

MULTIFUNCTIONALITY AND URBAN FORM: A NATURE-INSPIRED APPROACH TO SUSTAINABILITY IN LITHUANIAN CITIES AND TOWNS

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ABSTRACT

Motives: Urban form plays a crucial role in achieving sustainability, shaping accessibility, multifunctionality, and resilience within cities. However, the challenge remains in quantifying sustainable urban form in a way that captures both its spatial characteristics and its capacity to foster multifunctionality. **Aim:** This study explores the sustainability of urban form in Lithuania through a nature-inspired approach, integrating biomimicry principles with quantitative modeling and simulative mathematical graph-based analysis. The research draws from established urban theories, including New Urbanism, the compact city, the 15-minute city, identifying multifunctionality and bottom-up self-organization as fundamental characteristics of both natural and urban systems. Literature analysis highlights the growing interest in urban form and sustainability, revealing strong thematic linkages between land use, transportation, and public health. Empirical analysis is conducted at multiple scales, from the national level to individual city comparisons, employing graph-based spatial modeling to assess walkability, accessibility, and functional distribution. The methodology integrates GIS-based tools, simulative urban network modeling, and weighted centrality measures to identify urban structures that inherently support sustainability principles. Results demonstrate that Lithuanian cities exhibit

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distinct patterns of multifunctionality, influenced by their historical evolution, urban morphology, and planning paradigms. Findings reinforce the hierarchical and emergent nature of sustainable urban form, validating the concept of pervasive centrality in urban networks. Moreover, the study highlights the importance of spatial configuration over function quantity in fostering walkable, accessible, and resilient urban areas. While the proposed model successfully identifies clusters of 15-minute city neighborhoods, it also reveals limitations, including the role of large-scale infrastructure interventions and administrative boundaries in shaping urban accessibility.

Results: This research contributes to the ongoing discourse on sustainable urbanism by providing a quantitative, spatially explicit framework for evaluating urban form sustainability. It highlights the need for integrated planning approaches that balance bottom-up urban evolution with strategic policy interventions to create cities that are both sustainable and functionally diverse.

Keywords: biomimicry, GIS, multi-functionality, simulative mathematical graph-based modeling, sustainable urban form, 15-minutes city

INTRODUCTION

Sustainable urban development or sustainable urbanism focuses on theories, strategies, and practices that contribute to the long-term resilience and viability of cities (Bibri, 2020). In this research, the terms ‘sustainable’ and ‘sustainable development’ are used interchangeably. However, some scholars argue that the terms ‘sustainable development’ and ‘sustainability’ have been criticized as ambiguous and even potentially contradictory concepts (Spiliotopoulou & Roseland, 2020). We follow the perspective that sustainable urban form is intrinsically linked to the broader goals of sustainable development. To avoid well-known generalities, we begin the introduction by focusing directly on Lithuania’s urban context, supported by official statistics. Sustainable urbanism aims to design urban environments that are aesthetically distinctive, socially cohesive, and environmentally sound. Key principles include efficient land use, multifunctional territories, green areas systems, sustainable transport options, and the preservation of cultural heritage (Zaleckis & Kamičaitytė-Virbašienė, 2012). Sustainable cities are also defined by measurable attributes such as compactness, efficient resource use, optimal construction density, integration of green spaces etc. (Zaleckis & Kamičaitytė-Virbašienė, 2012).

In the context of Lithuania, the urban system is composed of the capital city, five regional centers, and numerous small and medium-sized towns. Approximately two-thirds of the population (around

1.9 million people) live in urban areas, which also serve as economic and cultural hubs generating the largest share of GDP of the country (Official Statistics Portal, 2022). As principles of sustainable development gradually influence urban planning, Lithuanian scholars have articulated goals for urban sustainability of the country. These goals emphasize healthy environment (clean air, land, and water, biodiversity, and sustainable resource use), a robust and adaptable economy, and social well-being, including affordable housing, high-quality public services, and active community participation (Steponavičienė & Juškevičius, 2000).

Achieving these goals requires a transition from abstract statements to actionable frameworks. While sustainable urbanism offers some universal principles, each city must formulate its path to sustainability according to its unique context. This diversity of approaches justifies the utility of scenario-based planning. Sustainability scenarios do not precisely predict future outcomes but instead explore potential pathways under varying conditions, such as shifts in policy or environmental constraints (Zagorskas, 2008). Lithuanian researchers have identified various sustainable city scenarios, including compact, healthy, green, ecological, smart, technological, inclusive, and productive cities (Baltrušaitis & Makrickas, 2022). Each scenario emphasizes different priorities, with some (e.g., compact cities) focusing on urban form and others emphasizing technological or social dimensions. Regardless of the chosen scenario,

researchers consistently highlight the important role of urban form in achieving sustainability (Bibri, 2020).

This recognition drives the need to identify quantitative indicators of sustainable urban form and their relationship with broader sustainability characteristics, such as multifunctionality. Previous studies (Gražulevičiūtė-Vilenišké et al., 2024; Zaleckis et al., 2024, 2025) have demonstrated that sustainable urban form exhibits parallels with natural systems and that quantitative methods, including simulative modeling, can reveal hidden characteristics of such systems in urban settings. Building on this foundation, the present research analyses the sustainability of urban form across the entire urban network of Lithuania and raises the following objectives:

- to quantitatively evaluate the sustainability of urban form across Lithuanian cities and towns using spatially explicit indicators;
- to explore how multifunctionality and bottom-up self-organization, the principles inspired by natural systems, can be identified and measured within existing urban structures;
- to develop and validate a methodological approach integrating biomimetic concepts into practical tools for assessing and enhancing urban sustainability.

This study applies quantitative modeling and indicators within a nature-inspired framework, emphasizing the connection between multifunctionality and sustainable urban form.

LITERATURE REVIEW

Specialized theories and models related to sustainability of urban form

Sustainability has emerged as a benchmark for evaluating urban solutions, playing a fundamental role in assessing the built environment (White & Ellis, 2007). As urban development increasingly prioritizes sustainability, it becomes essential to identify quantitative and tangible characteristics and indicators that reflect the sustainability of urban form. These characteristics are critical for developing measurable frameworks to assess and guide urban

sustainability. Numerous researchers have explored the characteristics of sustainable urban form, contributing to a growing body of knowledge on the topic (Arundel & Ronald, 2017; Coppola et al., 2014; Jabareen, 2006; Jones and MacDonald, 2004; Lewin, 2012; Qureshi, 2024; Sassi, 2006; Usman & Abdullah, 2018). For instance, Sassi (2006) highlights compact living, mixed land uses, public transport-oriented designs, pedestrian-friendly streets, well-defined public spaces, the integration of nature into urban development, and designs based on walking and cycling distances as key characteristics of sustainable urban form. Similarly, Jones and MacDonald (2004) emphasize the significance of mixed land uses, density, transport infrastructure, and the physical layout of the built environment in fostering sustainability. However, these characteristics are frequently linked to specific models or theories of sustainable urbanism, such as New Urbanism, the compact city, and the 15-minute city.

New Urbanism. New urbanism emerged in the late 1980s and early 1990s as a reaction to suburban sprawl in North America, framing itself as a pathway toward sustainable, walkable, and human-centered urban environments (White & Ellis, 2007). It promotes core principles: compact, mixed-use neighborhoods; transit-oriented and infill development; pedestrian- and cyclist-friendly streets; and well-designed public spaces and civic buildings that reflect regional character (Ellis, 2002; White & Ellis, 2007). These principles strongly intersect with sustainability goals by reducing car dependence and fostering cohesive urban communities (Boutreux et al., 2024). Recent studies reinforce the relevance of these ideas: a 2025 review highlights the ongoing potential of New Urbanism to shape sustainable, vibrant, and equitable urban spaces (Jones, 2025). Thus, New Urbanism continues to provide a valuable lens for understanding and modeling sustainable urban form in the 21st century.

Compact city. Gaining prominence in the 1990s, particularly in European urban policy, the compact city is widely recognized as a central approach to sustainable urbanism (Bibri, 2020). Although lacking

a universally accepted definition, it is typically described as a high-density, mixed-use urban form that promotes efficient public transport and active mobility, while minimizing urban sprawl, energy use, and pollution (Bibri, 2020; Gutiérrez and De la Plaza Hidalgo, 2019). Jabareen (2006) outlines its core features as compactness, density, diversity, and sustainable transport. Baltrušaitis and Makrickas (2022) further emphasize efficient spatial structure, quality public spaces, and infrastructure regeneration. The compact city model supports the effective use of urban infrastructure, reduces commuting, mitigates congestion, and preserves agricultural land (Šaparauskas, 2004). According to Kotharkar et al. (2012), it promotes accessibility, spatial identity, and the revitalization of underused urban areas. More recent literature highlights challenges associated with compact cities, such as socio-spatial inequalities and affordability issues, indicating that compact urban forms require careful planning to ensure equitable outcomes (Mouratidis, 2019).

15-minute city. The COVID-19 pandemic revealed the need to rethink urban life, accelerating interest in the 15-minute city concept, introduced by Moreno (2024). As a form of chrono-urbanism, it aligns with goals of smart, inclusive, and resilient cities, consistent with the UN Sustainable Development Goal 11 (Moreno et al., 2021; Transforming..., 2015). The model emphasizes access to daily needs within walking or cycling distance, supported by four key dimensions: density, proximity, diversity, and digitalization (Moreno et al., 2021). Capasso Da Silva et al. (2020) propose a similar 20-minute city, prioritizing accessibility over transportation planning. The 15-minute city also echoes Perry's (1929) neighborhood unit, which aimed to foster community through proximity to services. While the model encourages decentralized, polycentric urbanism, it also recognizes the ongoing value of central hubs for cultural, educational, and specialized experiences.

General theories applicable in the context of urban form sustainability

Lessons from cities worldwide provide valuable insights into achieving sustainable urban forms, yet it is widely acknowledged that there can be no universal set of rigid strategic guidelines applicable everywhere. The attainment of sustainability is context-dependent, shaped by complex, interwoven factors that must align with local conditions and circumstances (Bibri, 2020). The analysis of literature has demonstrated that multifunctionality emerges as a recurring theme across various approaches to sustainable urbanism, such as New Urbanism, the compact city, the 15-minute city. It is possible to note that multifunctionality is a fundamental characteristic of natural systems as well. Besides multifunctionality, self-organization and particularly bottom-up self-organization, emerge as other fundamental characteristics of natural systems that can inform sustainable urban form. This principle is well reflected in urban theories such as New Urbanism and the 15-minute city, which emphasize decentralized, community-driven development, adaptable public spaces, and locally embedded urban structures that evolve in response to the needs of users. These and other similarities between urban and natural systems has led to growing interest in applying biomimicry to urban environments as a strategy for achieving sustainability. Some biomimicry-driven approaches to design and planning advocate for drawing direct inspiration from natural systems to inform urban design and development (Amanda et al., 2025; Dicks et al., 2021). However, it is also hypothesized that the principles and characteristics of natural systems, such as form fits function, fostering cooperation, contextual responsiveness, continuity, diversity, integrity, self-organization, redundancy, decentralization, multifunctionality, energy efficiency, hierarchy, and fractality, often discussed within the biomimicry literature (Zaleckis et al., 2024), might not require direct emulation of natural forms in the built environments. Instead, these attributes could be inherently present in certain

urban forms, including historic urban structures, or could be achieved through urban planning and design processes without directly replicating features of natural environments. Such urban forms support dynamic, inclusive, and adaptable spaces where people can engage in various activities while efficiently navigating the city, contributing to both localized quality of life and broader urban connectivity. For example, a multifunctional and self-organized urban environment not only enhances resilience and sustainability but also benefits both local residents and transit users by ensuring accessibility to essential services, fostering diverse and vibrant neighborhoods, and promoting seamless mobility (Mirza & Jain, 2025).

Considering these insights from literature, biomimetic principles will be further operationalized in this research through quantitative modeling of multifunctionality and bottom-up self-organization, key attributes observed in natural systems. Specifically, these characteristics will be translated into measurable spatial indicators, allowing the identification and assessment of inherent biomimetic properties within existing Lithuanian urban structures.

MATERIALS AND METHODS

Based on the literature review, the 15-minute city could be seen as quite a simple yet functional urban concept that is focused on the identification of the urban “cells” while supporting walkability, multifunctionality, compactness, social interactions, resilience, decentralization, and self-sufficiency. From one side, the concept is clear enough to give a background for searching for quantitative indicators such as service areas or quantity of reachable while walking or cycling destinations; from another side, the 15-minute city model could be seen as the version of the New Urbanism neighborhood, walkable city, etc. The first problem that could be pointed out and the weaknesses of the model is related to its inability to address higher hierarchies of urban structures as only local – 15-minute distances are considered. The second problem is related to the fact that even the same number of reachable objects or functions

within the same distance does not mean that the two situations are equal in terms of multifunctionality and other aspects of the 15-minute city concept.

