ESIC2024, Vol 8.2, S1 Posted: 15/07/2024

Mathematical Graph Based Urban Simulations as a Tool for Biomimicry Urbanism?

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Abstract

Biomimicry studies natural systems and attempts to use the gained knowledge and understanding to solve human problems. Can biomimicry, if applied in urban planning, help to make our cities more sustainable or, precisely, more friendly for walkable and 15-minute city models?

Various researchers identify the following features of natural systems as form fits function, catalysis of cooperation, local contextuality, continuity of development, diversity, integrity, redundancy, decentralization, multifunctionality, and less energy consumption (e.g. TOD if the energy needed for transportation is considered), hierarchy, fractality, etc.

The presented research has two objectives:

• analyze the possibility of describing and evaluating the degree of expression of the features of natural systems in urban spatial structures to use them for comparison, benchmarking, or creation of a biomimicry index;

• evaluate if cities with more strongly expressed biomimicry features could be considered more walkable and close to the 15-minute city concept.

To give answers to the above-presented questions Riga, Vilnius, and Tallinn were investigated. They represent both certain similarities and differences in terms of history, urban planning, political context, size, etc. A simulative mathematical graph model was used as the main tool to describe and analyze complex urban structures based on spatial configurations. Various graph centralities were employed to describe and compare the expression of natural systems' features in the selected cities. OSM data was used to overlap graph models with such information as the density of inhabitants, concentrations of various points of interest in order to evaluate walkability and 15-minute city friendliness.

The research results could be seen as an important step for better understanding of informal principles of biomimicry that can help transform urban areas.

Keywords: biomimicry, urbanism, mathematical graph model, biomimicry index, sustainability.

1. Introduction

Urban areas, with their constant need for energy and resources, have a significant impact on the environment. The construction, maintenance, and operation of cities contribute to global environmental issues such as loss of biodiversity and climate change. In fact, urban areas are responsible for 70% of global carbon emissions and are also the cradle of many social problems [1,2]. As a result, there is a growing worldwide commitment to nature conservation and efforts are being made to enhance the green elements and features in urban environments [3]. In fact the domains of architecture and urban planning are turning back to nature as well. As researchers [4] have pointed out, humanity's approach to nature has evolved from fear of nature to imitating nature, getting inspiration from nature, domination over nature, to studying nature, and learning from nature. One of the approaches to learning from nature is biomimicry, which involves studying nature and using its principles to design sustainable and self-sufficient built environments [1].

It is widely agreed that Biomimicry in urban planning can offer sustainable solutions by mimicking nature's resource efficiency and waste reduction. It enhances resilience to natural disasters and climate change through adaptable designs. Incorporating natural elements improves health, well-being, and aesthetic appeal. Efficient transportation networks can be inspired by animal movement patterns. Natural water management strategies help cities handle stormwater and conserve water. Passive heating and cooling systems derived from nature reduce energy consumption. Integrating green spaces supports biodiversity and provides ecosystem services. Biomimetic designs can also reduce costs and attract sustainable investments, creating more livable and resilient urban environments, etc. Despite the optimism regarding usage of the biomimicry, there is not much research on its application at the urban scale and most often just general principles that could be interpreted in different ways are described. On the other hand, the biomimicry perspective, if applied to a city, suggests looking at it as some kind of organism, which, in turn, could be either more organic or artificial. Maybe, having in mind a long history of urban planning, it is possible to speak about some kind of inherited, natural, hidden biomimicry in urban structures even if it was not applied in a conscious way. Such expectation would be logical, especially if we speak about a certain degree or presence of organic development in urbanism which could be seen as an additional valuable resource, in assuring urban sustainability.

What value does biomimicry create if it is applied to urbanism? Can biomimicry degree be measured? The presented research tries to give an answer to this question in the following stages:

- Analyzing, based on the literature review, which biomimicry principles are in essence applicable to urbanism;
- Asking if they could be described based on quantitative and measurable indicators and on what theoretical base;
- Applying mathematical graph models, which are based on a view of any modeled system or structures as networks, for the above-mentioned purpose;
- Checking possibilities of the proposed quantitative modeling in comparison of three

capitals of Baltic states: Vilnius, Riga, and Tallinn.

- Looking deeper into possibilities to use the proposed model for comparison of neighborhoods within one city (Vilnius).

- Discussing if the results of the comparison are valid and meaningful within the urban sustainability context.

2. Literature review on urban biomimicry

In response to the challenges posed by urbanization and the need for sustainable development, there has been a shift towards incorporating nature and nature-inspired features in urban design. These solutions involve working with nature to address societal challenges and promote human well-being. Examples of these approaches include biophilic design, biophilic urbanism [5,6], nature-based solutions [7], and biomimicry [8,9,10]. While these concepts may seem like recent developments, they have been present in human-designed environments since ancient times.

Biophilic design and biomimicry are two approaches that have gained traction in the field of urbanism. Biophilic urbanism focuses on creating environments that are abundant in nature and provide opportunities for people to connect with and experience nature [3]. On the other hand, biomimicry can be defined as learning from nature and creatively applying its principles in order to design sustainable, self-sufficient and resilient built environments [1,11,12,13]. Both of these approaches have the potential to address sustainability and climate change challenges in urban areas. However, according to Y. Uchiyama et al. [1], biophilic design is a subcategory of biomimetic design and can be understood as a biomimetic application aiming at human well-being. Such an approach explains common principles between biomimicry and biophilia.

J. M. Benyus [11] identified the following laws, strategies and principles of nature: nature uses sunlight; nature uses only as much energy as it needs; nature reconciles form with function; nature recycles everything; nature rewards cooperation; nature is based on diversity; nature requires local expertise; nature internally curbs excess; nature harnesses the power of limits. Benyus proposes that nature should be seen as a Model, Measure, Mentor [13]. Living organisms and the natural world are considered a key source of ideas for the functional design of a sustainable built environment [1]. A. Quintero et al. [2] distinguish three main levels in biomimicry: organism, behavior, and ecosystem. The organism level refers to a specific organism, such as a plant or animal, where part of it, or the whole organism can be mimicked. The second level refers to the imitation of behavior, where an aspect of behavior is translated into a broader human design context. Finally, the third level is the imitation of entire ecosystems and their principles for working successfully, along with their actual functions. Within each of the levels, there are five possible dimensions: form, material, construction, process, function [2]. Other authors also present levels and principles of biomimicry including the works of D. Mansour [14], A. Sheta [15], M. Pawlyn [16].

According to G. Pohl and W. Nachtigall [12], technology is nothing other than the continuing of natural evolution with other means. Thus technology, epistemically speaking, is not something principally different from nature according to this outlook. G. Pohl and W. Nachtigall [12] note, that aside from pragmatic needs for differentiation, there are no compelling reasons why nature and technology should then be considered as opposites, as it has occurred in the past. Considering this approach, 12 features of natural systems - form fits function, catalysis of cooperation, local contextuality, continuity, diversity, integrity, redundancy, decentralization, multi-functionality, less energy consumption, hierarchy, and fractality - were distinguished based on literature. Below each feature is presented as it appears in natural systems and its possible applications in urbanism are elaborated.

Form fits function. In natural systems, this principle is exemplified by structures evolving to optimally perform their functions, such as the streamlined shape of a fish for efficient swimming or the branching pattern of trees for maximizing sunlight exposure. According to H. Mansour [14], nature fits form to function, utilizes a variety of nonorthogonal forms and design methods in its constructions to ensure maximization in terms of structural efficiency. It minimizes the required input of material. Curvilinear shapes are more efficient in terms of structural strength to weight ratio, stress and strain, integration with aerodynamics and multidirectional forces [14]. According to Y. Uchiyama et al. [1], nature has inspired built space since antiquity, when natural proportions were borrowed for aesthetic purposes; however, currently, the focus is less on aesthetics and more on mimicking functional aspects of living systems. In urbanism such an approach can be applied by designing city spaces and structures that directly serve their intended purposes efficiently, such as creating pedestrian-friendly areas to encourage walking or using green roofs and walls to improve air quality and manage stormwater. Form fits function biomimicry principle in urbanism can ensure that urban forms are functional, sustainable, and responsive to the needs of their inhabitants. When analyzing the existing urban structures, this principle can be reflected in correspondence between certain spatial configurations and their functionalities, for example, more dense urban morphology corresponds to higher functional diversity, city center or higher inhabitant density, etc.

Catalysis of cooperation. In natural systems, this principle is evident in symbiotic relationships, such as bees pollinating flowers while obtaining nectar, or mycorrhizal fungi and plant roots exchanging nutrients [17]. In urbanism, this principle reflects the kind of added value created by urban space for certain functions that brings / attracts them together. Biomimicry principle catalysis of cooperation can be implemented in urbanism by designing spaces that foster community interaction and cooperation, such as mixed-use developments that combine residential, commercial, and recreational areas, or public spaces like parks and community centers that encourage social interaction and collective activities. This promotes a sense of community, resource sharing, and collaborative problem-solving within the urban environment.

Local contextuality. In natural systems, local contextuality is reflected in organisms and ecosystems adapting to their specific local environments, such as cacti thriving in arid conditions or mangroves in coastal areas. According to M. B. Yassine and A. Razin [13], the morphology of organisms is perfectly adapted to the environment in which they live. H. Mansour [14] notes that nature cooperates to fully use the habitat materials in site, it utilizes local expertise and thus remains in balance with the biosphere. Local contextuality principle partially corresponds to behavior biomimicry in design according to E. Jamei and Z. Vrcelj [18], as it mimics how organs or organisms behave in the larger context. However it can be expressed in other ways too. For example E. Tanov [19] recommends using elements that come from the earth in a specific locality, as it “roots these fabrics directly to the native landscape in design”. In urbanism, this principle can be expressed as correspondence to local / cultural distributive and correlative codes and can be purposefully applied by designing buildings and city layouts that consider the local climate, culture, and geography, such as using local materials for construction, incorporating climate-responsive design features, and respecting existing topography and cultural heritage. This ensures that urban development is sustainable, resilient, and harmonious with its surroundings.

