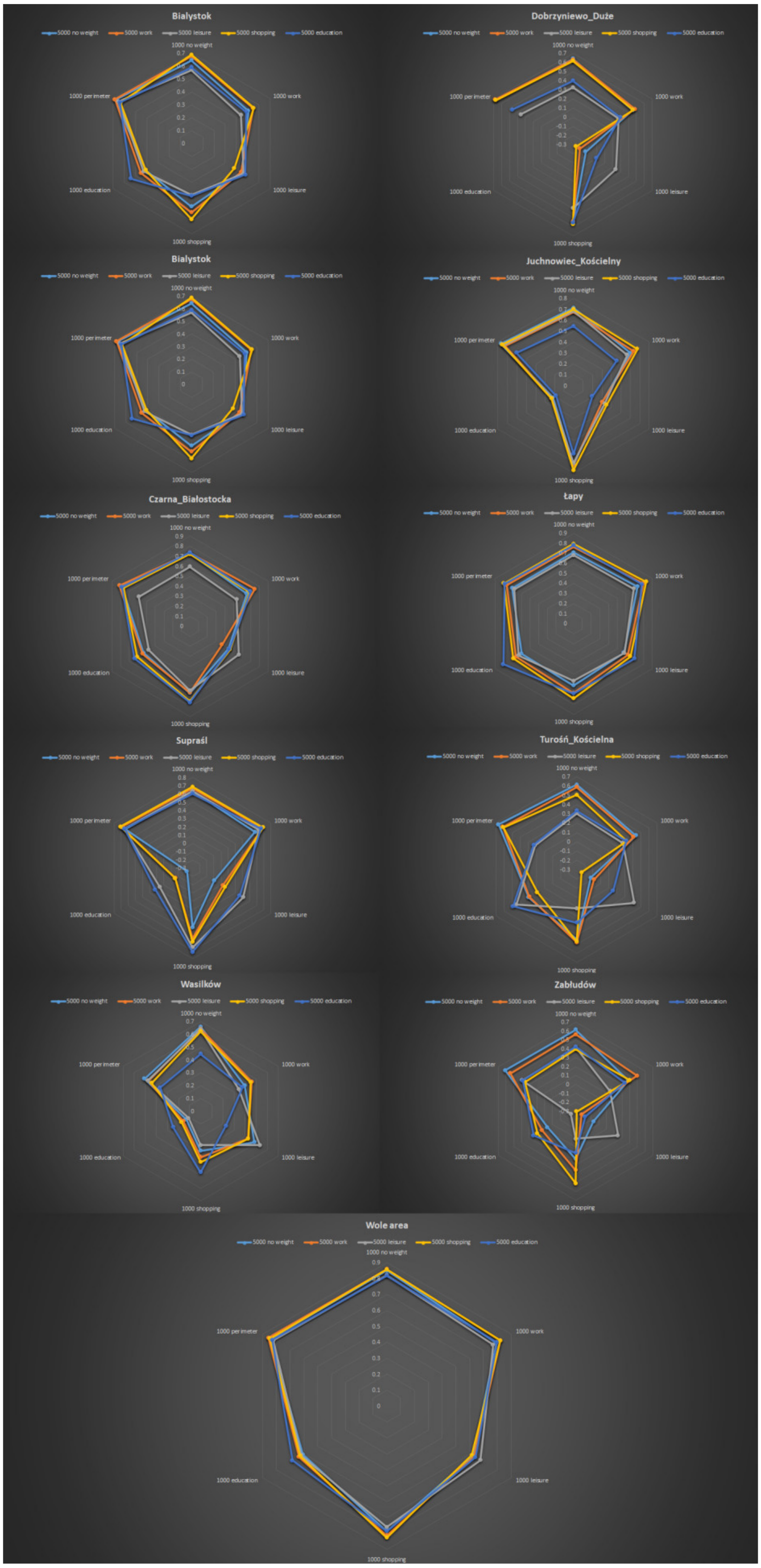

Figure 11. Pervasiveness evaluation results in radius 5000 m, in accordance to each of community and all of them together and in dependence with each of the functional relations on the scatterplots.