The first problem, at least at a theoretical level, preliminary, could be addressed based on such principles of biomimetics as the following:

1. Urban system is made out of cells.
2. Connections of cells form a network of interactions.

Those interactions via a network create a background for bottom-up self-organization, which, in turn, makes a background for the appearance of structures of the higher hierarchical level. In terms of biomimicry, it could be said that local interaction inside cells and between neighboring cells creates global patterns.

As it was mentioned earlier, the 15-minute city could be seen as an urban analogy of cells in biomimicry. The question is how can we reflect bottom-up self-organization in urban networks? First of all, we can refer to some ideas by Hillier regarding mathematical symmetry as a specific type of direct connection between two spaces where both of them are equally accessible from each other (Hillier & Hanson, 1984). According to him, symmetrical spaces share or bring people, activities, and functions together while asymmetric – separate them. A simple example of symmetrical urban spaces is two intersecting streets where people can move easily from one to another and back. Of course – symmetry is possible only between neighboring cells so, if connections between all pairs of cells in the urban network are analyzed, then, there is a small number of symmetrical connections and a big number of asymmetrical connections. While reacting to that, Hillier has introduced the concept of Depth describing it in the following way: “Depth exists wherever it is necessary to go through intervening spaces to get from one space to another” (Hillier & Hanson, 1984). If cells have a bigger depth or in other words – are located more far away from the other cells in the network, then they are potentially more segregated and mono-functional. Thus, symmetrical relations between cells define its local functionality while depth – its accessibility and positioning in the higher

hierarchical functional levels of urban structure. What could be the interrelations between the symmetry and the depth? If a single street segment is seen as a cell or node of a cell then its symmetry could be defined as the number of connections with neighboring streets – more intersections, more possibilities for functional interaction and symmetry. The observed higher densities of the street network in the city center, especially if organically developed urban structures are considered, allow us to assume that such cells or streets with high symmetry degrees form clusters and, in this way, form urban centers of higher hierarchical levels. Of course, such a hypothesis addresses just bottom-up, organic development of urban structures and does not refer to possible top-down restrictions or limitations created by the master plans of a whole city or region, but it suits the needs of the presented research and investigates important layer of urban structures created in a bottom-up way based on local interaction.

How can we model and analyze such bottom-up interactions and processes in a city influenced by its spatial configuration? Batty in his famous book “The New Science for Cities” offers one possible solution: “Cities can be understood as systems of flows, and networks are their skeleton. Graph theory provides the essential framework for representing these flows and for analyzing the structure and function of urban space” (Batty, 2013, p. 78). In the presented research we employ a simulative, mathematical graph-based model while looking at a city as a network of streets and simulating the behavior of people (e.g.: movement, the concentration of transit, the most accessible spaces, etc.). Various similar models are used for this purpose as Space Syntax by Hillier (Turner, 2004), Urban Network Analysis Toolbox (Turner, 2004), Decoding Spaces (Decoding, 2025), Urbano (Dogan et al., 2020). For the presented research the Spatial Design Network Analysis Tool (sDNA) by Cardiff University was chosen because of the good integration with ArcGIS Pro (Cooper, 2024), the wide variety of indicators to experiment with, and the flexible possibilities to add weights to the calculations as it will be explained later.

The Spatial Design Network Analysis (sDNA) model is grounded in mathematical graph theory, where urban street networks are represented as graphs composed of nodes (intersections) and links (street segments). As Diestel (2017) states, “A graph is a mathematical abstraction used to model pairwise relations between objects” (p. 1), making it an ideal structure for analyzing spatial networks in urban systems.

According to the chosen sDNA model, the central line of each street between intersections or intersections and dead ends is seen as a link, while intersections – are referred to as nodes in the mathematical graph terminology. Each link corresponds to the so-called Face-Block as the informal, smallest form of neighborhood according to the ideas of New Urbanism (American Planning Association, 2006). Each link could be weighted e.g.: by the reachable area of buildings or certain functions. The link was seen as a node of the urban cell while its service area from which it is reachable within 15 minutes of 1000 m distances as its permeable membrane. In such a case service areas or permeable membranes overlap with each other allowing us to evaluate possible interaction between the links not only based on connections with the intersecting streets but on wider zones. These membranes embody the concept of porosity, one of the five essential qualities of Integral Urbanism, alongside hybridity, connectivity, authenticity, and vulnerability. This framework advocates for nature-based approaches to urban development, reimagining cities as dynamic ecosystems. Porosity establishes fluid, overlapping boundaries that facilitate continuous interactions, which are crucial for nurturing resilient, vibrant, and authentic urban environments. Nonetheless, these membranes safeguard the intrinsic identity of each urban cell, ensuring that permeability does not completely dissolve the distinct boundaries (Ellin, 2006). In order to check the model in different situations territory of the whole of Lithuania was chosen as the investigated area.

Traditional applications of sDNA focus on calculating centrality indicators such as betweenness, close-

ness, and gravity, using metric, angular, or topological distances to model accessibility and predict human movement. For example, sDNA has been used to assess walkability in Cardiff (Cooper & Chiaradia, 2015), simulate pedestrian flows in historic environments (Thompson et al., 2019), and explore the relationship between network integration and land values (Ellis et al., 2017). The authors of this research used the traditional sDNA model for comparison of Vilnius, Riga, and Tallinn in terms of multi-functionality (Zaleckis et al., 2024). The initial idea of the presented research was to use the indicator of so-called gravity centrality or Network Quantity Penalized by Distance (NQPD) in sDNA – an index which in essence is calculated as the ratio between the density of the street around the calculated link and the sum of distances from it to the rest of the reachable links within radius 1000 m. The higher values of NQPD show clusters of more dense and well-reachable street networks within the radius. After the initial testing, it was discovered that in the territory of the whole of Lithuania, this indicator, despite not bad correlations with inhabitant density or concentrations of urban functions reflected by the points of interest (POIS) from the Open Street Map (OSM), has certain limitations: it is not working well in city centers affected by transformations of modernistic soviet urbanism such as orientation to automobile traffic, cancellations of private land property and destruction of borders of land plots in historical urban parts; NQPD could reach high values in not urbanized areas where few links meet, etc.

While reacting to the above-mentioned limitations of the “traditional” gravity indicator and, in contrast to these approaches, the presented study shifts the focus from pure network of graph based centrality to the geometric configuration of the network-covered area within a defined radius. Instead of calculating centrality purely through graph connectivity, we analyze the spatial morphology of areas reachable within 1000 m, using a custom indicator (it was called “accessibility” and is explained beneath) that captures accessibility as a geometric and functional expression of urban form of street network. This spatial-envelope-based approach reflects not only street layout but

also functional synergy between built form and open space. It provides a complementary lens to graph-based centralities and is especially useful in evaluating multifunctionality across diverse urban morphologies, including fragmented and irregular areas where topological centrality alone may be insufficient. It is also essential to acknowledge methodological limitations related to administrative boundaries, which can artificially divide functional urban areas and create edge effects in spatial analyses (Tao et al., 2018). Future research should consider refining models through more granular data collection, exploring detailed building-level data, and validating the proposed methodology across various geographic and cultural contexts to enhance its applicability and generalizability. The proposes an alternative accessibility indicator that is not so sensitive to the density of the street network. The so-called hull area or area of the polygon of territory covered by the street network within a radius of 1000 m, squared and divided by hull perimeter, was used instead of NQPD. As a result, a bigger value shows more evenly in all directions, spreading, well-connected service area of the calculated link or street segment. Division by perimeter controls for elongated or fragmented areas, which may be less efficient in terms of accessibility. The squaring hull area emphasizes large polygon areas, making the metric more sensitive to reachability. In addition, the new “accessibility” measure was combined with a weight of buildings and different functions thus reflecting complex interactions between open urban spaces and buildings. The final formula is the following:

$$\text{Accessibility} = \sqrt{HA^2 / HP \cdot w} \quad (1)$$

where:

HA marks a polygon area covered by the street network within a radius 1000 m from the calculated link; *HP* means the perimeter of the polygon; *W* – built-up area or area of functional zones reachable within selected radiuses from the calculated link as it will be explained later.

The calculation of geometric mean was selected as less sensitive to differences of scales between the combined indicators and reflections of either positive or negative synergies between them because of multiplication. Possibility of such approach in essence is supported in discussing the interplay between spatial form and resilience by Marcus and Colding (2014), where they observe that the axial map, a fundamental construct in spatial network modeling, “constitutes a network... in which different properties of this network are possible to measure, including closeness or integration centrality”. This insight supports our methodological shift: rather than focusing solely on graph centralities, our study prioritizes the geometric morphology of areas reachable from each street segment, using the HA²/HP indicator to capture how space configuration itself contributes to multifunctionality and resilience.

The theoretical novelty of the presented model lies in its integration of spatial network analysis with biomimetic and Integral Urbanism principles, enabling a biologically inspired understanding of urban multifunctionality. In contrast to conventional models that evaluate accessibility through geometric or topological metrics alone, the proposed model conceptualizes the urban structure as a network of interrelated “cells,” each with porous membranes allowing multi-scalar interactions. This framing reflects bottom-up urban

processes such as self-organization and the emergence of hierarchical spatial patterns within urban networks.

Within the context of the sDNA model, a key methodological innovation is the introduction of the HA²/HP (Hull Area Squared / Hull Perimeter) indicator as an alternative to traditional gravity-based metrics such as Network Quantity Penalized by Distance (NQPD). While gravity models often overemphasize street density, the proposed HA²/HP indicator captures the geometric efficiency and directional balance of the service area surrounding each street segment. Squaring the area emphasizes broad, well-connected reachability, while dividing by perimeter penalizes irregular or elongated configurations. This makes the metric more robust in identifying functionally coherent and spatially integrated urban cells, particularly in contexts where traditional indicators fail, such as fragmented historic centers or peripheries shaped by modernist planning. Its novelty lies in treating accessibility not merely as a function of proximity or quantity, but as a morphological expression of spatial synergy.

Before the final simulation, the initial model was validated while checking if it reflected real urban processes. For this purpose, correlations between Accessibility initially weighted by the area of building polygons reachable within a radius of 400 as the size of the urban block and various data on the functioning of the investigated territory were calculated (Table 1).

Table 1. Spearman’s rho between Accessibility and data on the functioning of the urban network as the density of POIS, the density of companies based on data of national register, inhabitant density, etc.

	POIS* density r200	POIS* density r400	Population density in 1 km grid	Density of compa- nies r200	Density of companies r400	Reachable areas of urban blocks r400	Reachable areas of urban blocks r200	The reachable number of inhabitants in urban areas r400	The reachable number of inhabitants in urban areas r200
Accessibility weighted by the sum of area of building poly- gons reachable within r400	.419**	.540**	.818**	.611**	.696**	.936**	.853**	.885**	.789**

* Points of Interest (POIS) – geolocated objects representing functional urban destinations (e.g., retail, services, public institutions, leisure facilities) extracted from OpenStreetMap (OSM) data.

** All marked correlations are significant at 0.01 level.

Source: own elaboration.

As we can see in Table 1, weight accessibility in the territory of Lithuania demonstrates moderate, strong, and very strong positive correlations with POIS density, the density of companies, and inhabitants density. Correlations with the reachable area of urban blocks are extremely strong, but should not be considered as the important argument as weighting (sum of the area of building polygons within $r400$) and area of urban blocks should be seen as interrelated. On the other hand, if this correlation would be weaker, then it would mean that the model is not working correctly. While generalizing, based on statistical analysis, it could be stated that the proposed model is working well and could be developed further.

While investigating different accessible functions within 1000 m of every street segment, it was decided to evaluate the accessibility of the following: commercial function (e.g. shops); public function (e.g. schools); density of buildings as, based on some research it correlates with attractiveness of streets for walking (World bank report, etc.); accessible green area; accessible area of water bodies; accessible inhabitant density. The accessible green areas were identified based on the following data: Corina land cover data on the year 2021 with 10 m resolution – needle leaved trees and broadleaved deciduous trees cover was used (Copernicus Land Monitoring Service, 2021); information on functions of land plots from State Enterprise Centre of Registers.

During the next step of the development of the model, the following radiuses and procedures for calculations of weights were made:

1. The first weight represents urban density. As the investigation is focused on the 15-minute city concept and walkability, then only buildings supporting street culture were used in weight calculations: living houses, and commercial and public objects. The final weight was represented by the geometrical mean between the sum of the area of building polygons within radii 30 and 400 m from each calculated link. 30 m were considered as distance representing information about a street façade while 400 m representing information about an urban block behind the façade.