Continuity. In natural systems, continuity is reflected in the seamless flow and interconnectedness of ecosystems in space and time. Nature does not have restrictions as H. Mansour [14] notes. In nature habitats, food chains, and nutrient cycles are uninterrupted, promoting biodiversity and ecological stability. According to M. B. Yassine and A. Razin [13], the goal of biomimetic architecture is not only to shape and measure space but also to develop synergistic relationships between the building and its environment. The continuity aspects can be related with ecosystem biomimicry [2,10]. In urbanism, this principle can be reflected by designing continuous and interconnected green corridors, such as linear parks, greenways, and urban forests. These green spaces can link neighborhoods, provide wildlife habitats, mitigate urban heat island effects, and offer recreational opportunities, fostering a more sustainable and resilient urban environment. Additionally, continuity in urban design can promote walkability, cycling, and public transit, reducing dependency on cars and enhancing overall urban connectivity and livability. According to the researchers, ecosystem biomimicry may be the most effective way to respond to climate change and biodiversity loss [2,10]. The time aspect of continuity can be reflected as evolutionary development of urban spatial structure as well.

Diversity. In natural systems, the principle of diversity is reflected in the variety of species and ecosystems, which enhances resilience, adaptability, and ecological balance, such as the biodiversity of a rainforest contributing to its stability and productivity. According to H. Mansour [14], nature runs on diversity, constantly transforming and adapting the flow of change, increasing its complexity, diversity, and efficiency over time. In urbanism, this principle can be reflected as a diversity of functions and / or spatial codes and achieved by creating diverse land uses, housing options, and public spaces, promoting a mix of cultural, social, and economic activities. This diversity enhances the city's resilience, vibrancy, and inclusivity, catering to the different needs and preferences of its inhabitants while fostering innovation and adaptability.

Integrity. The principle of integrity in nature is reflected in the cohesion and stability of ecosystems, where each component, from organisms to processes, works together to maintain balance and health, such as the interconnected roles of plants, animals, and microorganisms in a forest. According to M. Pawlyn [16] and Y. Uchiyama et al. [1], characteristic of ecosystems is the tendency to optimize themselves for the good of the whole (total optimization), rather than for individual parts, while maintaining the diversity of elements [1]. Thus integrity and diversity are simultaneously present in the ecosystems. In urbanism, this principle can be applied by ensuring that all elements of the city, including infrastructure, public spaces, and services, are integrated and function cohesively and that urban structure would present itself as not broken urban structure without missing parts of large gaps. This can involve comprehensive urban planning that promotes seamless transportation networks, interconnected green spaces, and cohesive community services, ensuring the city operates as a unified, efficient, and resilient system.

Redundancy. In natural systems this principle is reflected in the presence of multiple species or processes that serve similar functions, providing backup and enhancing resilience, such as various pollinators ensuring plant reproduction or multiple pathways for nutrient cycling. When applying the principle of redundancy in design and searching for inspiration in natural systems, N. Taylor Buck [20] recommends looking at organism “families” that face and solve the same problem in slightly different ways. In urbanism, this principle can be reflected as the existence of alternative choices for the same function, e.g. movement and achieved by designing redundant systems for critical infrastructure, such as multiple transportation routes, backup power sources, and decentralized water management systems. This ensures that the city can continue to function smoothly in case of failures or disruptions, enhancing overall resilience and reliability.

Decentralization. In natural systems, the principle of decentralization is reflected in the distributed control and functionality across various organisms and processes, such as ant colonies operating through local interactions without a central authority or the widespread root networks of plants distributing nutrients and support. According to M. Pawlyn [16], ecological systems are distributed and diverse, anarchically self-regulating. In urbanism, this principle can be expressed as a heterocentric spatial structure and applied by creating a decentralized urban structure with multiple, self-sufficient neighborhoods that have their own amenities, services, and infrastructures. This reduces dependency on a central core, enhances local resilience, and promotes more balanced and sustainable urban growth.

Multi-functionality. In natural systems, the principle of multi-functionality is reflected in elements that serve multiple roles, such as wetlands providing habitat, water filtration, and flood control, or trees offering oxygen production, shade, and habitat. When applying the principle of multi-functionality in design and searching for inspiration in natural systems, N. Taylor Buck [20] recommends looking at organisms or systems with single solutions that solve multiple problems simultaneously. In urbanism, this principle can be expressed as mix of various functions in the same territory and applied by designing spaces and infrastructures that serve several purposes, such as green roofs that offer insulation, stormwater management, and recreational space, or public parks that provide social areas, environmental benefits, and spaces for physical activities. This maximizes the utility and efficiency of urban areas, making them more adaptable and resource-efficient.

Less energy consumption. In natural systems, this principle is reflected in efficient energy use and resource optimization, such as birds migrating using thermal currents to conserve energy or plants maximizing sunlight absorption through optimal leaf arrangements, material in the honey bee hexagonal colonies shape is allocated only to the places where it is most needed [14]. According to H. Mansour [14], nature optimizes rather than maximizes, using the least materials for optimal structure and function. As M. Pawlyn [16] notes, ecological systems run on current solar income. According to Y. Uchiyama et al. [1], energy-use optimization has been a central subject in biomimetic architecture. In urbanism, this principle can be applied by designing energy-efficient buildings, promoting public transportation, and integrating renewable energy sources. Urban planning can also emphasize transit-oriented development, and compact, walkable neighborhoods to reduce the need for long commutes, thereby lowering overall energy consumption and enhancing sustainability.

Hierarchy. In natural systems hierarchy is reflected in organized levels of structure and function, such as ecosystems being organized into species, populations, communities, and biomes, each level interacting and supporting the others. According to H. Mansour [14], nature uses an ordered hierarchy of structures. M. Pawlyn [16] distinguishes such features of hierarchical structure as the capability of growth and self-repair, environmental responsiveness, environmentally influenced self-assembly, growth by adaptive accretion, and separate control of stiffness and fracture. In urbanism, this principle can be expressed as strongly expressed patterns of center and periphery at different levels and applied by structuring cities with clear, functional hierarchies, such as central business districts, secondary commercial areas, residential zones, and local neighborhoods. This hierarchical organization ensures efficient resource distribution, easy navigation, and effective management of urban growth and services. According to G.Pohl and W. Nachtigall [12], the principle of hierarchy is visible even in “naturally grown” cities in developing countries, which often give the impression of chaos or at least randomness. However, one should not overlook the fact that the in-between structure of narrow alleys - the accommodative street network - is the central framework, around which and to which the individual buildings are developed, expanded, changed and adapted [12].

Fractality. In natural systems fractality is expressed in self-similar patterns repeating at different scales, such as the branching patterns of trees mirroring the patterns of their branches and twigs. Fractality is often underlined as an important principle in natural systems that can be employed in designing artificial environments [21, 22]. Researchers encourage exploring natural growth patterns and their application in architecture [1]. According to A. Gertik and A. Karaman [22], cities that are designed with fractal form play an important role in ensuring the continuity of urban space and the interrelationships of urban parts. In urbanism, this principle can be reflected by demonstration of similarity to fractal structure in terms of variety of scale, porosity, etc., and achieved by designing city layouts and structures that exhibit fractal-like characteristics, where smaller-scale elements like street patterns or building designs echo larger-scale patterns in the city's overall layout or architectural style. This can create visual coherence, optimize land use, and enhance connectivity across different scales within the urban fabric.

3. The possibility of describing biomimicry urbanism principles by mathematical graph model and data preparation

As it was mentioned in the introduction, the biomimicry perspective, if applied to a city, naturally suggests looking at it as some kind of complex organism. Modeling of complex systems, according to R. Siegfried [23], requires specific simulative models that help us to understand such systems better and create additional predictive possibilities which are very important while keeping in mind the dynamic nature of a city as a complex system [24]. Three types of simulative models are used for urban planning: agent-based modeling, cellular automata, and mathematical graph-based models. The last one, based on multiple applications could be seen as the most universal in terms of fields and scales of applications and even potentially serving as a background for the other models – e.g. agent-based modeling. Usage of the mathematical graph model for architecture and urban structures was introduced by various researches since 1980 independently or in collaboration with each other: B. Hillier created Space Syntax theory which offers possibilities to analyze both urban structures based on the simulation of movement of people and visually perceived either architectural or urban spaces based on visual connectivity and analysis of so called isovistas as visually perceived polygons of spaces [25]; The Depthmap software was created and later offered for open use for Space Syntax modeling [26]; S. Porta and V. Latora offered multiple centrality assessment models and tool for urban modeling [27, 28]; M. Batty in his influential book "The New Science of Cities" advocated for the usage of mathematical graph model in urban modeling [29]; Sevtsuk used the same mathematical model for analysis and modeling of pedestrian movement in cities while offering GIS-based tool for that purpose [30, 31]; S. McElhinney developed further so-called visual graph analysis of Space Syntax and created a special tool for this [32]; C. H. V. Cooper and A. J. F. Chiaradia developed their own approach and GIS tool based on similar principles as Space Syntax, but with wider calculation possibilities for modeling at urban scale if compared to Depthmap [33], etc.

As stated above, despite the relatively wide variety of models, names, and tools, all the approaches mentioned above are based on the same mathematical graph model. According to it, each spatial structure is seen as a network of nodes and links. In different models, depending on the scale and purpose of research, it could be differently defined what is represented by a node and what is represented by a link. E.g.: Depthmap and Space Syntax offer possibilities to see visually straight axes, street segments, and "cells" of visually perceived space as nodes; correspondingly intersection of streets and visibility is represented by links or edges [26]. Multiple Centrality Assessment Tool [34] used a little different approach while seeing intersections of streets as nodes and segments of streets as links. Sevtsuk in UNAT tools sees buildings as nodes and streets as links [31], etc. Despite the above-mentioned differences, all the models see the city as a network of spaces or objects that enable various social, economic, and cultural interactions in a similar way as Gabriel Dupuy while formulating his idea of Network Urbanism [35].

The mathematical apparatus of graph theory is focused on the calculation of the importance or so-called centralities of the graph nodes. Exact formulas and various centralities used for the modeling in the presented research will be discussed later so here a simple principal explanation is offered. Three basic types of centralities could be mentioned:

- Degree centrality [36] is a sum of connections that a node has with its immediate neighbors. In the case of urban space, it would correspond to a number of entrances-exits which connect this space with other spaces. A higher degree of centrality might mean better visibility, accessibility, openness of space, etc.

- Closeness centrality [37] is calculated as a sum of the distance from the chosen node to the rest of the nodes within a network. Distance could be calculated while using meters, turn angles, speed, time, etc., but in any case, the smallest sum identifies the node that is the most reachable in a network. In an urban setting, such well-reachable space will attract more users and objects, create higher densities of buildings, etc.