4. Discussion and Conclusions

Shaping the city with attention to the multifunctionality of the structure and the self-sustainability of the individual units refers to the classical idea of the city, ensuring that most of the needs can be met within a walking radius. This is in line with the idea of New Urbanism [16]. Following its assumptions should ensure less functional–spatial fluctuations and thus save the energy required for moving long distances. This also alludes to the idea of a sustainable economy. This type of solution referring to the classical urban structure was attempted by E. Plater-Zyberk and A. Duany in Seaside, Florida Kentlands, Maryland [17].

Of course, the example of the Bialystok Functional Area under study is not such an ideal or experimental case. It is an object of research that aimed to find an answer to the question as to what extent, or if at all, it is possible to effectively optimize the functional–spatial structure in terms of energy savings.

Here, it was useful to apply the concept of "gravity fields" to the functional–spatial structure. A model of the structure was created, in accordance to Objective 1, referring to the space syntax approach of B. Hillier. However, in contrast to Hillier's models, data stratified in terms of specific spheres of city life, relating to the basic daily needs of the inhabitants, were used. In the second step, the origins and targets of trips were identified.

According to Objective 2, the modeling of the operation of the structural system was performed.

The correlations between two types of trips in accordance to the identification of two different distances (Objective 3) gave us the possibility to understand synergies between different types of destinations.

The results showed that the greatest energy-saving potential should be attributed to peripheral areas: these have longer distances from the center and the worst accessibility of services and infrastructure. It seems that the broadest perspective for further research lies in the analysis of energy-saving potentials as a function of population density. Is the energy-saving potential of a reduction in over-population where the shorter journeys of a larger number of inhabitants (core zone) predominate or where the longer-distance journeys of a smaller number of inhabitants predominate?

The presented scatterplots could be used as a support tool for designing decision-making systems while identifying the weakest synergies which should be increased (e.g., by increasing building density or allocating new schools) or by identifying the local standard of the sustainable urban neighborhood form. As mentioned earlier, the scatterplots not only present synergy between these different zones of urban structure but also, at least indirectly, show the possible higher dispersion of energy usage.

The presented model could be employed not only for the analysis of energy usage but in essence could also be employed for the evaluation of the multifunctionality and sustainability of the urban form based on the concept of pervasiveness [11]. The potential of the presented model is increased by the principles of New Urbanism, focused on the multi-functionality of neighborhoods, specialized districts, and urban corridors. In this case, the proposed methodology can help to evaluate not only the degree but effectiveness, based on synergy, of combinations of different functional objects. It should be pointed out that use of the Open Street Map (OSM) data on single objects allows us to perform analysis at various hierarchical levels of urban planning: informal neighborhood or street level, formal neighborhood or administrative unit or a city or region, the whole city or region, etc. The simulative nature of the employed model, as was mentioned earlier, gives a predictive power to the model, thus enabling us to use it in comparison with alternatives or even parametric urban planning. Depending on the exact needs of urban planning or the decision maker, the model could be presented in a traditional form of urban plans or as a type of sustainability compass, thus demonstrating its flexibility.

The further development of the presented model should be focused on the following tasks:

- Validation and testing of the model in the other cities;
- Validation of the model with the direct data on energy consumption where it is available;

- Expansions of the list of the indicators of the model besides the one used, as more indicators can allow a more precise modeling of both energy consumption and multifunctionality.

The main challenges of the presented work, which have a direct influence on the possibilities of its application, could be related to the lack or scarcity of data and the modeling process. OSM still has some gaps as the street network is digitalized in different manners and at a different detail level for different cities. OSM as well could not be seen as a full and precise source of information on the allocation of various travel destinations—the precise data on each building would be needed from national agencies. Data on energy consumption, which would allow both more precise validation and further calibration or expansion of the model, could be found just for relatively small urban areas in the needed resolution. The modeling procedure requires special skills and is not very user friendly as it is based on a combination of various software tools, some of which require expensive licenses, thus making it not accessible for all municipalities or urban planning offices.

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