2. The weight of the commercial objects was calculated as the sum of the area of commercial building polygons within radii 50 m. 50 m were chosen as the most accurate working distance in the case of Lithuanian cities where some commercial objects have big parking lots in front of them.
3. The weight of the public objects was calculated as the sum of the area of public building polygons within radii 100 m. 100 m were chosen as the most accurate working distance in the case of Lithuanian cities where a big part of public objects such as schools or kindergartens have big land plots.
4. The weight of water bodies was calculated as the reachable area from the street central line within 100 m. Such distance was chosen as potentially meaningful for the perception of a water body as the active element of a visual field.
5. The weight of greenery was calculated similarly to the weight of urban density by calculating the geometric mean between the area of greenery reachable from the street line within radii 50 and 150 m. 50 m here represent the green façade of the street perceivable in detail while 150 m show the background of the facade thus expressing the difference between just lines of trees and bigger green bodies. Both weights of greenery and water bodies could be considered as an important factors while assuring subjective thermal comfort according to Johansson and Yahia (2011).
6. The weight of inhabitants was calculated as a sum of the number of inhabitants of housing based on Construction Sector Development Agency (Statybu sektoriaus vystymo agentūra (SSVA) in Lithuanian) data within radii 20 m. Such distance was chosen in order to avoid the assignment of inhabitant weight to two-level and circular intercessions of car-oriented streets and proved to be working quite well.

The use of empirically based radii for calculating the weights, accounting for the functional logic of different land plots (e.g., large parking areas for commercial zones or open spaces adjacent to schools), further increases the model's precision and should be named as novelty within sDNA model context.

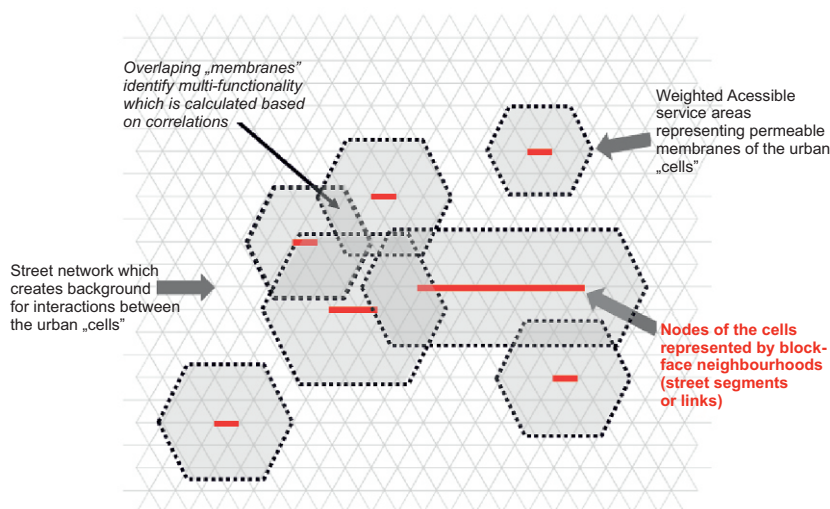


Fig. 1. Scheme representing the idea of the proposed multifunctionality analysis
Source: own elaboration.

The second weaknesses of the 15-minute city model, namely the need to evaluate allocation and relation between different functions and not just plain numbers, were addressed by calculating correlations between weighted accessibilities. In such a case, stronger correlations mean that different functions are better accessible between themselves. Correlations were calculated within formal boundaries of cities in Lithuania with neighboring administrative units with higher density of buildings that function as suburbs, added. The results of the modeling were analyzed and classified while using various scatterplots as it will be shown in the result section.

Tools used in modelling: ArcGIS Pro (ESRI, 2025), sDNA plugging (Cooper, 2015), IBM SPSS (IBM, 2019), Excel.

Data used:

1. Street network at the scale 1:10000 of Lithuania from geoportal.lt (open data).
2. Polygons of buildings of Lithuania from geoportal.lt (open data).

3. Data of land plots of Lithuania with functions received from SSSA specifically for this research.
4. Data on water bodies of Lithuania from geoportal.lt (open data).
5. Data on land cover from the Copernicus web site (open data).
6. Data on population density (SSVA, 2024).

It was expected that the proposed and described methodology would allow evaluation of the multifunctionality of urban areas from the perspective of pedestrians and would support the 15-minute city model with the exact quantitative indicators. As well, it was also intended to check if the modelled bottom-up interaction of urban cells corresponds not only to the present situation of local neighborhoods, but if it allows the identification of urban centers of higher hierarchical importance.

The biomimicry-based idea is graphically summarized in Fig. 1, and the main steps of the whole methodology in Fig. 2.

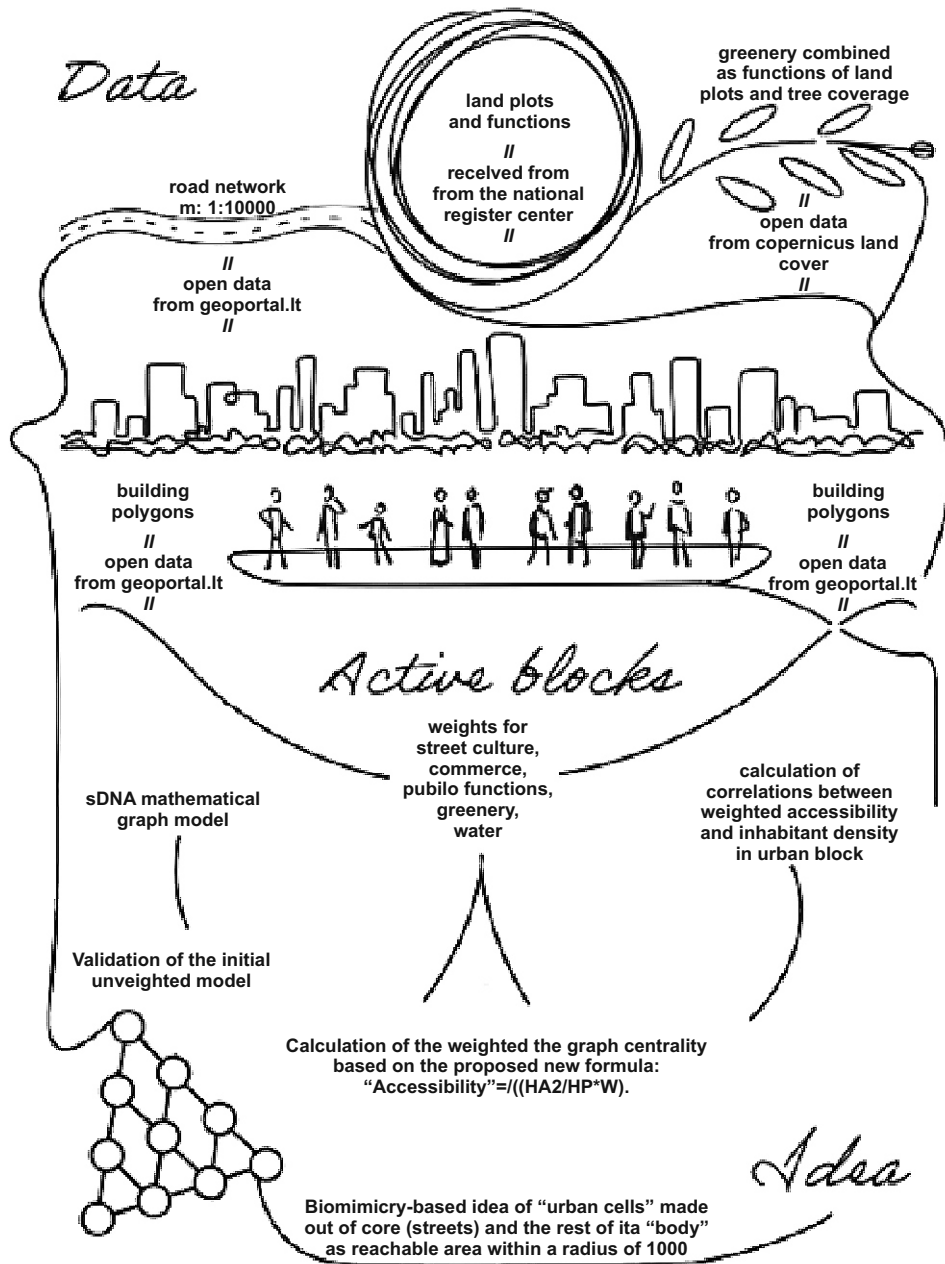


Fig. 2. Scheme representing the main steps of the research methodology
Source: own elaboration.

RESULTS

The presented research produced the results which could be analyzed at various levels:

1. The whole of Lithuania with a focus on the observed clusterization of both high and low values of weighted graph centralities or “accessibility”. The main question of interest in this case is if the modeling results reflect differentiation between urban and suburban areas. The results will be analyzed based on the visualizations and statistical analysis. They are important for the evaluation of the model in the country or region as positive results will allow us to conclude if the proposed bottom-up simulative model can identify clusters of 15-minute city neighborhoods or “urban cells” at the higher hierarchical level of urban structures, e.g.: as a whole city.
2. The individual city comparison will allow us to check the sensitivity of the model at more precise scales. As there are 103 cities in Lithuania and comparison one by one is more suitable for a book or study than an article with size limitation, the comparison will be conducted and presented in the following way:
 - a. individual comparison based on visualization and statistical analysis of the three biggest cities of Lithuania: Vilnius as its capital and the biggest city which represents a more or less concentric model of a city; Klaipeda – harbor city with the most linear spatial structure stretched along the Baltic shore; Kaunas – the second biggest

city of Lithuania with quite clearly expressed sectoral geographical model;

- b. statistical analysis of all cities with the 20 biggest ones pointed out based on statistical analysis.

The results obtained at the national level

First of all, the correlations between weighted calculated centralities of the graph and data on the functioning of urban structures were analyzed. The following data was used: density of pois within a distance of 400 m; density of “urban” pois which are expected to be found mainly in an urban structures which were identified by eliminating such objects as camping sites, mounds, ruins, etc. within a distance of 400 m; population density in 1x1 km grid; density of companies based on addresses from national register agency within a distance of 400 m; density in urban blocks identified in SSSA data within the distance of 400 m; total accessible area of urban blocks identified in SSSA data within the distance of 400.

As we can see in Tables 2 and 3, both Pearson correlation and Spearman’s rho gave quite similar results. Correlations vary from moderate with “urban” pois to strong with population density and the total area of reachable urban blocks. Weaker are correlations with “accessibility” weighted by commercial and public buildings and stronger if weights of all buildings and buildings supporting street culture are used. In essence, it could be concluded that the model is working quite well. If the results of validation are compared with preliminary validation (Table 1)

Table 2. Pearson correlation between weighted graph centralities and the data on the functioning of urban structures

	“urban” pois r400	pois r400	Population density within 1 km grid	Companies r400	Population density in urban block r400	The total area of urban blocks r400
HA2P Weight of buildings supporting street culture	.405*	.406*	.395*	.428*	.366*	.588*
HA2P Weight of public buildings	.464*	.459*	.352*	.460*	.352*	.345*
HA2P Weight of commercial buildings	.428*	.418*	.354*	.493*	.345*	.369*
HA2P All Buildings weight	.421*	.419*	.428*	.459*	.406*	.635*

* 0.01 level of significance of the correlations.

Source: own elaboration.

Table 3. Spearman’s rho between weighted graph centralities and the data on the functioning of urban structures

	“urban” pois r400	pois r400	Population density within a 1 km grid	Companies r400	Population density in urban block r400	The total area of urban blocks r400
HA2P Weight of buildings supporting street culture	.330*	.333*	.538*	.450*	.575*	.567*
HA2P Weight of public buildings	.408*	.362*	.312*	.375*	.328*	.317*
HA2P*weight of commercial buildings	.375*	.325*	.289*	.378*	.298*	.315*
HA2P All Buildings weight	.347*	.362*	.558*	.483*	.595*	.615*

* 0.01 level of significance of the correlations.

Source: own elaboration.

some of the correlations are weaker. Such change might explained in the following way: weighting in the preliminary validation (Table 1) was made simply by taking a sum of the area covered by buildings within a distance of 400 m from each street link while in the final model, it is done in different ways for different types of buildings: with smaller radiuses for commercial (50 m) and public (100 m) objects; calculating a geometrical mean between buildings reachable within 30 m and 400 m distance for both all buildings and buildings supporting street culture. In the first two cases, the resolution of the weighting was made more precise thus potentially affecting the strength of the correlations. In the third and the fourth cases, the geometrical mean focused more precisely on the identification of zones where the density of buildings is higher within 400 m distance and the density of the street perimeter is higher at the same time – it increased the precision of the model. In this case, weaker correlations reflect the potential results of soviet urbanization based on modernistic planning where streets lost their social-cultural functions and were transformed into monofunctional, car-oriented zones. It is important to note, in this case, that the proposed model addresses just bottom-up, generative, the most important for implementation of the 15-minutes city concept processes of urbanization. Besides it, the top-down generated processes exist, e.g. based on large infrastructural development, regional or state level planning, etc. In such a case, very strong correlations would possibly mean dominance of bottom-up processes in Lithuania and it is far away

from the truth because of the long period of soviet urbanization and focus of various municipal and regional master plans just on certain, the most important aspects of spatial planning. Based on the above presented considerations it is possible to agree that the found correlations validate the presented model successfully based on the presented statistical analysis results.