- Betweenness centrality [38] is calculated as the sum of all potential shortest journeys between all pairs of nodes that cross the calculated node. In urban modeling, it represents the most intensive transit spaces.

Space syntax model was chosen with the street segment seen as a node as it allows to focus on urban public open spaces as the main element of human interaction. For calculation, SDNA offered by Cardiff University [33] was used in combination with ArcGIS [39] software because of the high diversity of centralities calculated and diverse possibilities to apply weighting to the nodes while using available GIS data, e.g.: considering the model more important if more shops are concentrated around it, etc.

How and what graph centralities or analysis of those can be offered to describe the principles of biomimicry applied in urban settings?

In terms of urban networks, it could be stated that form fits function if spatial networks support social, cultural, economic, or other networks, e.g.: the most reachable place coincides with a city center, the highest betweenness of spatial structure corresponds to the allocation of the objects important for logistics, etc. To evaluate the degree of realization of this principle in a city simple statistical analysis with correlations between calculated graph centralities, density of points of interest (POIS) from the Opens Street Map (OSM) as indicators of higher multi-functionalities and urban centers and population density (POP) could be calculated. This test could be seen as a validation of the graph model as well because if there are no correlations at all, it means that the model is not able to catch and simulate the functioning of real urban structures. The four basic centralities were used for this purpose:

- Mean Euclidean and angular distance (MED, MAD) of Farness in SDNA tool, which corresponds to Total Depth in Space syntax is counted based on the following formula [40]:

$$\text{Farness (x)} = \frac{\sum_{y \in R_s} d_M(x,y)W(y)P(y)}{\sum_{y \subset R_x} W(y)P(y)}$$

Where $d_M(x,y)$ means the distance between node x for which the calculation is conducted and every other node y in the graph. W(y) is the weight of the node y which while analyzing just urban configuration is equal to 1. P(y) is the proportion of the street segment as a node that falls within the calculation radius – it could be equal to one or less. R_x means the radius of calculation from the node x. Three radii in calculations were used: 1000 m as a pedestrian and 15-minute city radius; 5000 m as a public transport radius based on some investigation in Vilnius; and 11000 as a car-oriented radius. Based on the results by B. Hillier [40] the shortest distance between nodes was calculated in meters for radii 1000 and angles [41] in radii 5000 and 11000. A smaller number means that the node is better reachable within the spatial structure. It might show urban centers or reflect the integrity of how close urban spaces are to each other within a city in general.

- Network quantity penalized by a distance (NQPD) is calculated by the following formula [40]:

$$\mathrm{NQPD}\ (\mathrm{x}) = \sum_{\mathrm{y} \in \mathrm{R_x}} \frac{(\mathrm{W(y)P(y)})^{\mathrm{nqpdn}}}{\mathrm{d_M(x,y)}^{\mathrm{nqpdd}}}$$

Degrees nqpdn and nqpdd allow us to represent a different significance of the weight of the node and distance in a different urban setting, but, because it would require additional research and calibration the default value of 1 was used. The other symbols have the same meaning as in the previous formula. The bigger values of NQPD, if weighting is not used, show the most dense parts of urban structure. In essence it shows more precisely potential city and local centers then MED and MAD.

- Betweenness (BtE) is calculated by the following formula [40]:

$$\mathrm{Betwenness(x)} = \sum_{\mathrm{y} \in \mathrm{N}} \sum_{\mathrm{x} \in \mathrm{R_y}} \mathrm{W(y)W(z)P(z)OD(y,z,x)}$$

Where y and z are the starts and ends of the journeys along the shortest route between them, W is the weight of those nodes, and P – proportion as in the MED calculation. OD(y,z,x) is a coefficient that is equal to 1 if x was found as a node on the shortest route between y and z as the first option during calculation, 0,5 if x is equal to either y or z, 0,33 if x = y = z or all journeys are simulated on the same street segment-node.

- Two-phase destination (TPD) is calculated by the following formula [40]:

$$\mathrm{TPD}\ (\mathrm{x}) = \sum_{\mathrm{y} \in \mathrm{N}} \sum_{\mathrm{x} \in \mathrm{R_y}} \frac{\mathrm{W(x)P(x)}}{\text{total weight (y)}}$$

Where total weight (y) is a sum of weights or simply the total number of y if weighting is not applied; N is a set of polylines in the global spatial system is denoted and it means that total weight (y) is calculated not within a radius, but within the whole network thus acting as a kind of normalization value for the weight of x (W(x)). The bigger TPD shows nodes that are dominant within calculated radii and have fewer competitors within the network as potential destinations.

- Total length (Len) is calculated by the following formula [40]:

$$\mathrm{Len} = \sum_{\mathrm{y} \subset \mathrm{R_x}} \mathrm{L(y)P(y)}$$

Where L(y) means the length of the street segment-node y reachable from x within radius R_x. It shows the total reachable length of the street network within radii. According to Peponis [41] while he calls it Metric Reach, it identifies urban zones that catalyze social interaction positively.

Catalysis of cooperation, if addressed from the perspective of social interaction first of all, could be expressed by the above-mentioned LEN within pedestrian radii 1000 meters based on the ideas of Peponis [41]. If just 1000 meters radii is used in all compared cities then no normalization is needed and simply a bigger value means stronger catalysis.

Diversity could be seen as the diversity of street network configurations, first of all, if a whole city level is analyzed. For its comparison, the Diversion Ratio (Div) was used. It is calculated by the following formula [40]:

$$\mathrm{Div}\,(x) = \frac{\sum_{y \in R_z} \frac{d_M(x,y)}{\mathrm{CFD}(x,y)} W(y)P(y)}{\sum_{y \in R_x} W(y)P(y)}$$

CFD(x,y) means a straight line of „crow flight“ distance between the nodes x and y. The other symbols were explained earlier in this chapter. In essence, the formula compares the shortest real distance to the straight-line distance, and by Peponis is called Path elongation [42]. Different elongation values could be related to different typologies of urban configuration. A bigger variety of elongations, in such a case, might show a bigger diversity of urban networks. In the presented research it was chosen to use the standard deviation of the biggest and smallest values of Div as an indicator of a greater diversity of the street network. The other option for the evaluation of diversity is simply the usage of Len1000 as a straightforward indicator of different typologies.

Integrity as a property of the urban system which means that all spaces and objects are closely related, was measured by MAD at different radii. Angular shortest route measurement was chosen as, based on the research by Dalton [43] people quite often perceive distance based on a number of turns, but not meters, especially if the situation is not very well known. On the other hand, a smaller angular distance even if the metric distance is bigger, still can show a higher probability of visual connections between spaces which is important for perception of urban fabric. Because calculation is conducted just within limited radiuses so normalization of MAD was not needed.

Redundancy could be described as the possibility of alternative routes. In the mathematical graph, it could be measured in different ways but the proposal was based on the idea of Sevtsuk [30] that elongation of the shortest path up to 20 percent is still acceptable for travelers while choosing a route. For comparison of redundancy in the compared cities Div values, which could be considered as normalized already based on the earlier presented formula, were used where a smaller Div value means bigger redundancy.

Multifunctionality in urban settings simply means the concentration or overlapping of different functions in space with each other. NQPD in essence shows potentially the most multifunctional zones in a city. To have a possibility to evaluate and compare multifunctionality more precisely it was offered to apply weighting to NQPD calculation and focus just on a 1000 m radius as multifunctionality could be felt in the best way while walking. For this purpose, four types of journeys from living places to the city or local center were named: leisure, work, education, shopping. OSM data was used to identify four types of places based on available polygons of functions, polygons of buildings, and POIS. Later on, this data was intersected with a street network within a radius of 400 meters (200 meters was considered as the smallest urban block which could be placed on both sides of a street). The density of such objects was used as a weight for NQPD calculation. Correlations between different NQPD values were used as an indicator of multifunctionality with bigger values meaning that gravity fields created by different types of destinations overlap more.

Decentralization and hierarchy were seen as interrelated properties with stronger expressed hierarchy, especially at the bigger radiuses which means lower decentralization and vice versa. Those properties were analyzed from the perspective of urban centers (NQPD) and transit (BtE) by simply comparing maximal and average values within three radii. A lower max/mean ratio means that hierarchy is expressed less and there is more alternative, similarly well-reachable or suitable for transit spaces.

The fractality of urban structure means its self-similarity, porosity, variety of scales, etc. It is similar to the idea of pervasiveness by B. Hillier „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“ [44]. In simple words, pervasiveness means that the same area serves as a center within various radiuses thus supporting and creating a variety of offers for inhabitants of the neighborhood, city part, and a whole city. It was evaluated in a similar way as multifunctionality but while calculating correlations between weighted NQPD within all three radii used. Stronger correlations and more expressed pervasiveness and fractality.

Local contextuality and Continuity of development were not addressed in the present research as they could be based on all the above-mentioned centrality calculations and comparison of how their values change while looking from a historical perspective. It would require a separate research.

The information about street networks, allocations of functional zones, buildings, and POIS were taken from OSM. For modeling the centralities weighted by the density of journey destination, types of journeys were identified as mentioned earlier: work, leisure, shopping, and education. Based on OSM, as work journey destinations the following zones, building polygons and POIS were selected: '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: '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 education: 'college' , 'kindergarten' , 'library' , 'museum' , 'school' , 'swimming_pool' , 'university'. For shopping: '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'. Decription of selected attributes is presented in the same form as in ArcGIS software. Data on inhabitant density was obtained from the national open data sources.

4. Results of analysis and comparison of the selected cities

Three European capitals with relatively similar recent history, influence of modernist urbanism, and size yet with different historical backgrounds if the period till the 19th century is considered, were chosen: Vilnius, Riga, and Tallinn. Similarity of urban development in the 20th and the 21st centuries was used as the criterion for selection intentionally with the idea that the proposed modeling should be able to catch and reflect subtle different nuances of three cities. After the comparison of three cities, the possibility to apply one of the essentials – multifunctionality modeling within Vilnius while comparing formal neighborhoods within it (elderlies) was made.

Form fits function analysis was based on the calculations of correlations between POIS (Fig. 1) and inhabitants (POP) density as representations of functionalities and graph centralities as city functioning simulation results based purely on its form.

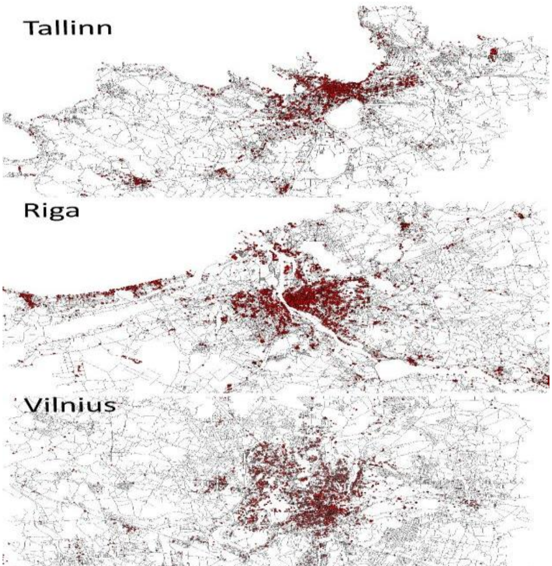

Fig. 1. POIS shown as red dots over the street network.

The results of the statistical analysis, presented in Table 1, could be seen as validation of the mathematical graph model in all three cities because, first of all, form and function are interrelated and affect each other in real cities. It could be assumed that certain correlations should be expected, and if they were not found, the employed model is wrong. Both Pearson correlation and Spearman's rho were calculated with in essence the same tendencies shown. Still, Spearman‘s rho demonstrated a little stronger correlations thus meaning that dependency between form and function is not linear which seems quite logical, e.g.: good reachability is important for a city center, but when the distance becomes relatively big, its further increase makes a smaller influence on movement behavior of inhabitants.

Table 1. Spearman‘s rho between graph centralities and POIS and inhabitant densities. Orange color marks strong (above 0.7), yellow – moderately strong (0.5 – 0.699), and green – moderate (0.3-0.499) correlations.

		MED1000	NQPDE1000	BtE1000	TPD1000	Len1000	MAD5000	NQPDA5000	BtA5000	TPD5000	Len5000	MAD11000c	NQPDA11000	BtA11000c	TPD11000c	Len11000c
Vilnius																
Spearman's rho	POIS	.230**	.648**	.433**	.114**	.635**	.018**	.711**	.321**	.424**	.702**	-.204**	.704**	.264**	.680**	.713**
	POP	.350**	.597**	.435**	.031**	.656**	.087**	.805**	.369**	.419**	.821**	-.114**	.782**	.299**	.712**	.798**
Riga																
Spearman's rho	POIS	.279**	.717**	.584**	.170**	.757**	-.023**	.685**	.410**	.398**	.660**	-.246**	.603**	.311**	.571**	.566**
	POP	.358**	.728**	.618**	.147**	.786**	.007*	.725**	.437**	.376**	.705**	-.189**	.642**	.333**	.540**	.607**
Tallinn																
Spearman's rho	POIS	.314**	.766**	.600**	.142**	.763**	.018**	.724**	.423**	.397**	.719**	-.289**	.655**	.297**	.581**	.675**
	POP	.383**	.723**	.595**	.118**	.762**	.035**	.732**	.429**	.332**	.725**	-.224**	.661**	.305**	.534**	.659**

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

As mentioned in the previous chapter, three radii were used in simulative modeling: 1000, 5000, and 11000 meters. They represent three hierarchical scales of the cities accordingly which function based on pedestrian movement, public transport movement, and both public transport and individual car usage. The following differences could be noticed in Vilnius, Riga and Tallinn:

- Positive moderate correlation in three cities, especially between MED1000 and POP density shows some kind of multi-layered local structures that create more privacy for local inhabitants. A similar tendency could be noted with POIS in Tallinn thus meaning a similar tendency in local centers.

- NQPD demonstrates significantly stronger correlations with both POIS and POP in Vilnius at radius 11000 and both Riga and Tallinn at 1000 and 5000. NQPD1000 for all three cities is presented in Fig. 2. It means that Vilnius is a much more individual car-dependent city with a strongly expressed mono-centric structure. Tallinn and Riga demonstrate a more multicentered and pedestrian-friendly city. It is additionally confirmed by moderate-strong correlations with BtE1000 in both cities thus showing that local neighborhoods have a spatial structure that catalyzes concentrations of pedestrian movement in certain streets which means a higher probability of critical mass of pedestrians from the functioning of local centers.

- The highest correlations between TPD11000 values and both POIS and POP in Vilnius say that the most reachable central part of the city is a dominant alternative destination for the majority of movement and support the impression of the monocentric structure pointed out by NQPD correlations.

- Only moderate positive correlations could be observed between BtE (Fig. 3) especially in higher radiuses and both POIS and POP. It reflects the car oriented nature of a modernist urbanism with more alternative routes available. In Vilnius those correlations are the weakest those representing the most car-oriented nature of the city.

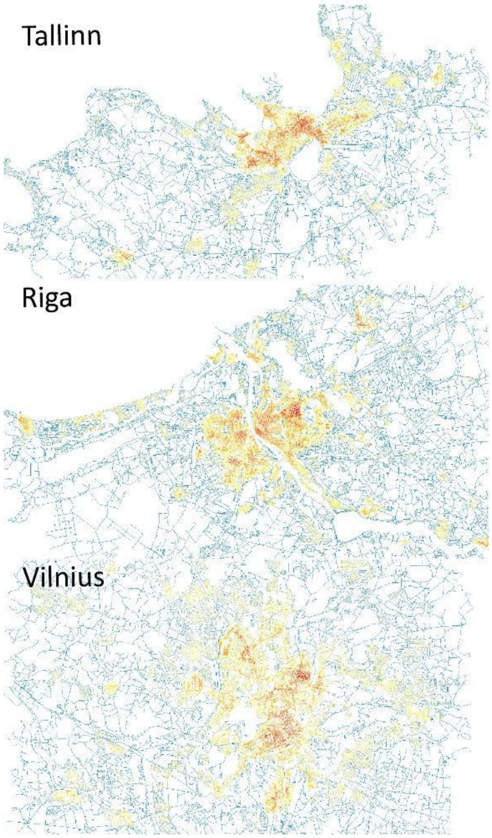

Fig. 2. NQPD1000/ Red color means higher numerical values, blue – lower.

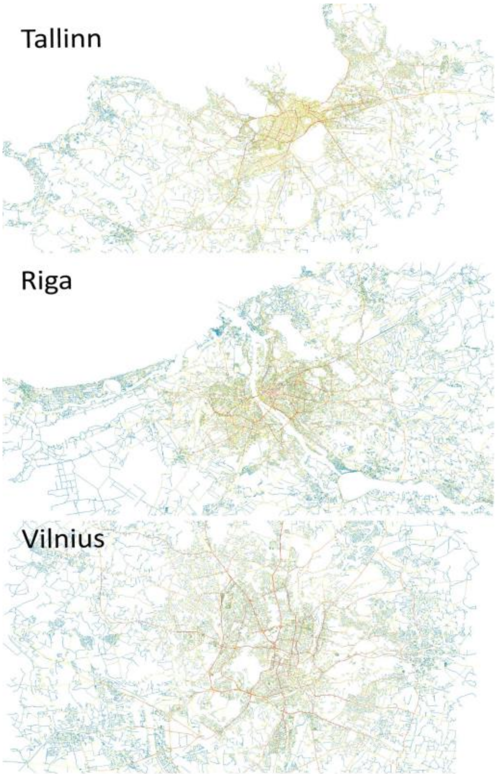

Fig. 3. BtA1100/ Red color means higher numerical values, blue – lower.

In conclusion for form-fits-function analysis, it should be said that how a city functions, or how it wants to function, depends on the aims raised by the community, politicians, and city planners. If the urban system is seen as a 15-minute city then Riga and Tallinn fit this functionality better in the present situation. In this case, Vilnius quite well fits the functioning of the Soviet modernistic, car-oriented city model and could be seen as less sustainable in terms of transit-oriented development (TOD), fuel consumption, and potential CO_2 pollution, etc.

Diversity comparison results based on Div analysis are presented in Fig. 4. Standard deviation was used as a tool for normalization of data where within one standard deviation to both sides from average values 68 percent of all values fit. A bigger standard deviation means a bigger variety of values.

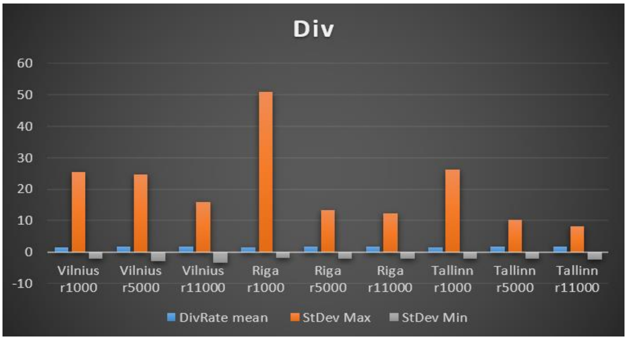

Fig. 4. Values of Diversion Ratio (Div) divided by size of standard deviation.

In Vilnius diversity is quite similar at all three scales. In Riga and especially Tallinn, the higher diversity is seen at the lower radiuses of neighborhood level thus corresponding to the impression of a more heterogeneous urban structure as identified earlier. The concept of three laws of architecture by Nikos A.Salingaros states that the integrity of composition at the smallest scale is based on contrast and oppositions while at the higher scale, it functions on the basis of similarities [45]. If, based on the obtained data potential conceptually perceived mental maps of three cities are imagined, it could be stated that in Vilnius contrast between different urban morphologies at the lowest level is lower but at higher levels – higher if compared to Riga and Tallinn. As a result, it allows us to guess that pedestrians perceive less and car drivers more diversity in the urban structure of Vilnius. Lower values of the ratio between maximal and mean values (Table 2.) Len1000 supports lower diversity perceived in Vilnius but possibly adds additional information to the results of Riga. The smallest ratio in this case together with the highest Div normalized values at radius 1000 possibly reflects a more scattered urban spatial network divided by green areas that corresponds to reality.

Catalysis of cooperation was based on the Len1000 comparison. The results are presented in Table 2.