If visualized data of the research results is analyzed (Fig. 2), the following patterns could be observed:

1. In essence all weighted graph centralities (Centrality weighted by the weight of buildings supporting street culture presented in Fig. 2), if visualized while using the Jenks Natural Breaks method which optimally groups values into seven distinct categories to minimize variance within classes and maximize differences between them. This approach helps reveal natural patterns of calculated centralities. The classification provides a clear differentiation between urban and rural regions with bigger clusters representing big cities and smaller clusters – smaller towns. Clusters with high values of calculated centralities overlap with areas of cities shown in Fig. 4.
2. To statistically validate spatial patterns, a Getis-Ord Gi hot spot analysis was performed using a 3-meter fixed distance band. Such a distance considers only immediate neighboring street segments, revealing micro-scale clustering in street networks and local accessibility variations. This approach highlights fine-grained urban structure effects, such as pedestrian-friendly streets

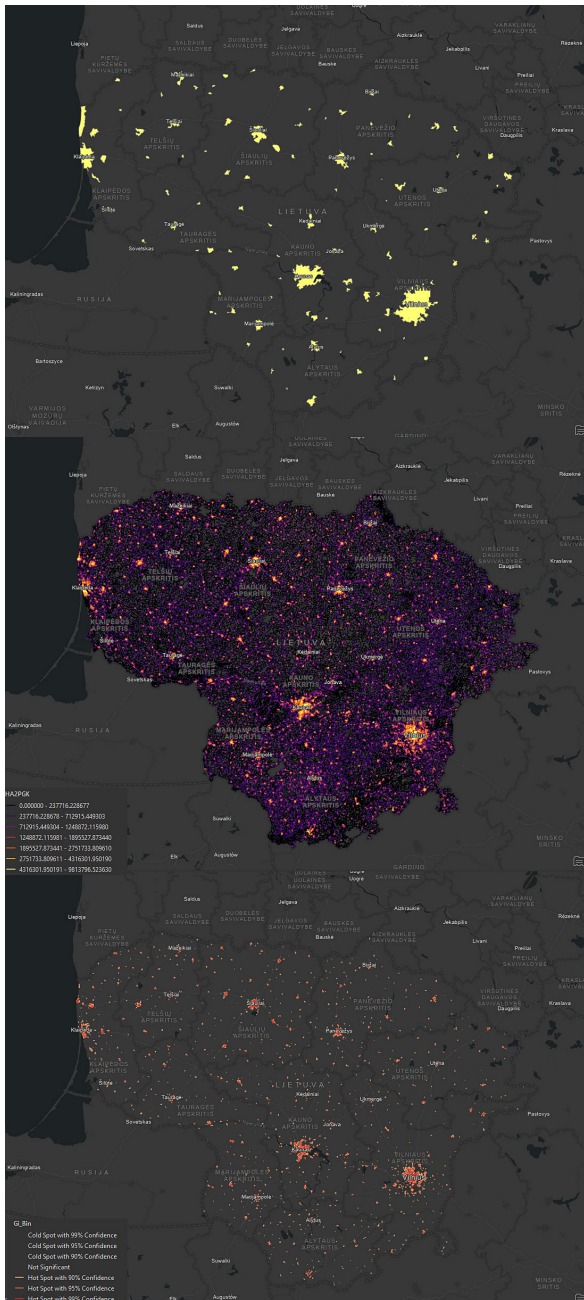


Fig. 3. Some of the results of modeling compared with boundaries of urban areas. From the top to bottom: polygons of urban areas in Lithuania (marked in yellow) (top); “Accessibility” weighted by area of the buildings supporting street culture visualized based on Natural Breaks (middle); a Getis-Ord Gi hot spot analysis (bottom, visualized just hot spots)

Source: own elaboration.

or commercial corridors. Areas with statistically significant high values (hot spots) and low values (cold spots) indicate zones with systematic concentration or deprivation of accessibility and density. As can be seen in Fig. 3, the location of the hot spots coincides with the allocation of high-value clusters based on Natural Breaks visualization and boundaries of cities. These findings complement the natural breaks classification, ensuring that observed patterns are not just visual artifacts but statistically meaningful clusters.

The comparison of the 21 cities

From 103 cities available in Lithuania, 21 cities were selected for more detailed analysis and representation in this text considering size, regional distribution, economic roles, and urban character. In terms of size and regional representation Vilnius, Kaunas, Klaipėda, Šiauliai, Panevėžys area representing different regions and serving as regional economic and cultural centers. Medium-sized towns such as Alytus, Marijampolė, Mažeikiai, Telšiai, Utena provide a cross-section of urban development beyond the main metropolitan areas. Smaller towns such as Plungė, Raseiniai, Ukmergė, Birštonas reflect local dynamics and smaller-scale multifunctionality. In terms of functional specialization and diversity, Kaunas, Klaipėda, Panevėžys, Šiauliai, Mažeikiai could be seen as industrial and economic hubs with strong economic bases, logistics and industry. Palanga, Druskininkai, Birštonas, and Trakai represent tourist and resort towns, accordingly specialized in seaside tourism (Palanga), spa tourism (Druskininkai, Birštonas) and historical and tourism-driven functioning (Trakai). There are two towns planned according to the principles of modernistic urbanism: Elektrėnai (Soviet-era energy town) and Visaginas (nuclear power plant legacy). Kėdainiai, Telšiai and as well Trakai could be seen as heritage and culture-focused urban fabrics. It does not mean that those dimensions are not present in the other cities as Vilnius, Kaunas or Klaipėda, but here they could be seen as a kind of dominant asset or landmark in urban functioning.

In terms of urban morphology some cities have more radial, organically grown structures (Vilnius, Kėdainiai), while others follow grid-like or planned layouts (Panevėžys, Elektrėnai, Visaginas), etc.

Comparison of multifunctionality of the cities was conducted while calculating correlations between weighted centrality measures as described in the Methodology chapter. Correlations were calculated within all urban areas and each selected city thus presenting an average multifunctionality value for the 15-minutes city urban “cells” in all Lithuanian cities and each investigated city. Mean values of the all cities were selected as kind of benchmark values during the comparison.

Is it enough to provide a multifunctionality index based on correlations for urban planners? In our opinion the amount of evaluated functions which in the presented investigation is represented by weights, is important as well. E.g.: if even a small park is located in a very central position in a city then, despite its small size correlations with the other functions might be strong and the opposite – if even a big amount of green areas is located in the periphery of a city then correlations with the other functions

will be weak or even negative. On the other side, information on both correlations and weights allow to identify problems of a precise urban system more clearly, e.g.: weak correlation and big weight means that connectivity of the weighted areas should be increased via creation of new pedestrian links, etc.; relatively strong correlation and small weight calls for increase of quantity of weighted features, etc.; if both indexes are weak then we have a situation which should be improved in both ways; if both correlations and weights have big values then we have a kind of standard situation from the perspective of the presented research, etc. Weights and correlations can be compared in pairs, e.g.: weight of green areas and correlation between green areas and population density. As we have 5 centralities plus inhabitant density as an important indicator in the research then it produces 30 weight-correlation pairs for analysis and representation. For the present article just those which were the most interesting and actual in the context of Lithuanian urban development are presented and discussed further. The idea of the scatterplot for visualization of the weight-correlation pairs is presented in Fig. 4.

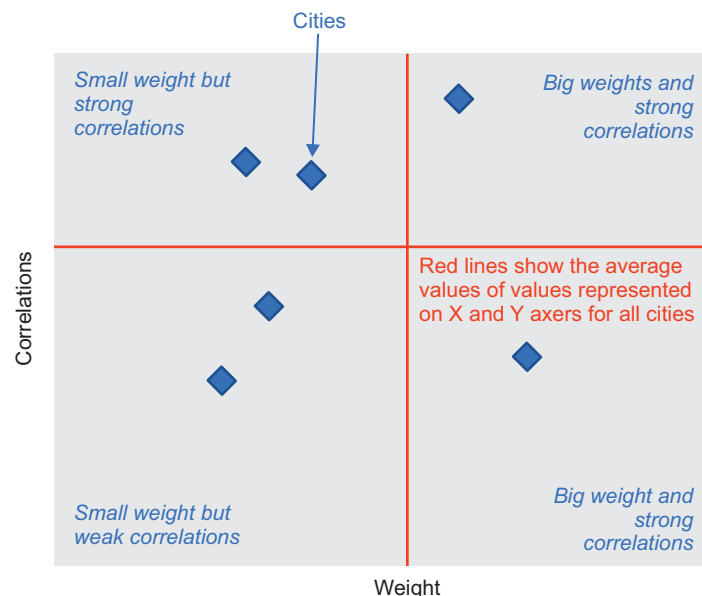


Fig. 4. The principal scheme of the scatterplot for analysis of relations between weights and correlations

Source: own elaboration.

If it is analyzed how higher densities of inhabitants overlap with easy reachable by walking higher densities of buildings that support street culture (Fig. 5), the following tendencies could be observed:

1. The general trend line shows that, reachable by walking from the living places, the density of buildings that support, at least potentially, street culture, is decreasing with the increased inhabitant density. It might mean a few things: better overlapping of both indicators could be expected in small towns which despite the smaller number of population reachable within 1 km, still demonstrate a more functionally homogenous morphological and less segregated functionally structure; change of correlation reflects concentrations of the biggest part of inhabitants in the modernistic housing areas with streets transformed into monofunctional transport corridors in bigger cities.
2. The average value of the correlation is close to 0.6. It means that in general the situation is not so bad and even modernistic urbanizations in big cities were not able to depopulate zones of traditional urban fabric with placement of buildings close to a street totally. It could be illustrated by the cluster of 5 from the ten biggest Lithuanian cities

in Fig. 5 which demonstrate correlations above 0.5: Vilnius, Kaunas, Šiauliai, Mažeikiai, Jonava. Alytus and Panevėžys are in a little distant position from the cluster of five, but still demonstrating not bad correlations and keeping positions above the trend line. It should be remembered here that the correlations were calculated for a whole area of a city based on its formal administrative boundaries with some suburban areas added. In such a situation suburban sprawl areas which exist in the majority of big cities in Lithuania affected the results and even stronger correlations should be expected in central, historical zones of the cities. Quite a large number of towns demonstrate even stronger correlation between allocation of inhabitants and well reachable urban fabric: Raseiniai, Ukmergė, Telšiai, Marijampolė, Plungė, Palanga, Trakai, Bištonas. Such a result could be explained by combinations of more compact urban forms and smaller functional zones of those towns. The “worst” situation is in three cities: Druskininkai, Elektrėnai and Utena. Druskininkai represents the resort town with scattered urban fabric between green areas. Elektrėnai is a typical modernistic Soviet city with buildings scattered

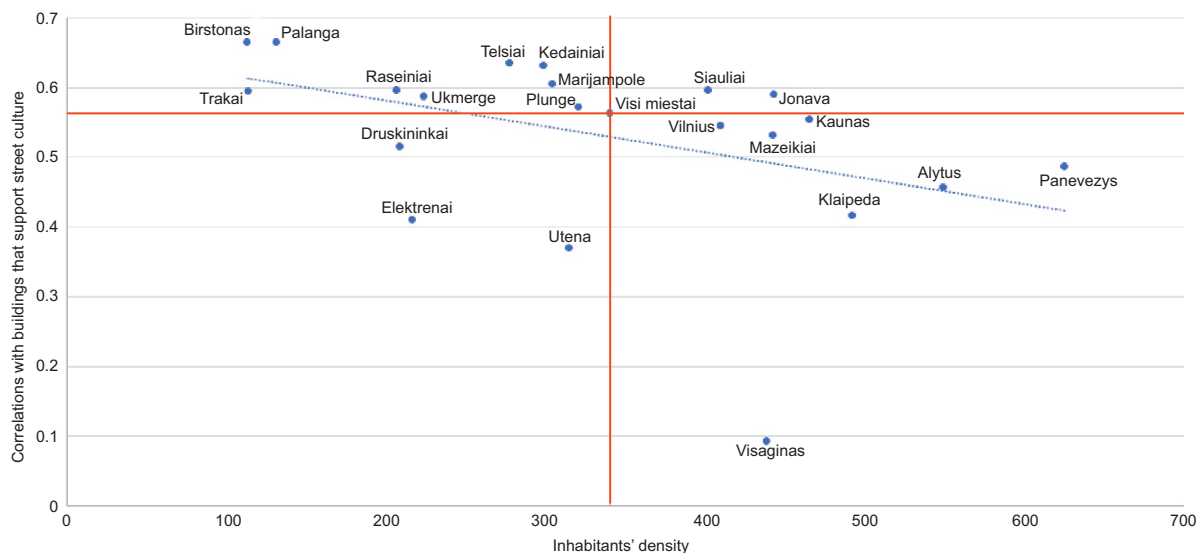


Fig. 5. Inhabitants' density and its correlation with street culture. The dotted lines show the trend line; red lines are the mean values if all cities are calculated

Source: own elaboration.

in “greenery” and monofunctional streets. Utena presents a little unexpected result, but it possibly reflects the impact of two lakes – Vyžuonaitis and Dauniškis, located close to the city center and dividing urban fabric. Visaginas, a bigger modernistic city if compared to Elektrėnai (~19000 vs 11000), demonstrates very low correlations but higher inhabitants’ density – the results are quite logical and expected. The low correlation but relatively big density is shown by Klaipėda, the third biggest city in Lithuania. It could be explained by high depopulations of the historical center and concentration of the majority of inhabitants in the southern part of the so-called “linear city” of Lithuania. It should be noted that all cities beneath the trend line are located besides water bodies thus raising a question if such a situation affects accessibility of the higher building densities. At the moment we can not give an answer, but the question should be addressed in the future.