Table 2. Len1000 mean and maximum values in three cities

	Len1000 mean	Len1000 max	Max/mean
Riga r1000	17076.6	52965.48	3.1016406
Tallinn r1000	18370.23	62687.25	3.4124364
Vilnius r1000	16021.15	54035.9	3.3727851

Peponis and his colleagues, while analyzing the connectivity of street networks noticed „... a strong correspondence between the average volume of pedestrian movement and the average density of streets (Metric reach or Len) and land development“[46]. Based on that notion, Len could be seen as a very simple, yet informative indicator of a potential of a street network to catalyze social and functional interactions. If three cities are compared Vilnius demonstrates the lowest mean Len1000 and Tallinn the highest. The maximal values are the biggest in Tallinn as well as the max/mean ratio which in essence shows the possible diversity of Len1000 within a city. Interpretation of the result should be done within existing urban models: if the 15-minute city model is considered then it means that within reachable for pedestrian distance more multifunctionality, possibilities to interact with people or street culture, etc. should be found. In this case, Tallinn could be pointed out as a „winner" with one warning: a bigger max/mean ratio might mean that there are some neighborhoods with much lower Len values. On the other hand, the presented comparison at the whole city level is very general, and for purposes of strategic or urban planning each city neighborhood should be analyzed – such possibility and its usefulness will be demonstrated later.

Integrity was compared based on Mean angular distance (MAD). To exclude the factor of even small differences in the sizes of the territories, MAD was normalized by dividing by the number of segments thus getting a kind of „pure" comparable values which reflect an urban genotype of spatial configuration directly. The results are presented in Fig. 5.

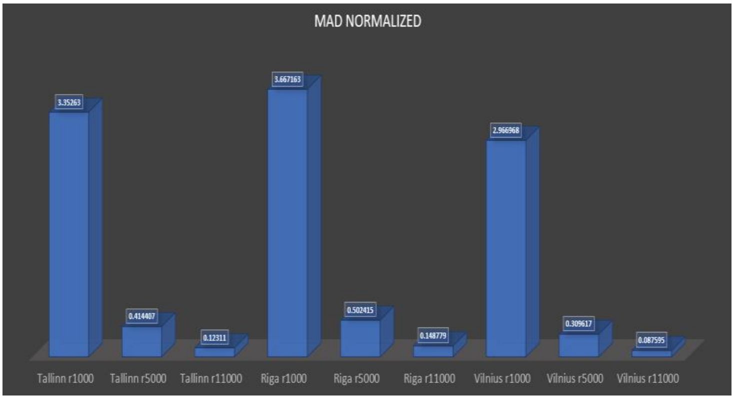

Fig. 5. Comparison of normalized MAD in Tallinn, Riga, and Vilnius.

In all cases, the normalized values demonstrate a more integrative nature of local structures and a decrease in integration when the radius is increased. Such a tendency quite well reflects in essence growing heterogeneity of bigger territories while local neighborhoods can be more homogenous. Within radiuses 1000 and 5000 Vilnius demonstrates less integrity which quite well corresponds to its lower correlations with POP and POIS at those radiuses. At a radius of 11000, it demonstrates the biggest integrity as a monocentric urban structure. Riga in this case demonstrates the lowest integrity from the point of view of car users, and it could be confirmed by observation of some detached satellite developments of modernist housing there.

Redundancy comparison was simply based on not normalized Div, where smaller numbers simply mean bigger randomness. The results are presented in Table 3.

Table 3. Div average values.

	Div mean
Vilnius r1000	1.513191
Vilnius r5000	1.645963
Vilnius r11000	1.613091
Riga r1000	1.456137
Riga r5000	1.645205
Riga r11000	1.636391
Tallinn r1000	1.467051
Tallinn r5000	1.643007
Tallinn r11000	1.585344

According to the numerical data, at a radius of 5000 all three cities demonstrate very similar results. At the radius of 11000, the biggest randomness could be seen in Tallinn and the medium in Vilnius. At the pedestrian radius, the biggest randomness is seen in Riga. The differences could be seen and it looks like the indicators are working, but it is important to notice that, according to Sevtsuk [30] in all cases, the „easily acceptable" elongation 1.2 is exceeded. Probably it could be found at the level of urban blocks or parts of neighborhoods. Maybe it should be analyzed according to street categories, etc. From another perspective, such a result may demonstrate that certain, bigger than 1.2 path elongation is unavoidable in urban structures which cannot function without specialization and separation of spaces.

Multifunctionality comparison, as described in the methodology chapter, was based on the calculation of Spearman's rho between NQPD weighted by the density of travel destinations (work, leisure, education, shops) and within a radius of 1000. Additionally, one weight of the reachable perimeter of buildings as a potential indicator of dense urban fabric, which is related to attractiveness for walkability according to the World Bank report [47] was used, and correlations with inhabitant density (POP) were calculated. Stronger correlations show more overlapping gravity zones created by travel destinations and origins (POP). A calculation with five different values of weighted NQPD1000 and POP gives 15 different centralities for each city, then it was decided to simplify the comparison by calculating average values of Spearman's rho between each type centrality and all the other 5 centralities except itself, e.g.: mean values for NQPD1000 work was counted as a sum of NQPD1000 leisure, NQPD1000 education, NQPD1000 shops, NQPD1000 perimeter, and POP. The results are presented in the Fig. 6:

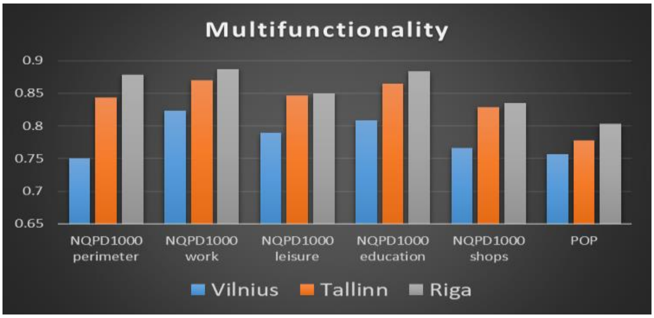

Fig.6. Multifunctionality as average values of Spearman's rho between weighted NQPD1000

and other 5 centralities. All correlations are of 0.01 significance.

Based on the results of the simulative modeling it could be clearly stated that Vilnius has the least multifunctional spatial structure. The lowest values are related to NQPD weighted by building perimeter, density of shops, and allocation of inhabitants thus showing the following: a potentially significant part of shops concentrated in big shopping malls or commercial zones which are separated from housing areas and the strong influence of modernistic morphological typology of single standing buildings in land plots. The presented results show just mean values for a whole city so the variation between different types of neighborhoods could be quite high as will be demonstrated later. At the same time, it should be noticed that a correlation equal to 1.0 is practically impossible in a city as it would contradict with specialization and spatial differentiation of urban structure. From this perspective, correlations close to 0.9 should be considered as really high.

Decentralization and hierarchy were compared from the perspective of urban centers and routes of movement while counting the ratio between the max and mean values of NQDP and BtE accordingly. The bigger number shows that either the most reachable potential centers or the main streets attract more users than the average number in a city thus, potentially demonstrating more differences in terms of number of visitors, functions, users, densities, etc. The results of the comparison are presented in Fig. 7 and Fig. 8.

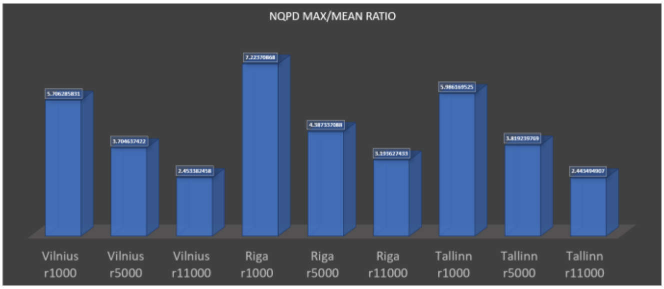

Fig. 7. NQPD max/mean ratio.

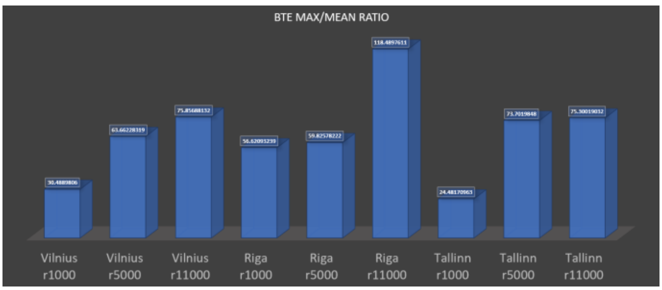

Fig. 8. BtE max/mean ratio.

The clearest hierarchy of urban centers is expressed in Riga at all scales. The biggest values, if compared to the other two cities, at r1000 and r5000 mean bigger decentralization or are more clearly expressed in space and functionally of local centers there as well (Fig. 7). In Vilnius, despite its monocentric structure as identified in form-fits-function analysis earlier, the results do not show the biggest hierarchical dominance at r11000. From the first point of view, it looks illogical, but, if we look at BtE-based hierarchy analysis (Fig. 8), Vilnius demonstrates the second max/mean ratio size after Riga. It means that the main logistical routes attract a bigger percentage of traffic thus supporting at least part of functions which are traditionally identified with city centers: shopping, offices, etc. In terms of geographical models, it is called a peripheral city pattern (Urban design standards), which is present in Riga as well.

Pervasiveness was calculated as a correlation between NQPD1000 weighted by four types of destinations and the weighted NQPD5000 and 11000.

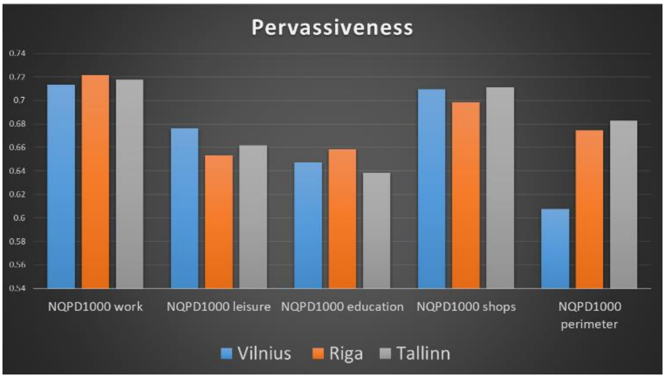

Fig. 9. Pervasiveness comparison

Results differ between the cities but do not show a “clear winner” in terms of the pervasiveness of urban centers. In Vilnius work and leisure places reachable at three radii overlap more with the same and all the other central functions than in Riga and Tallinn. The better situation with leisure destinations which include nature might be related to the concentric structure of the city and relatively good accessibility of those green areas. Very low is the pervasiveness of potentially perimetric placement of buildings represented by traditional urban fabric in Vilnius meaning that such urban morphologies are found mainly in the historical city center.

So, the conducted modeling demonstrates the possibility of using simulative Mathematical Graph-based models for comparison and evaluation of urban form and how it reflects principles of urban biomimicry. Some of the principles and indicators give quite logical results, some of them should be elaborated more or could be better understood in the contexts with the other graph centralities. The results will be summarized a little later, but before, it is important to check if the presented models could be applicable within one city while comparing its neighborhoods. In our opinion, such a possibility is of extreme importance for urban planning as a city demonstrates different typologies of its parts with certain limitations of application of urban biomimicry principles for them. For this purpose, five neighborhoods in Vilnius were selected:

- Senamiestis is the old town of Vilnius. It’s the most historical part with a big concentration of various cultural and commercial functions yet still a relatively big number of inhabitants in the area.

- Naujamiestis is a historical 19th-century part of the city that represents the classicistic urbanism-based expansion of the medieval town after the inclusion of Lithuania into the Russian Empire. The area combines multi-flat housing with urban villas in some areas and former industrial areas. A large number of new business companies and commercial objects are functioning there nowadays.

- Žvėrynas is a former, 19th-century suburb of urban villas for upper-class members. It still represents its character despite some new infill multi-flat or commercial development which is limited in numbers and concentrated beside the main streets thus protecting the privacy of quiet living areas away from them.

- Žirmūnai represents a modernist housing area. Its construction started in 1962. Initially 5, 9, and 12-story living houses were planned with 5-story houses making the dominant part. Local centers were designed and constructed as well. It could be noticed, that in 1968 the state award of the Soviet Union was given to the urban project of the area in recognition of the quality of its urban design and human scale. Today the neighborhood includes a former Soviet military area which is transformed into urban technology parks partially based on the principles of New Urbanism.

- Lazdynai could be seen as a traditional modernist housing area with clear monofunctional zoning, car-oriented streets, and all the other features of modernist urbanism inspired by the ideas of Le Corbusier. Its construction started in 1874 and was finished in 1985.

- Antakalnis is a former historical suburb allocated along the Neris River with a dominant main street and even in the Soviet period found a vertical mix of functions in buildings placed along it.

- Pilaitė is a peripheral neighborhood in Vilnius. The bigger part of it is occupied by multi-flat housing which construction started in 1989 and continued after 1990. In comparison to the modernistic housing areas in Vilnius for the Soviet period, Pilat4 demonstrates a higher diversity of housing typologies thus reflecting social and economic changes in Lithuania after 1990.

The results of the multifunctionality analysis of the 7 neighborhoods in Vilnius were calculated in the same ways as for the cities and are presented in Fig. 10.

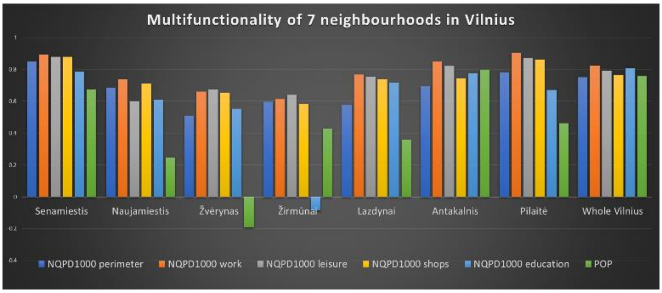

Fig. 10. Multifunctionality of 7 neighborhoods in Vilnius compared between themselves and with the whole Vilnius area.

While analyzing the results, Senamiestis could be pointed out as the most multifunctional area, and such a result was expected because it combines many functions in reality: living neighborhood, specialized historical district, part of the city center, attractiveness for pedestrians, etc. The second most multifunctional area is Antakalnis. Despite its construction based on the principles of Soviet modernism, it still incorporates some historical urban elements, vertical functional zoning has been used in it since the Soviet times. The dominance of the main street as a kind of corridor in terms of New Urbanism possibly makes an impact on such results as well. Žvėrynas some of the lowest results with even negative weak correlations between inhabitant density and objects forming local urban centers. Even if such a result is e a little unexpected, it looks quite logical keeping in mind the relatively small number of inhabitants and quiet neighborhood dominated by urban villas and small multi-flat houses in the area. It is interesting to notice differences between two modernist Soviet housing areas – Žirmūnai and Lazdynai. Žirmūnai demonstrates a better overlap between various functions and inhabitants while Lazdynai shows the presence of more concentrated local urban centers. Lower correlations between commercial and public objects in Žirmūnai could be explained by the new development of a Technology Park in a former military area which as an urban specialized district has a certain degree of autonomy. Reflection of a specific location of educational facilities as schools and kindergartens further away from the streets and beside green areas is reflected by weak negative NQPD1000 of such objects with the rest of the functions in Žirmūnai. Naujamiestis demonstrates just moderate positive correlations between various functions of the city center and inhabitant density while other correlations are strong. It possibly reflects bottom-up, step-by-step conversion and development of former industrial areas with a focus on services not just for the neighborhood and not so compact form of territory which partially souring the historical city center as a kind of concentric ring. Finally, Pilaitė demonstrates similar results to Žirmūnai and Lazdynai as initially based on the same principles of modernist urbanism but with better correlations between POP and the other centralities. It could be seen as a reflection of the diversity of housing typologies which were developed there after 1990.

How can the results of the comparison of the three cities and 7 neighborhoods be generalized? Can we say which spatial urban structure is the closest to the principles of biomimicry urbanism?

- All cities demonstrate a certain degree of biomimicry principles especially in the older parts thus allowing us to think about inherited biomimicry as a feature of traditional, especially organically developed urban form.

- It could be seen, based on the presented comparison, that the proposed model is offering indicators that in essence are reflecting differences of even relatively similar cities with a similar history in a quite sensitive way and could be used not just for comparison, but for prediction, identification of weak aspects of urban structure, etc. This is especially true if the modeling is done inside a city.

- The question of which city corresponds to the principles of biomimicry possibly can be hardly generalized on the simple answer as it should be related to the hierarchical level at which analysis was conducted represented by radii and possibly focus on the most actual principles or indicators in the analyzed city. It was seen in form-fits-function analysis, that in terms of 15-minute cities, Riga and Tallinn demonstrate better results while Vilnius is more a car-oriented city. Vilnius demonstrated the least multifunctionality, catalysis of social interaction, and pervasiveness in terms of urban structure supporting street culture. All three cities indicate that the pervasiveness of shops is in essence stronger while one of educational and leisure objects is weaker. Evaluation of randomness, decentralization, and hierarchy demonstrated quite similar results and should be tested in more different urban structures to decide about possible usefulness, etc.

5. Evaluation of the results and discussion

While discussing the results of the modeling the first question is if the presented modeling results are valid and do reflect the functioning of real cities. Mathematical graphs and Space Syntax models are validated in various research. “(A number of) studies have shown that the location of shops, retail, national and international firms, and the location of urban centers in general, depends on a high degree of integration of the street net on various scales" [48]. Despite the recognized validity of the graph-based models cities can differ in terms of predictability as the allocation of functions could be affected by a variety of economic, social, political, environmental, and other factors and the role of street network can vary from city to city. More organic, based on bottom-up processes and free-market conditions urban development is expected to produce stronger correlations with urban functions than top-down initiated and defined modernistic urbanism which looked at a city as a machine but not an organism. In this case, significant strong and medium correlations between the calculated graph centralities, POIS density, and POP in Vilnius, Riga, and Tallinn are of high importance as the three cities were quite heavily affected by the Soviet modernist city planning. POIS density and POP demonstrate the most important layers of urban structure – travel destinations or urban centers and travel origins. Spearman’s rho values above 0.7 should be considered as a good result which is reaching potential maximal value, because of the above-mentioned complex factors affecting the formation of a city.

The second question is if the proposed indicators make sense in terms of sustainable urban development. If the sustainable urban form is considered, we can refer to various research and methodological tools. The first one is the Urban Scale Sustainability Compass as a tool directly focused on the subject [49]. It identifies the following aspects of urban form as important for sustainability: spatial quality, environmental impact, and social impact. Such more detailed qualitative criteria as collective mobility; slow mobility; private mobility; access to commercial, educational, recreational, and socio-cultural facilities; building shape, etc. could be seen as directly related or described by the proposed indicators. On the other side, research on sustainable urban form could be summarized in the following keywords: compactness, optimality for public transport or so-called Transit Oriented Development (TOD), density, mixed function, identity and continuity, spatial promotion of social interaction, diversity, accessibility on foot, place identity, spatially expressed community, open public spaces, etc. [50]. In the majority of cases, the proposed indicators could be seen as helpful in measuring the above-mentioned aspect of the sustainability of urban form.

The third question is if the proposed quantitative indicators have any value for urban planning. From that perspective, the proposed simulative quantitative indicators could be divided into two groups. The first group – indicators that could be directly applied in parametric design, identification of weak spots of urban structure, and creation of sustainable development strategies. Those are form-fits-function, multifunctionality, pervasiveness, and catalysis of cooperation indicators. The indicators of diversity, integrity, redundancy, centralization, and hierarchy, based on a comparison of the three cities, could be more useful for classification and further exploration.