While analyzing correlations between inhabitants’ density and commercial functions (Fig. 6) the positive trend line could be seen. It shows that commercial functions become more accessible in those “cells”

of a 15-minute city, where they could be reached by a bigger number of people. The results are logical and expected in a free market-oriented economy, but there are still differences in cities. The biggest cities which represent the most economically active nodes of the urban network of the country make the cluster with both high inhabitants’ density and relatively stronger correlations: Vilnius, Kaunas, Šiauliai, Mažeikiai, Klaipėda, Alytus, Panevėžys. Visaginas makes the exception in terms of size and heterogeneity of urban morphology in this group and the stronger correlation might mean the only thing – strategically well chosen locations for such objects within good walking reachability from living places. The group of smaller yet compact towns with good correlations include Birštonas, Palanga, Raseiniai, Kėdainiai, Plungė, Telsiai. The worsen situation is in the rest of the settlements with Trakai and Druskininkai representing unexpectedly very low correlations. In both cases it possibly reacts to the administrative borders of the towns: in Trakai it includes not only the historical center but big territories around the lakes surrounding it; in Druskininkai – a wide green belt surrounds the urban core.

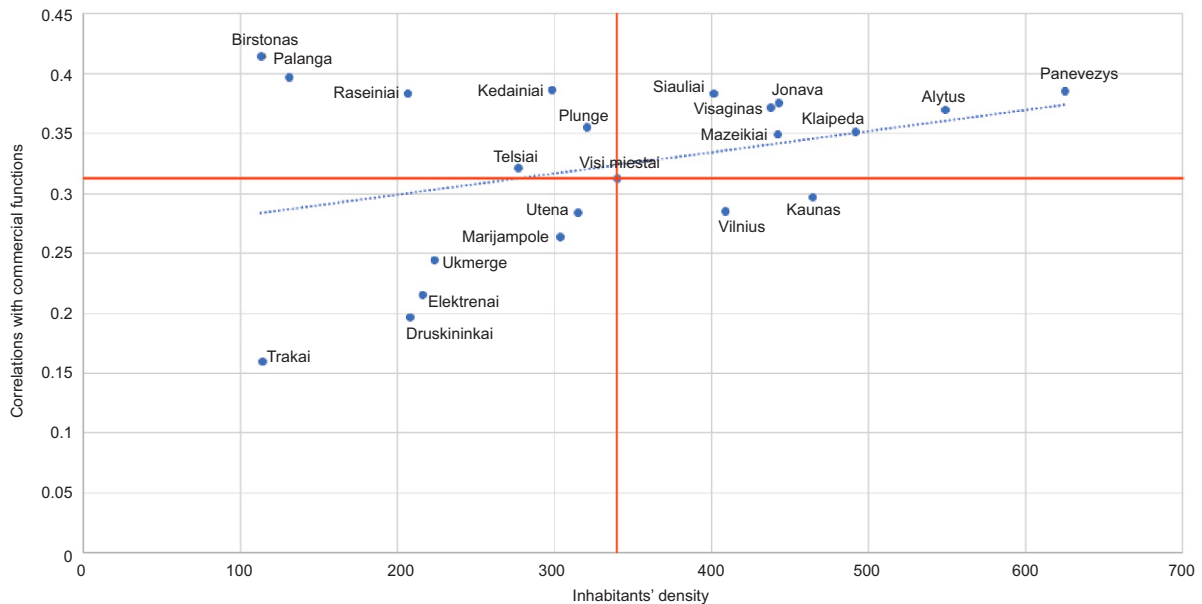


Fig. 6. Inhabitants’ density and its correlation with commercial function. The dotted lines show the trend line; red lines are the mean values if all cities are calculated

Source: own elaboration.

It should be pointed out as well, that both mean and the highest correlations were just moderate – 0.3 and less than 0.45 accordingly. It means that in terms of allocations of commercial objects reachable by walking improvements are needed in every city if the 15-minutes city model is considered. Such a situation could be affected by a dominance of big, car-driver oriented shopping malls in many cities and influence of monofunctional modernistic zoning in the big multi-flat housing areas in many Lithuanian cities created during the Soviet period.

If allocation of inhabitants is compared with allocation of public functions (Fig. 7) then the trend line demonstrates negative dependency between more densely populated parts of the cities and accessibility of the functions. The average and the strongest correlations are falling into the moderate-weak gap thus showing that the public functions are poorly accessible by walking from home in general. In this case few cities with better results could be mentioned:

1. Palanga sea-side resort town. According to the administrative borders it includes few relatively small and compact, more or less even in area neighborhoods such as Palanga itself, Šventoji,

Kunigiškė. Those neighborhoods are divided by greenery belts and demonstrate similarities with the 15-minutes city neighborhoods de-infrastructurized (Baumgartner, 2021) to a certain degree. Such a situation, we believe, potentially explains the received result.

2. Elektrėnai reparents, as it was mentioned earlier, the modernistic town which, if even was designed with car dominated streets, but, possibly because of small territory of the urban core and strategically well-chosen locations of the public buildings by the urban planes, demonstrates not so bad correlations.
3. The good results in Jonava could be explained by its relatively compact urban form and kind of concentric structure.

In general, weak correlation in the pair “inhabitants-public functions”, we believe, reflects the fact that a small number of new public objects in Lithuanian cities appeared recently with the main “backbone” of schools, kindergartens, universities, etc., defined in the soviet period. The other possible explanation could be related to the diverse typology of the objects hidden under the “public” function of the land plots in Lithuania. In this case it would be useful to test

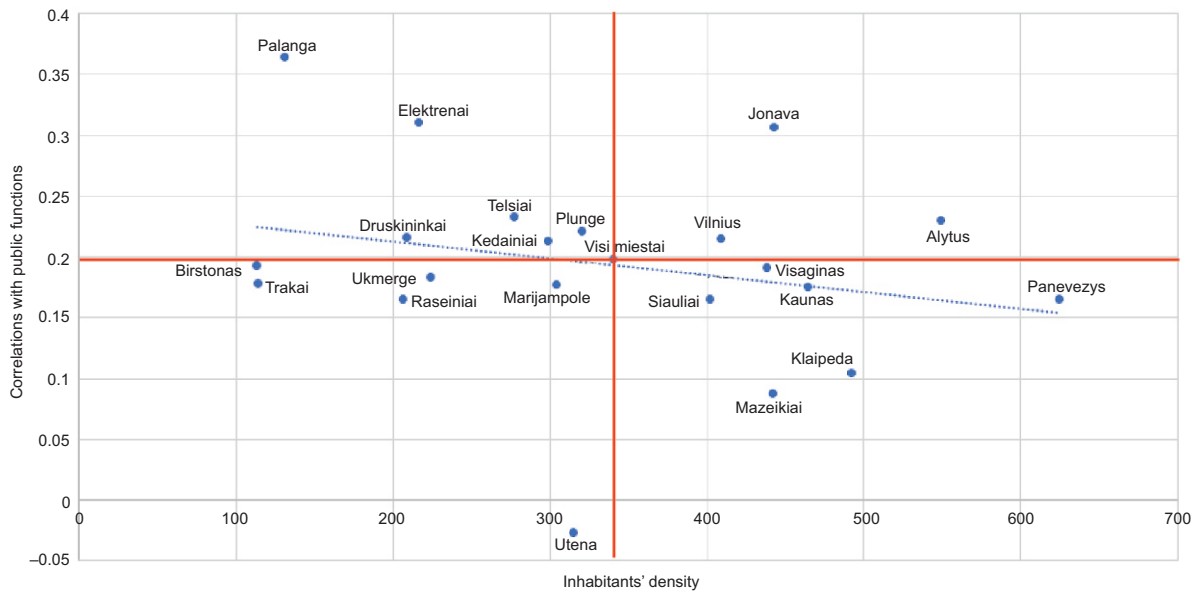


Fig. 7. Inhabitants' density and its correlation with public functions. The dotted lines show the trend line; red lines are the mean values if all cities are calculated

Source: own elaboration.

the modelling results with just data on certain types of public objects obtained, e.g.: schools, kindergartens, community centers, etc.

If reachability and quantity of green areas is checked for the correlations against allocation of inhabitants (Fig. 8), the following tendencies are identified:

The correlation generally is very weak or even negative thus reflecting the essential opposition between “green” and “urban”. On the other side it demonstrates the fact that the right location but not the amount of green areas is the most important in the presented case.

The “best” groups are relatively strong within the obtained scale correlations and the biggest number of green areas is demonstrated just by two cities: Elektrėnai and Alytus. We believe in the first case it demonstrates the results of the modernistic concepts “houses standing in a park”; small, in essence easy walkable size of the urban core and well reachable position of the bigger parks and green squares. In the second case, the good correlations are obtained

because of the big territory of the so-called “green frame” which closely surrounds the center of the city from East-South-West sides.

A little unexpected negative correlation in Trakai, Palanga, Birštonas and Druskininkai – locations known because of the connections with nature. Such a result does not show the small amount of greener or green and blue areas in those cities which is confirmed by their presence in “Week correlations – big weight” quarter of the scatterplot. The result simply means that those natural areas are not easily accessible within 15 minutes’ walk from the majority of living houses. The situation is quite logical for the resorts of Birštonas and Druskininkai where parks were even designed for longer walks and included into the borders of the cities based on geographical locations. In the case of Palanga the results represent the fact that the town itself is allocated not immediately on the sea shore and separated from it by the green wide belt which needs 15 minutes or even more to be crossed by walking. Administrative borders of Trakai, as it was mentioned earlier, include not only the town located

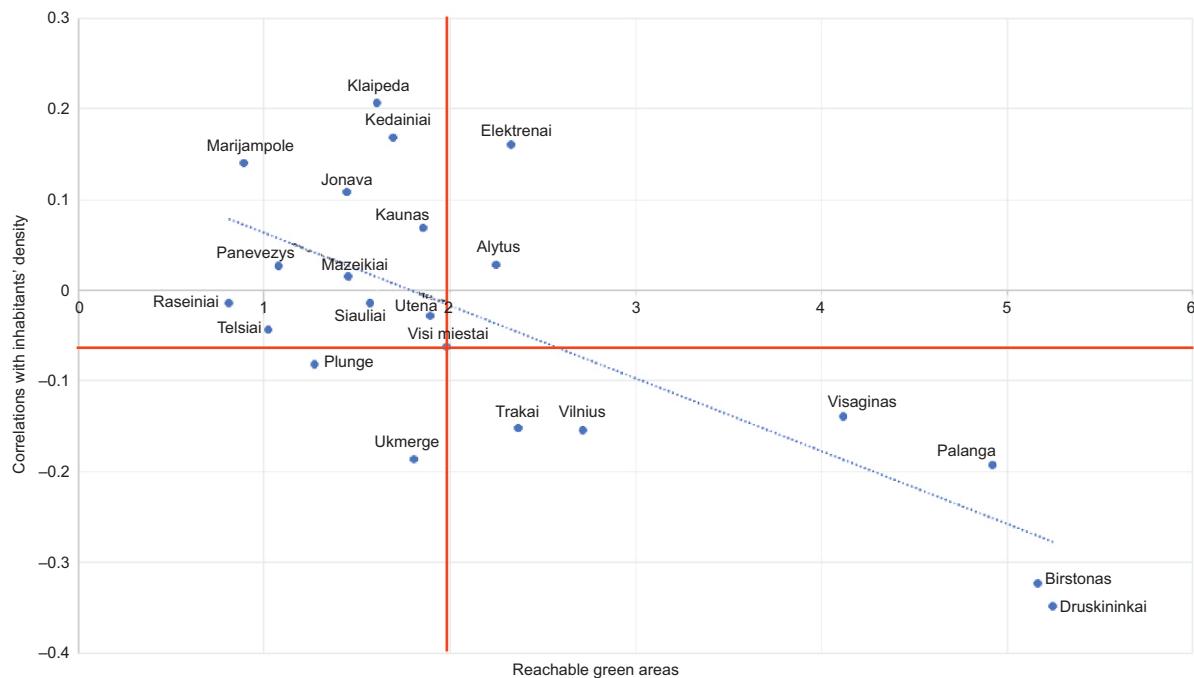


Fig. 8. Quantity of green areas and their correlation with inhabitants’ density. The dotted lines show the trend line; red lines are the mean values if all cities are calculated

Source: own elaboration.

in the peninsular between the lakes, but the other shores of the lakes where the majority of green areas are allocated. On the other hand, we believe that the majority of touristic accommodations, which are not represented in census data, would demonstrate much better correlations with greenery.