The fourth question is if the results of the modeling could be confirmed by the other available data while comparing the three cities. Let's first review what cities have built into their sustainability strategies and what they have achieved. For example Tallinn has received the European Green Capital Award for 2023, highlighting its holistic approach to sustainability. Key initiatives include improving energy efficiency in buildings, reducing carbon emissions, and enhancing urban biodiversity through projects like the "Pollinator Highway" which converted 13 kilometers of unused space into urban meadows [51], also important to mention, that the Estonia 2035 strategy has been updated to align with the European Green Deal, focusing on green and digital transitions. Local governments are being empowered to implement sustainability measures, with a significant emphasis on data standardization and innovative solutions [52]. One of the biggest achievements for Estonians was improving its global sustainable development ranking, moving to 10th place. Key areas of focus include renewable energy, accessible education, and effective healthcare, though challenges remain in gender equality and waste management [52]. In the other hand, Riga has committed to developing a climate-neutral city by 2050. This is part of Latvia's broader national energy and climate strategies. Riga's "Bold City Vision 2050" aims to decarbonize its energy system, building on the earlier "Riga Smart City Sustainable Energy Action Plan 2014-2020" and evolving it into the "Riga Sustainable Energy and Climate Action Plan until 2030" (SECAP-2030). Key areas include energy efficiency, clean mobility, and circular economy initiatives [53]. Riga's strategy involves cross-sectoral collaboration to improve building energy efficiency, promote renewable energy technologies, and develop electromobility solutions. The city is also focusing on creating Positive Energy Districts (PEDs), starting with the Skanste neighborhood as a pilot site. This involves integrating various energy-saving and renewable technologies to create districts that produce more energy than they consume [54]. Last but not least, Vilnius has joined the Green

City Accord and set a target of planting 100,000 trees, 10 million shrubs and 300,000 vines to improve the city's biodiversity and the quality of its green spaces [55]. Renovation projects such as the “Reformatai” garden will contribute to the development of green spaces by creating comfortable and aesthetic public spaces. The new Vilnius Master Plan focuses on sustainable mobility solutions, the development of pedestrian and cycle paths and the modernisation of the public transport network [56]. Vilnius water supply company “Vilniaus vandenys” plans to upgrade two wastewater treatment plants and upgrade water and wastewater networks to reduce environmental pollution and improve living conditions with support from the European Investment Bank [56]. Also the city is investing in energy-efficient buildings and monitoring air quality, and has banned the burning of coal and peat from 2023 to reduce air pollution [55].

According the data we could split cities into separate categories and make a straightforward conclusions: Sustainability Goals and Awards; Energy Efficiency and Renovation; Green Spaces and Urban Infrastructure; Transport and Mobility and Policy and Strategic Initiatives.

Sustainability Goals and Awards

Tallinn - Awarded the European Green Capital for 2023, recognizing its comprehensive approach to sustainability. The focus is on improving building energy efficiency, reducing carbon emissions, and enhancing urban biodiversity with projects like the "Pollinator Highway." Riga - Committed to becoming a climate-neutral city by 2050, aligning with Latvia’s national energy and climate strategies. The city is transitioning from the "Riga Smart City Sustainable Energy Action Plan 2014-2020" to the "Riga Sustainable Energy and Climate Action Plan until 2030" (SECAP-2030). Vilnius - Joined the Green City Accord with a target to significantly enhance its green spaces by planting 100,000 trees, 10 million shrubs, and 300,000 vines, and is focusing on sustainable infrastructure and public spaces.

Energy Efficiency and Renovation

Tallinn - Emphasizes improving energy efficiency in buildings and urban biodiversity. The "Pollinator Highway" project, which converted 13 kilometers of unused space into urban meadows, highlights its commitment to sustainability.

Riga - Focuses on increasing energy efficiency and clean mobility. The city is developing Positive Energy Districts (PEDs), starting with the Skanste neighborhood, which aims to produce more energy than it consumes. Vilnius - Invests in energy-efficient buildings and has implemented a ban on burning coal and peat starting in 2023 to reduce air pollution.

Green Spaces and Urban Infrastructure

Tallinn - Concentrates on biodiversity with less emphasis on specific green space projects. Riga - Prioritizes energy efficiency and clean technologies but has less focus on specific green space development. Vilnius - has a concrete plan to increase green spaces through extensive planting projects and renovation of public areas like the “Reformatai” garden.

Transport and Mobility

Tallinn - Enhancing energy efficiency but specific details on electromobility and public transport initiatives are less prominent. Riga - Focuses on electromobility and renewable energy technologies, including the development of Positive Energy Districts that integrate these technologies. Vilnius - Investing in sustainable mobility solutions, including the expansion of pedestrian and cycle paths and modernization of public transport.

Policy and Strategic Initiatives

Tallinn - Received the European Green Capital Award and updated the Estonia 2035 strategy to align with the European Green Deal, focusing on green and digital transitions. Riga - Adheres to national climate strategies with a long-term plan ("Bold City Vision 2050") that includes energy and climate goals. Vilnius - Joined the Green City Accord and is developing detailed plans for improving green spaces and infrastructure.

Additionally, if we look at the numerical - qualitative values, we can check the most walkable cities which was ranked by Forbes. Insider Monkey was used for ranking: "First, the analysts at Insider Monkey tapped into city walkability scores from sources like Tourlane and WalkScore, then mapped out distances between the top tourist attractions. And because you want to have good air quality when you're out and about—and to be safe—they analyzed IQAir data and safety indexes from Numbeo, to narrow down the list to 30 cities."

[58]. Results of the present modeling and especially multifunctionality analysis and form-fits-function analysis are in essence confirmed by the ranking as Riga takes the second and Tallinn – the seventh place with Vilnius absent there. Report on the quality of life in European cities 2023 [59] confirms that Vilnius has the biggest usage of cars within comparison of the three cities, while Tallinn is the second and Riga is the third (Figure 28: People using cars in a typical day, by city, p.59.). The report states that Riga is the first, Tallinn is the second, and Vilnius – the third in terms of usage of public transport (Figure 31: People using public transport in a typical day, by city (p. 62). By the number of people cycling during a typical day, Tallinn holds the first, Riga the second, and Vilnius the third position (Figure 33: People cycling in a typical day, by city (p.65)). If the amount of people walking in a typical day in a city is considered then Talin is the first, Vilnius is the second, and Riga is the third (Figure 35: People walking in a typical day, by city (p.67). In this case, data do not confirm the results of the presented investigation directly, but we should agree that walkability depends not only on urban configuration which is reflected in the simulative modeling but on security, urban design features, availability on the other transport types, culture, climate, etc. If data obtained from the local sustainable mobility plans and other local reports is analyzed then the situation looks the following:

- In Vilnius 24,1% of inhabitants use public transport, 1,5% cycle, 24,5 % walk, 49,0 % take a car and 0,9% use other measures for everyday travel in 2017 [60].
- In Riga 46,5% use public transport, 9% cycle, 13,5% walk, and 31,0% use a car according to data from 2018 [61];
- In Tallinn 31,0% use public transport, 4,0% cycle, 12,0% walk, and 53,0% use individual cars in 2018 [62].

The results contradict the data from the Report on the quality of life in European cities in 2023 [59] and do not support the findings of the present research, but the contradiction does not negate our findings directly as the choice of the transport type depends not only on urban configuration as it was mentioned earlier.

While generalizing the discussion, it could be agreed that the analysis and comparison of the three cities should be seen just as a case study to investigate if it is worth testing the presented model further. Some independent data on Vilnius, Riga, and Tallinn both confirm and do not support the received results indirectly. On the other hand, the results look quite promising as they at least partially overlap with other data on the subject, and develop some quite general indicators of urban sustainability further. The results could be especially useful in a subtle modeling of multifunctionality which could not be addressed in a straightforward way by functional zoning of urban planning.

6. Conclusion

- The analysis of the results of the tree cities based on biomimicry principles reveals that urban structures can have some inherited biomimicry features which could be identified more clearly after further investigation of various urban samples from different regions and cultures.

- The present research demonstrates that quite abstract quantitative indicators and principles of sustainable urban form and biomimicry could be related between themselves and described quantitatively thus opening a way for parametric urban design, comparison with benchmark samples, monitoring based on quantitative indicators, etc. The mathematical graph model could be seen as one of the potentially useful approaches in this case.

- It looks like the proposed model is more useful when applied at the neighborhood level at least within smaller radiuses as the results at the city level give a very generalized view that can be not sensitive enough to the diversity of situations within a city.

- Part of the proposed indicators that address multifunctionality and pervasiveness could be seen as quite practical in terms of urban planning and monitoring, while others as randomness, hierarchy, and integrity could be more useful for further investigation and classification of urban areas.

- Comparison of three cities in terms of biomimicry principles reveals that there is no single "winner": according to some indicators, one city demonstrates best results while according to other indicators - another one. Despite such a situation, the analysis could help to identify strong and weak aspects of urban structure in terms of sustainability and biomimicry and be used accordingly to improve the situation, propose criteria or a kind of "biomimicry index", evaluate the new urban project, formulate strategies, etc.

Acknowledgements

The presented research was conducted as part of the project Creative Interdisciplinary New European Bauhaus – NEB Research Centre. This project has received funding from the Research Council of Lithuania (LMTLT), agreement No: S-A-UEI-23-3.

WORKS CITED

Y. Uchiyama, E. Blanco, and R. Kohsaka. "Application of biomimetics to architectural and urban design: A review across scales". Sustainability, vol. 12, no. 23, 9813, 2020.

A. Quintero, M. Zarzavilla, N. Tejedor-Flores, D. Mora and M. Chen Austin, M. (2021). "Sustainability assessment of the anthropogenic system in Panama city: application of biomimetic strategies towards regenerative cities". Biomimetics, vol. 6, no. 4, 64, 2021.

T. Beatley and P. Newman. "Biophilic cities are sustainable, resilient cities". Sustainability, vol. 5, no. 8, pp. 3328-3345, 2013.

K. Bhatia and D. Hejib, D. (2018). "Biomimicry: architecture follows nature". In National seminar-PACE18, Maharashtra, India, 2018.

T. Beatley. "Biophilic cities". In: R. A. Meyers (ed.), Encyclopedia of Sustainability Science and Technology, Springer, 2020.

S. Milliken, B. Kotzen, S. Walimbe, C. Coutts and T. Beatley, T. Biophilic cities and health. Cities & Health, vol. 7, no. 2, 175-188, 2023.

N. Seddon, A. Chausson, P. Berry, C. A. Girardin, A. Smith and B. Turner, B. "Understanding the value and limits of nature-based solutions to climate change and other global challenges". Philosophical Transactions of the Royal Society B, vol. 375, 20190120, 2020.

M. Pedersen Zari. "Biomimetic urban and architectural design: Illustrating and leveraging relationships between ecosystem services". Biomimetics, vol. 6, no. 1, p. 2, 2020.

M. Pedersen Zari. "Regenerative urban design and ecosystem biomimicry". Routledge, 2018.

M. Pedersen Zari. "Can biomimicry be a useful tool for design for climate change adaptation and mitigation?". Biotechnologies and biomimetics for civil engineering, pp. 81-113, Springer International Publishing, 2014.