The majority of cities demonstrate not bad correlations with limited amount of green areas accessible: Klaipėda, Kėdainiai, Kaunas, Jonava, Marijampolė, Panevėžys Mažeikiai, Šiauliai, Panevėžys, Raseiniai, Telšiai. The cities of this cluster vary in size quite significantly so the result demonstrates that even small green areas could be made better accessible within various sizes of urban structures.

While summering the “green areas – inhabitants” results one question should be raised and addressed in the future more precisely: if correlations between urban densities or inhabitant densities and greenery could not be very strong or even unavoidable are negative, then what correlation values should be considered as a benchmark for urban planners?

Data on density of buildings that potentially support street culture and commercial functions is represented in Fig. 9. The trend line demonstrates very weak dependency between a density of built-up area and its correlations with the commerce. It reflects few things:

1. “Divorce” between “traditional”, perimetric, dense urban fabric and inhabitants caused by the modernistic urbanism models which affected the situation in Lithuania heavily.
2. Focus of commercial services on consumers who rely not on walking, but on other means of transportation or do shopping in combination with other journeys, e.g. while going home from work.
3. Concentration of the commerce in big shopping malls which very often are located not in walkable neighborhoods.

The average value of “street culture – commerce” correlation is moderate (~0.3) thus showing that the situation in many cities could be improved

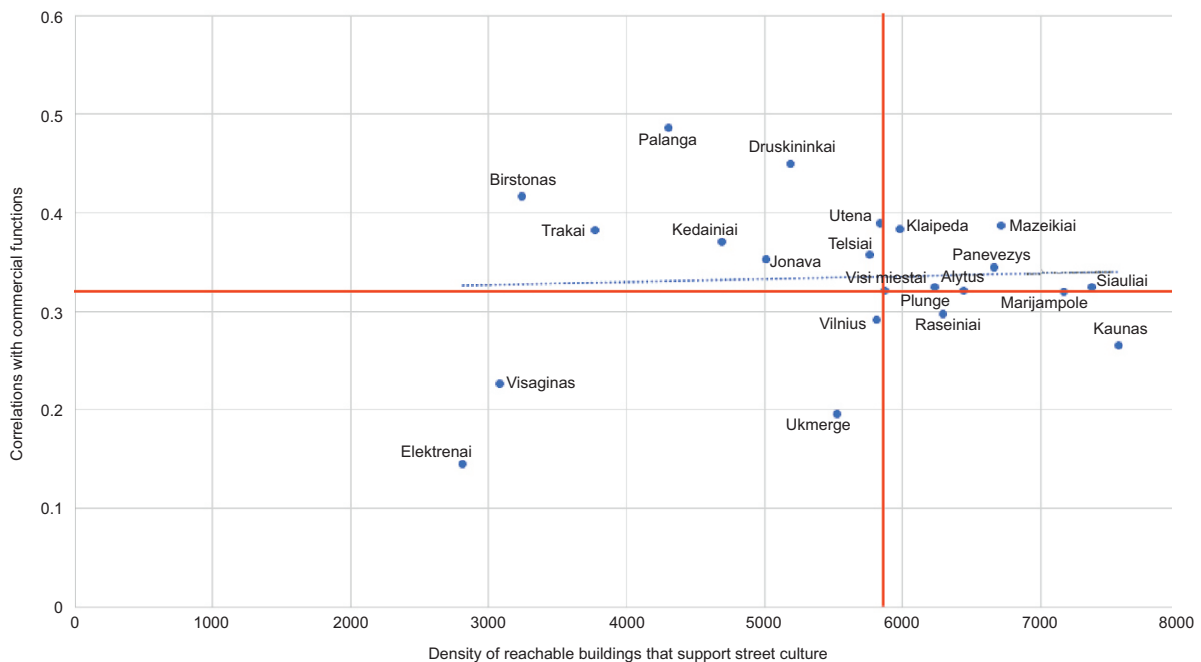


Fig. 9. Density of buildings that support street culture and its correlations with commercial functions. The dotted lines show the trend line; red lines are the mean values if all cities are calculated
Source: own elaboration.

significantly if the 15-minutes city model is considered. Relatively stronger correlation could be pointed out in the followings case:

1. Palanga, Birštonas, Druskininkai. In all three cases the resorts demonstrate quite compact urban cores which, even if stripped partially from inhabitants, demonstrate attractive for walker “traditional” street spaces with more perimetric placement of buildings where a big part of at least tourists oriented commercial functions are allocated.
2. In Trakai the historical urban core, which is the main attraction for the tourist and still holds some groups of inhabitants, is surrounded by lakes and incorporates both tourist and local inhabitants.
3. Some other medium size cities with more dense centers and less multi-nuclei cities or more concentric models expressed in spatial structure as Kėdainiai, Jonava, Utena, Telšiai.
4. Klaipėda is a specific case in which stronger correlations are possibly affected by its linear structure which incorporates the Old Town, the 19th century town, new modernistic neighborhoods, etc.

Availability of water surfaces in the cities is defined by geographical situation and in any case, it is more a reflection of the reality than wish of urban planning. Despite the geographical determinism, urban planners can affect accessibility of the water and its analysis in the presented model is interesting for its validation. In this case the question can be raised: is the model sensitive to real better accessibility to the water? The correlations between accessible areas of water bodies and inhabitants’ density are presented in Fig. 10. The trend line shows strong and logical dependency between the amount of present water bodies and its accessibility by inhabitants. Trakai as a town surrounded by the lakes is the absolute winner in this case. Jonava and Birštonas are small in terms of territory and compact towns allocated besides the big rivers (Neris and Nemunas) show relatively stronger correlations within the obtained scale (-0,25 – +0,25). Klaipėda and Palanga show, from the first glance, unexpected results with not bad correlations but small weight of water. If the real situation is checked, then the results look quite logical: Klaipėda,

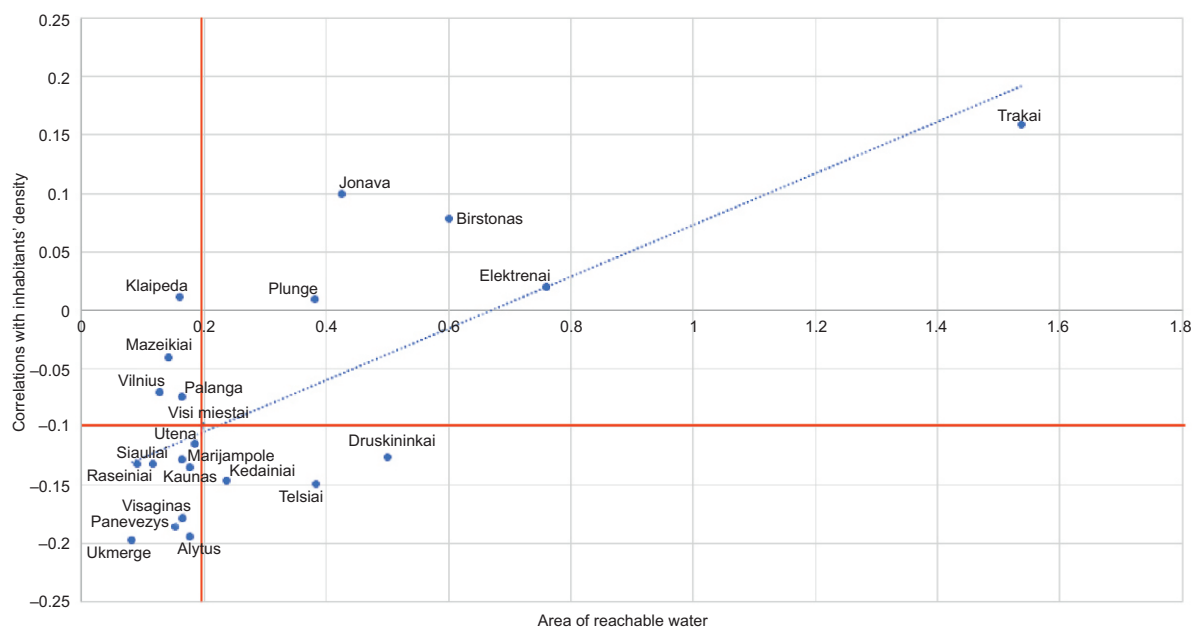


Fig. 10. Area of water and its correlation with inhabitants’ density. The dotted lines show the trend line; red lines are the mean values if all cities are calculated

Source: own elaboration.

if even allocated besides the Baltic Sea, has limited access to the sea shore because of harbor infrastructure; Palanga is separated from the sea by the wide belt of forest which is the important attraction for tourists besides the sea shore. Despite the clear tendency and the sensitivity to the real situation, the correlations between water and allocation of inhabitants is both positively and negatively weak thus reflecting a limited number of situations where urban fabric and water meet in one place in Lithuania.

The results at the single city level

Is the model sensitive enough at a single city level and does it reflect real differentiations of urban structure? The modelling results were visualized while

using the Jenks Natural Breaks method which, as was mentioned earlier, optimally groups values into seven distinct categories to minimize variance within classes and maximize differences between them. As it was described earlier as well, to statistically validate spatial patterns, a Getis-Ord Gi hot spot analysis was performed using a 3-meter fixed distance band (The results are presented in the Annex).

Visualization of accessibility weighted by the density of buildings which potentially support street culture are provided for the three biggest cities of Lithuania: Vilnius (Fig. 11), Kaunas (Fig. 12) and Klaipėda (Fig. 13). Despite belonging to the same size group, the all three cities demonstrated very different spatial configurations: Vilnius could be seen as more evenly dispersed radial structure; Kaunas, because

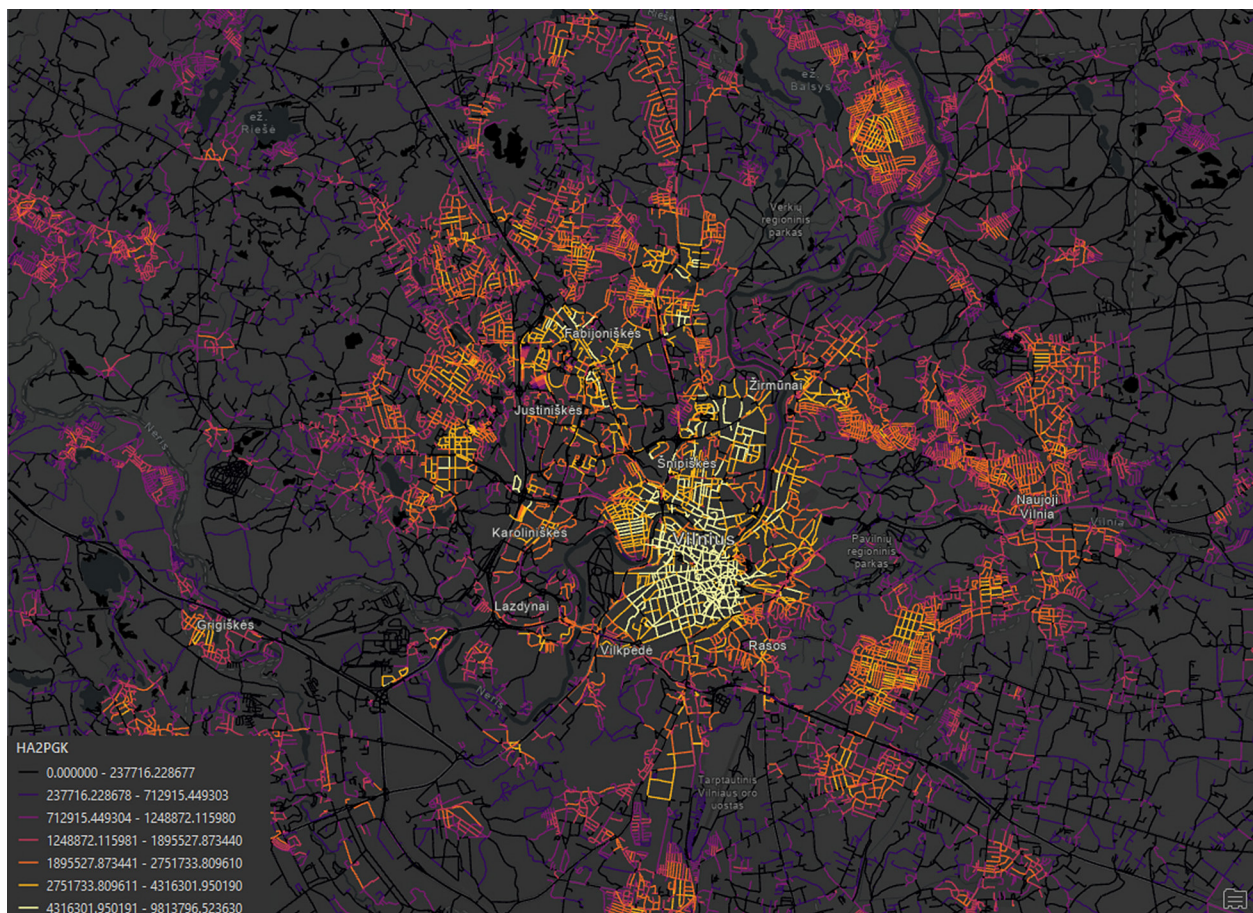


Fig. 11. Accessibility weighted by the density of buildings that potentially support street culture in Vilnius
 Source: own elaboration.