J. M. Benyus. "Biomimicry: Innovation inspired by nature", Harper, Perennial, 1997.

G. Pohl and W. Nachtigall, W. (2015). "Biomimetics for architecture & design: nature-analogies-technology". Springer, 2015.

M. B. Yassine and A. Razin, A. "Biomimicry architecture, from the inspiration by nature to the innovation of the Saharan architecture". Architecture and Engineering, vol. 3, no. 4, pp. 3-12, 2018.

H. Mansour.. "Biomimicry: A 21st century design strategy integrating with nature in a sustainable way". BUE, FISC, 12, 2010.

A. Sheta. "Biomimicry in environmental architecture. Exploring the concept and methods of the bio-inspired environmental architectural design. Faculty of Engineering", Cairo University, 2010.

M. Pawlyn. 2019. Biomimicry in architecture. Riba Publishing, 2019.

S. E. Smith and F. A. Smith. "Fresh perspectives on the roles of arbuscular mycorrhizal fungi in plant nutrition and growth". Mycologia, vol. 104, no. 1, pp. 1-13, 2012.

Jamei, E., & Vrcelj, Z. (2021). Biomimicry and the built environment, learning from nature's solutions. Applied sciences, 11(16), 7514.

E. Tanov. "Design by nature: Creating layered, lived-in spaces inspired by the natural world". Ten Speed Press, 2018.

N. Taylor Buck. "The art of imitating life: The potential contribution of biomimicry in shaping the future of our cities". Environment and Planning B: Urban Analytics and City Science, vol. 44, no. 1, pp. 120-140, 2017.

N. Salingaros. "Biophilia and healing environments. Healthy principles for designing the built world", Terrapin Bright Green, New York, 2015.

A. Gertik and A. Karaman. "The fractal approach in the biomimetic urban design: Le Corbusier and Patrick Schumacher". Sustainability, vol. 15, no. 9, 7682, 2023.

R. Siegfried, "Agent-based modeling and simulation" in Modeling and Simulation of Complex Systems R.Siegfried, Ed. Wiesbaden, Springer Vieweg, 2014. pp.11-47.

E. Stolk, M. Brömmelstroet, Ed., Model Town: Using Urban Simulation in New Town Planning. International New Town Institute: Sun Publishers, 2009.

B. Hillier, Ed., Space is the Machine: A Configurational Theory of Architecture. Cambridge: Cambridge University Press, 1996.

A. Turner, Ed., DepthMap4: A Researcher's Handbook. London: UCL, 2004.

S. Porta, V. Latora, E. Strano, "Networks in Urban Design. Six Years of Research in Multiple Centrality Assessment." in Network Science: Complexity in Nature and Technology, E. Estrada, M. Fox, D. J. Higham, G-L. Oppo, Eds. Springer, pp. 107–129, 2010.
S. Porta, P. Crucitti, V. Latora, "The network analysis of urban streets: a primal approach" Environment and Planning B: Planning and Design, volume 33, pp. 705- 725, DOI:10.1068/b32045, 2006.
M. Batty, Ed., The New Science of Cities. The MIT Press, 2017.
A. Sevtsuk, M. Mekonnen, "Urban Network Analysis Toolbox" in International Journal of Geomatics and Spatial Analysis, 22(2), pp.287–305, 2012.
A. Sevtsuk, "Networks of the built environment" in Decoding the City: Urbanism in the Age of Big Data, D. Ofenhuber, C. Ratti, Eds. Birkhäuser, pp. 192, 2014.
S. McElhinney (2019, Febr.). Isovists.org. Accessed on: May 3, 5054 [Online]. Available: https://isovists.org/
C.H.V Cooper, A.J.F. Chiaradia, "sDNA: 3-d spatial network analysis for GIS, CAD, Command Line & Python" SoftwareX, Volume 12, 2020 [Online]. Available: https://doi.org/10.1016/j.softx.2020.100525 . [Accessed June 5, 2024]
S. Porta, V. Latora, "Centrality and cities: multiple centrality assessment as a tool for urban analysis and design" in new Urbanism and Beyond, T. Haas, Ed. New York: Rizzoli International, pp. 140-145, 2008.
G. Dupuy, Ed., Urban Networks – Network Urbanism. Amsterdam: Techne Press, 2008.
R. Diestel, Ed., Graph Theory, 3rd ed., Berlin, New York: Springer-Verlag, 2005.
G. Sabidussi, "The centrality index of a graph" in Psychometrika, 31 (4), pp. 581–603, 1966.
L. Freeman, "A set of measures of centrality based on betweenness", Sociometry, 40 (1), pp.35–41, 1977.
Desktop GIS software: Mapping analytics: Arcgis pro (no date) Desktop GIS Software | Mapping Analytics. Available at: https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview [Accessed: 16 May 2024].
"Spatial Design Network Analysis (sDNA/sDNA+) Manual" (2012, June). Accessed on: May, 12, 2024. [Online]. Available: https://sdna-plus.readthedocs.io/en/latest/
J. Peponis, S. Bafna, Z. Zhang, "The Connectivity of Streets: Reach and Directional Distance" in Environment and Planning B: Planning and Design, 35, pp. 881-901, 2008.
J. Peponis, "Building Layouts as Cognitive Data: Purview and Purview Interface", Cognitive Critique, vol. 6., pp. 11-35, 2012
N. Dalton, "Fractional configurational analysis and a solution to the Manhattan problem", In Proceedings of the 3rd International Symposium of Space Syntax, J. Peponis, J. D. Wineman, S. Bafna, Eds. Atlanta: Institute of Technology, 26.8-9, 2001.
B. Hillier. "Spatial sustainability in cities: organic patterns and sustainable forms", in Proceedings of the 7th International Space Syntax Symposium, D. Koch, L. Marcus, J. Steen, J., Eds. Stockholm: Royal Institute of Technology (KTH), pp. k01.3-4, 2009.
N.A. Salingaros, „The laws of architecture from a physicist's perspective" in Physics Essays, 8(4), pp.638–643, 1995.
A. Ozbil, J. Peponis, B. Stone, „Understanding the link between street connectivity, land use, and pedestrian flows" in Urban Design International, 16, pp.125-141, 2011.
The World Bank (2019, January, 1). Pedestrian Mobility for Urban Growth: Walking and its Links to Transportation. Practical Guidance and Good Practice Examples. Report. Accessed on: June 5, 2024. [Online]. Available: www.worldbank.org
A. Nes, C. Y. van der Laag, C. Yamu, "Space Syntax: a method to measure urban space related to social, economic and cognitive factors" in The Virtual and the Real in Planning and UrbanDesign: Perspectives, Practices and Applications, C. Yamu, A. Poplin, O. Devisch, G. De Roo, Eds., Edition: 1 London and New York: Routledge, Taylor & Francis Group, pp. 136-151, 2018
Bureau Urbanisme (2014, December 7) "Urban Scale Sustainability Compass". Accessed on: June 10, 2024. [Online]. Available: http://sustainabilitycompass.eu
J.R. Jabareen, "Sustainable Urban Forms. Their Typologies, Models, and Concepts" in Journal of Planning Education and Research, 26, pp. 38-52 , 2006.
"Government updated action plan of 'Estonia 2035' development strategy" (2022, April). Accessed on: July 22, 2024. [Online]. Available: https://www.valitsus.ee/en/news/government-updated-action-plan-estonia-2035-development-strategy

"Tallinn wins European Green Capital 2023 award" (2021, March). Accessed on: July 22, 2024. [Online]. Available: https://news.err.ee/1608334235/tallinn-wins-european-green-capital-2023-award
"National development planning" (2023, March). Accessed on: July 22, 2024. [Online]. Available: https://www.mk.gov.lv/en/national-development-planning
"Riga: Developing a climate neutral city" (2020, October). Accessed on: July 22, 2024. [Online]. Available: https://smartcity-atelier.eu/allgemein/riga-developing-a-climate-neutral-city/
"Vilnius in implementing the Green City Accord hopes to improve quality of life for its citizens while supporting the city's climate ambition" (2022, December). Accessed on: July 22, 2024. [Online]. Available: https://environment.ec.europa.eu/news/green-city-accord-focus-vilnius-2022-12-07_en
"Vilnius adopts General Plan for the next 15 years" (2021, June). Accessed on: July 22, 2024. [Online]. Available: https://www.themayor.eu/en/a/view/vilnius-adopts-general-plan-for-the-next-15-years-8088
"Lithuania: Vilnius to improve water and wastewater infrastructure with European support" (2021, March). Accessed on: July 22, 2024. [Online]. Available: https://www.eib.org/en/press/all/2021-105-vilnius-to-improve-water-and-wastewater-infrastructure-with-european-support
L. Begley Bloom (2024, June). Ranked: The 30 Most Walkable Cities In The World, According To A New Report. Accessed on: Lyly 1, 2024. [Online]. Available:
https://www.forbes.com/sites/laurabegleybloom/2024/06/30/ranked-the-30-most-walkable-cities-in-the-world-according-to-a-new-report/?fbclid=IwY2xjawEAqexleHRuA2FlbQIxMQABHX26UiEfjP3N7Xmfoybbd1eRw86vwjILWa4YefPe4UymVS5bBqOHuBE2bA_aem_Xl6xkTIdPpXAKru-GMy6cw
European Commission (2023, Dec. 13). Report on the quality of life in European cities 2023. Accessed on: July 2, 2024. [Online]. Available: https://ec.europa.eu/regional_policy/sources/reports/qol2023/2023_quality_life_european_cities_en.pdf
Vilniaus planas (2018, December 19). Vilniaus darnaus judumo planas. Santrauka. Accessed on: July 2, 2024. [Online]. Available: https://drive.google.com/file/d/1DpFYlC5Lb8WbKJwJTKc3-GVNb_FN0P86/view
Cities Multimodal (2020, September 30). Factsheet - Riga, Latvia. Accessed on: July 2, 2024. [Online]. Available: https://www.cities-multimodal.eu/sites/cmm/files/cmm_fact_sheet_riga_nov_2018.pdf
"Tallinn Region Sustainable Urban Mobility Strategy 2035" (2019, August). Accessed on: July 2, 2024. [Online]. Available: https://www.hel.fi/static/kanslia/elo/sump-suunnitelma.pdf