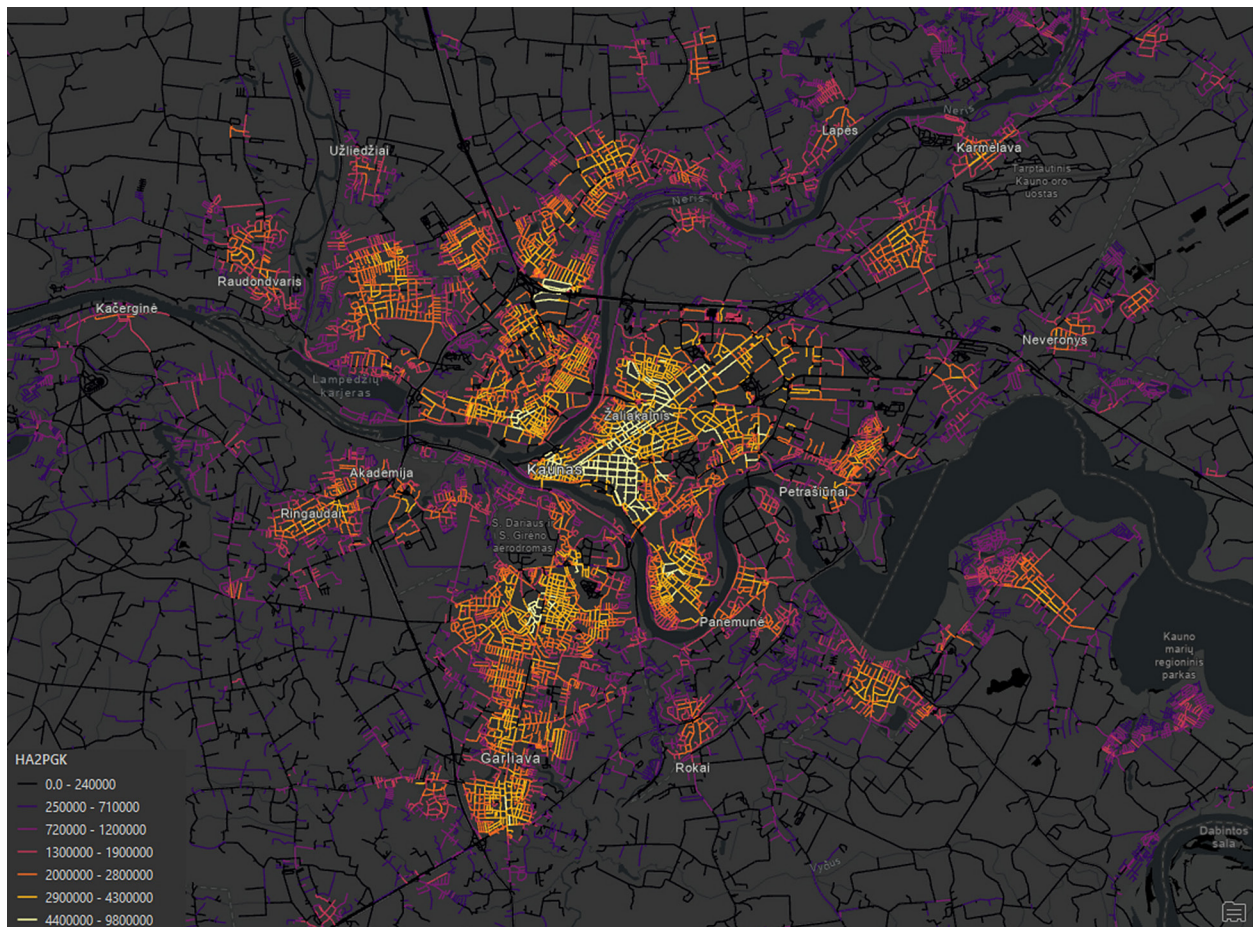


Fig. 12. Accessibility weighted by the density of buildings that potentially support street culture in Kaunas
Source: own elaboration.

of geographical limitations caused by confluence of two rivers demonstrates spatial structure which is developed along certain sectors asymmetrically regarding the historical center; Klaipėda, as developed along the sea shore, could be identified as the linear urban structure.

In all three cities, the bottom-up based model, demonstrates appearance of bigger clusters of the potential 15-minutes city “cells” which in essence correspond to the areas and informal neighborhoods in terms of New Urbanism which are observable in situ:

1. The model points out the Old Town as the most attractive walkable neighborhood in Vilnius. The areas surrounding it as the New Town,

Žvėrynas, the southern part of Šnipiškės with a mix of some historical elements and the newly developed center of the neighborhood, are shown as big and potentially clear 15-minute city clusters as well. Some smaller clusters which correspond to real situations could be seen in Užupis and the central part of Antakalnis, where they have clearly linear yet a little expanded to the sides form. Some more fragmented but still having the 15-minutes potential areas are so called Šiaurės miestelis (relatively new conversion of brown area to residents-oriented commerce town), southern part of northern Žirmūnai (ongoing brown area conversion to commerce territory) and so called Ozo parkas (relatively new development of commerce territory);

- linear urban center alongside Ukmergės str., one of the main transport arteries of Vilnius, passing through northern modernistic districts Šeškinė, Fabijoniškės, and Pašilaičiai, and even newly relatively newly developed Perkūnkiemis; Between Geležinio Vilko str. and Kalvarijų str., two other important transport arteries of Vilnius, a couple more clusters highlighted – lower part of late modernistic district Baltupiai and postmodernistic part of Santariškės – joining these more remote districts to the city core; small part of Pilaitė – another remote late modernistic district, etc.
2. The second, more distant from the center ring of potential 15-minutes centers is seen in Naujoji Vilnia, Grigiškės, Lentvaris, Pavilnys, Balsiai, etc. At the same time the model demonstrates the unattractiveness of the high streets for walking in the modernistic districts.
 3. In Kaunas the model points out the historical areas with the unique urban identities: the Old and the New town as the potential core of the 15-minute city model; historical center of Vilijampolė; the main multifunctional corridor of Žaliakalnis especially till it enters the zone of the modernistic housing blocks; historical center of Žemieji Šančiai and Petrašiūnai. In this case the differences between the center and the other mentioned neighborhoods is clearly visible: the Old and the New Town are shown as a one, quite homogenous in terms of building morphology are while the other zones demonstrate gradual decrees of the calculated values around the clear local cores thus reflecting real changes in the city. Some peripheral potential locations for future 15-minutes clusters could be seen in Vaišvydava, Neveronys, Karmėlava, Domeikava, Sargėnai and even such a small neighborhood as Akademija. The unattractiveness of high streets going through the modernistic of industrial districts for walkability (low accessibility values) could be seen in Kaunas as well. In this case interesting differentiation of streets within the modernist blocks is demonstrated: the main streets show low accessibility, while some inner streets have relatively higher values thus reflecting the real separation of traffic and pedestrian flows.
 4. In Klaipėda, the clusterization of the highest weighted accessibility values is observed along the main line formed by Herkaus Manto and Taikos streets, which connects the New Town in the North, the Old Town in the center and the Modernistic districts in the South. The Old Town demonstrates a little lower value thus reflecting the fact that its accessibility from the West is blocked by still largely industrial and infrastructural areas related to the harbor and from the East – by the former fortification and still not fully developed territory behind it. Danės river, which limits accessibility to the Old Town affects accessibility values as well. Rings of more distant potential central locations for the 15-minutes city “cells” could be seen in Jakai, Kiemiškės, Melnragė, etc.
 5. In Klaipėda some kinds of anomalies are clearly visible – very small clusters made of just a few streets not supported by gradually decreasing accessibility of the surrounding street. Such zones are normally places besides the street which have very low accessibility for pedestrians according to the model. Majority of them are located along Šilutės plentas – a street parallel to the previously mentioned Herkaus Manto_Taikos axe. Šilutės plentas goes through the mainly industrial areas with some infill development of the big commercial objects. Demonstration of such very small, “false” high accessibility clusters from one side reflects the present situation of urbanization, where huge shopping malls are created as introverted objects with a certain degree of imitation of a more traditional urban fabric. Similar “false” neighborhoods could be seen in Kaunas (e.g. huge suburban shopping mall “Mega”) and Vilnius (“Akropolis” shopping mall).
- In a similar way accessibility calculations weighted by the areas of commercial and public objects, greenery and water surface were compared with the present situation in the three cities. In all cases the results reflected present citations quite well while evaluating not only weights or the areas of the objects located

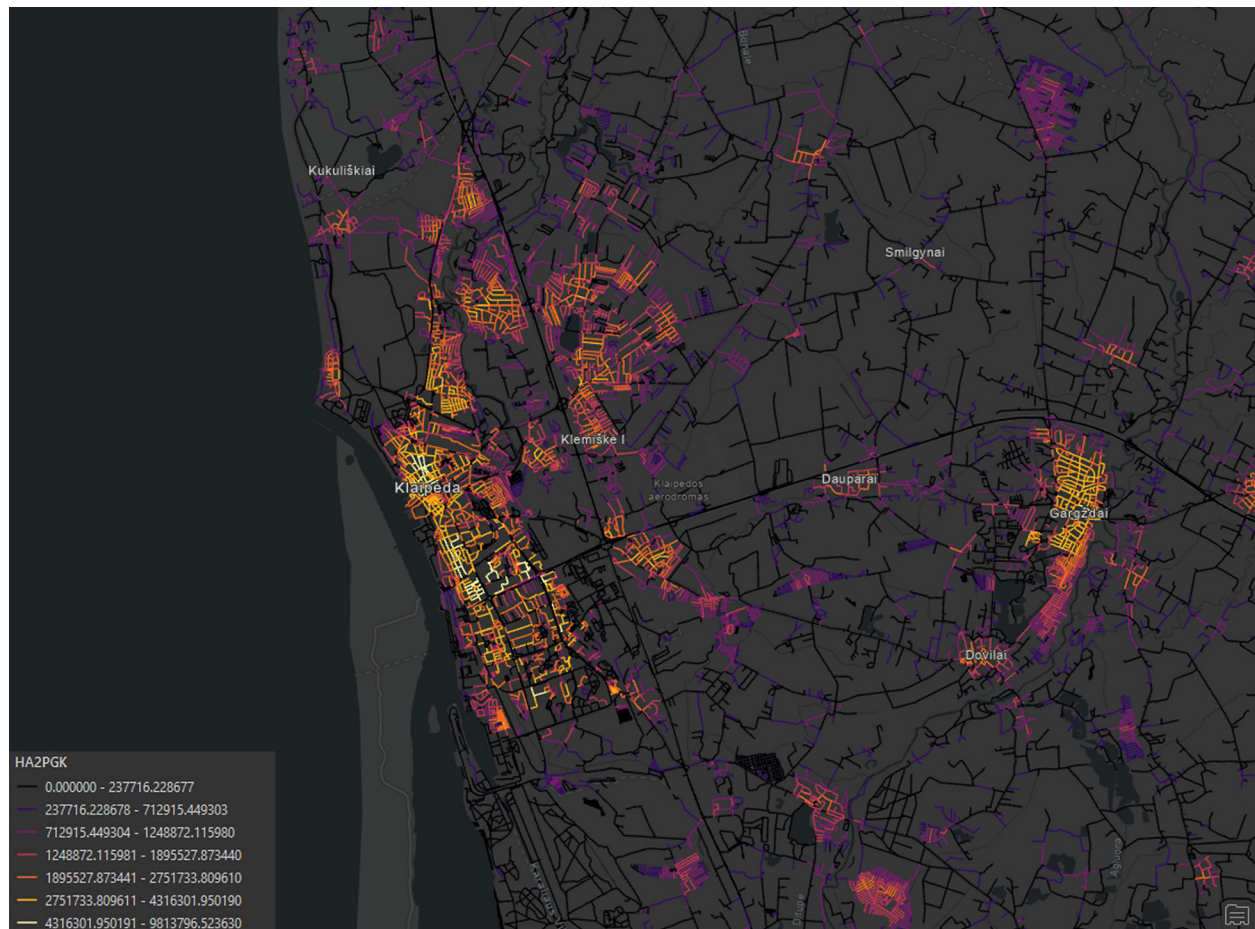


Fig. 13. Accessibility weighted by the density of buildings that potentially support street culture in Klaipėda
Source: own elaboration.

within buffers on both sides of the street lines, but taking into account its accessibility from the surrounding area within radii of 1000 m. Maps with those results are presented in the Annex.

While generalizing the presentation of the results, it could be confirmed that they are sensitive to the differences in real situations at the level of the whole Lithuania, at the level of city comparison and even if the results are viewed at the lowest level of the details – inside a city. Furthermore, it could be summarized, that the model reflects some of the essential regularities of urban functioning (importance of accessibility and reachability, dividing character of the main streets in the modernistic housing areas, bigger importance of the allocation of function over

its quantity, etc.). The statistical significance of the visualized clusters were confirmed by the overlap with the results of Getis-Ord Gi hot spot analysis (represented in Annex). Of course, certain limitations, mainly related to the data, became clear as well, e.g.: influence of the formal administrative boundaries of the cities on the modelling results – they will be discussed in more detail in next chapter.

DISCUSSION

The findings of this study contribute to the theoretical discourse on urban form sustainability by providing a quantitative framework that operationalizes key principles of contemporary urban models.

Existing concepts, including the Compact City, 15-Minute City, and New Urbanism Transit Oriented Development (TOD), emphasize accessibility, multifunctionality, and walkability as core attributes of sustainable urban development. However, a persistent challenge in these frameworks has been the lack of a standardized quantitative method for assessing their effectiveness in different urban contexts. It could be seen in various “sustainability” compasses based on quantitative description of urban form (e.g.: Bureau Urbanisme, n.d.) or even the models of neighborhood by New Urbanism, which despite the mainly quantitative descriptions could even be as the object treated differently as face-block, informal neighborhood, administrative neighborhood, etc. (American Planning Association, 2006). Our study addresses this gap by introducing a graph-based spatial model that quantifies accessibility and multifunctionality through simulation-based analysis and weighted centrality measures.

From a theoretical perspective, this research reinforces the idea that sustainable urban form is inherently hierarchical and emergent, aligning with biomimicry principles and self-organizing urban systems. The research and the model further develop the idea of “inherited urban biomimicry” presented by the authors of this research earlier (Zaleckis et al., 2024). The model, based on comparison of the modelling results and empirical data, demonstrates that bottom-up urbanization processes naturally generate functionally integrated urban cores, while top-down interventions, such as large-scale infrastructure and zoning policies, often introduce functional discontinuities. This finding supports Hillier’s theories on spatial depth and symmetry, where urban accessibility and functional clustering emerge as a result of network morphology rather than rigid zoning regulations. Such a result could be seen as an expansion of the De-Infrastructuring sub-models of the 15-minutes city concept (Baumgartner, 2021) or as a proof that “the idea of 15-minute cities has always been around” (Buro, 2025).

Moreover, the study validates the claim that the 15-minute city is not a monolithic structure

but a system of nested hierarchies, where smaller urban cells interact to form larger, interconnected urban fabrics. It corresponds and proves, based on comparison of the modelling results and empirical data, the idea of pervasive centrality by 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” (Hillier, 2009, pp. K01:3). This nuanced interpretation challenges the assumption that accessibility alone defines multifunctionality; rather, the model reveals that true urban multifunctionality depends on the distribution and spatial configuration of urban functions, not merely their presence within a given radius. This insight contributes to the refinement of urban sustainability theories by highlighting the need for dynamic, adaptable spatial metrics that reflect real-world urban complexity. The usage of the mathematical graph modelling puts the presented research besides the other complex and mathematical graph-based urban modelling attempts (Batty, 2013; Burke et al., 2022) thus aiming to create a critical mass of similar approaches. In the context of the two above mentioned researches, the presented research differs by its aim to focus on one yet maximally effective graph centrality instead of many.

Classic urban models

Urban sociologist E. W. Burgess, who created perhaps the first theoretical model of the spatial structure of the city, the concentric zone model, also took a nature-based approach to urban morphology. In developing this urban model, Burgess (2015) drew on the theory of human ecology, which was the fundamental theoretical paradigm of the Chicago School he represented. This school’s paradigm established the idea that human behaviour (and thus behaviour in the city, on the street) is determined more by the physical environment and social structure than by genetics or personal characteristics. In fact,

this model was based on the social (including criminological) structure of the urban environment. Moreover, Burgess and his colleagues, while developing their urban concept, also talked about the changes taking place in cities by comparing them with the approach of Ch. R. Darwin's theory of evolution (Park et al., 1925). Another well-known model in urban geography, the sectoral model, was developed by Hoyt (1939). The model was based more on the city's economic structure; in the model, the city's macro-forms (sectors) are not as symmetrical as in the first one – the configuration of the urban form is irregular. The third model of intra-urban land-use distributions was developed by the geographers Ch. Harris and E. Ullman (1945) and combined aspects of both the zonal and sectoral models. The multiple nuclei model, in contrast to the first two models, has already highlighted the complexity of the city and the more difficult hierarchical system of the functional zones of the city, in its expression it is a model of a polycentric city with a fragmented structure, as they have emphasised the fact that the residential areas of most of the urban areas are organised around several nodes, not only a single central business district (CBD).

Although it must be acknowledged that these models were developed for the US urban context and in the first half of the 20th century, the perception at the time was that urban areas were planned in a rather mono-functional way and that the concept of sustainability was still a long way from being understood. Many Lithuanian cities are also structured this way, especially due to the idea of modernist planning in the soviet era. But still, it can be said that the multiple nuclei model, although quite simple, could be quite suitable for the concept of a multifunctionality and 15-minute city. Applying these models to Lithuanian cities would require converting the city structure into a European system and considering the core of the city (CBD) as the Old Town and partly the New Town area (in Vilnius also CBD), complemented by other nodes – the hubs of the city's sub-centres. Looking at the equivalents of these classical urban models for the Lithuanian

major cities – Vilnius, Kaunas and Klaipėda can all be considered as multiple nuclei cities, but due to their specificity (which is also confirmed by this study and its schemes [Figs. 9, 10, 11]), they also have features of the other two models. For example, Vilnius, because of its structure and its partially strong centre, has features of the concentric zone model. In Klaipėda, on the other hand, the linear shape of the city and the distribution of industry allow us to see aspects of the sectoral model.

The results of this study can be directly applied to urban planning, and by periodically repeating these analyses with updated data, it becomes possible to monitor the evolution of cities and their separate areas. Such ongoing observation can help evaluate which territorial planning solutions have positively affected urban sustainability and the quality of the living environment. Moreover, it allows for the identification of cities that are progressing over time, as well as timely interventions can be made in areas showing signs of regression. For example, maps, weighted by buildings that potentially support street culture (A in the Figs. 14–19 in the Annex) can reveal zones where urban blocks are excessively large and street networks too sparse. This information is crucial for prioritizing improvements in pedestrian infrastructure – whether by creating a denser network of walkways or by installing elements that encourage walking (such as benches and drinking fountains). Similarly, maps, weighted by commercial area (B in the Figs. 14–19 in the Annex), can pinpoint locations with the greatest potential to evolve into local centers of polyfunctional urbanism. In line with TOD principles, these areas could be considered for establishing major public transport hubs, increasing development intensity, and promoting vertical functional differentiation (for instance, with commercial activities on the lower floors, administrative functions in the middle, and residential units on the upper levels). Analysis of maps, weighted by area of public buildings (C in the Figs. 14–19 in the Annex), can further identify gaps in social infrastructure, such as insufficient provision of kindergartens, schools, or primary healthcare services. Such evaluations should be complemented

by assessments of population density (accounting for different age groups, if decided) and the accessibility of public buildings, as well as comparing different parts of the analyzed city in scatterplot – by analyzing population density and correlation of social infrastructure. Additionally, maps, weighted by green areas (D in the Figs. 14–19 in the Annex) or water bodies can help identify areas where nature elements are lacking or where the accessibility of existing green zones and water bodies is poor, thereby informing decisions on where additional green zones, improved pedestrian infrastructure, or compensatory green infrastructure may be needed. This approach also enables the identification of urbanizing territories that already exhibit strong links to natural elements and thus have the potential to develop into high-quality living environments with minimal further investment.

Although the maps presented in this study depict only the central lines of streets, they allow for the straightforward identification of distinct urban structures – organically evolved historic centers (or their fragments), modernistic residential districts and suburban areas. By considering the naturally evolved historic urban fabric as the benchmark of human-scale design, it becomes possible to identify structural deficiencies in newly developed areas. In this sense, beyond its direct application to spatial planning and ongoing monitoring, the study's methodology and conclusions implicitly reveal shortcomings in the political and legal frameworks governing territorial planning in Lithuania.

At the core of Lithuanian spatial planning legislation lies the Territorial Planning Act of the Republic of Lithuania (Lietuvos Respublika, 2016, 2024a), that serves as the principal regulatory instruments for territorial planning and its quality control. However, these norms do not specify optimal parameters for the urban fabric – such as block sizes, the density of street and pedestrian pathway networks, or maximum length of cul-de-sacs – thus promoting an automobile-oriented culture and failing to create conditions conducive to small-scale business development. The current regulations do not address the accessibility of social infrastructure, meaning

that public amenities (such as kindergartens, schools, health-care services) often do not meet the actual needs of residents. No legislative measures exist to promote (horizontal or vertical) multifunctionality in urban structures, and it becomes almost impossible to evaluate the real situation as significant portion of commercial, public, and industrial activities can be carried out in premises without recording relevant function to the real estate registry (Lietuvos Respublika, 2022), and the legislation allows to register one's residence in premises of any recorded usage.

The Lithuanian legal framework also lacks typology for outdoor spaces. In urbanized areas, public spaces – including parks, botanical and zoological gardens, cemeteries, and other public spaces – are legally classified under the name of common-use territories (Lietuvos Respublika, 2024b), thereby obscuring the completely different social functions these spaces serve.

With regard to green spaces, the legislation distinguishes between forests and wooded areas (in non-urbanized territories) and green zones (in urbanized or urbanizing territories) (Lietuvos Respublika, 2016). Green zones are further classified into public green areas – developed on separate plots with public access, and private ones, which are integrated into urbanized plots (Lietuvos Respublika, 2024c). Nonetheless, in practice, it is not mandatory to formally delineate the plots for green public spaces thus many de facto public green areas remain omitted from official records, while private green spaces cannot be reliably assessed on a citywide or national scale as well. To more accurately capture the real situation, official green plot data was supplemented with Copernicus satellite data on trees-canopy. This integration revealed that informal green public areas and street-side vegetation play a significant role in urban fabric, particularly in modernist districts, where designated plots are absent, and buildings stand amidst open lawns. As a result, this analysis provides a depiction of greenery in Lithuanian cities that more accurately reflects human perspective. Moreover, despite the fact that the Greenery Act of the Republic of Lithuania defines a green zone as an area featuring vegetation, lawns, and flowerbed,

while vegetation refers to trees, shrubs, or climbers growing naturally outside of forested areas (Lietuvos Respublika, 2025), no quality criteria have been established for either public or private green zones regarding the composition of vegetation – meaning that lawns are evaluated in the same manner as shrubs or trees. From a human-scale perspective, a single mature tree with a broad canopy can offer greater ecological and social benefits than a vast, uniform lawn. Therefore, further development of this analysis could contribute to establishing a methodology for effectively assessing multi-layered greenery.

In addition to green spaces, global practice has already recognized the importance of blue spaces – water bodies that contribute significantly to the quality of life. The inclusion of blue spaces in this study has considerably enriched the depiction of urban sustainability in Lithuanian cities. However, current Lithuanian legislation still does not acknowledge water bodies as an essential component of residential quality. It is hoped that this study will encourage policymakers to assign greater importance to water bodies in future legal regulations, thus achieving a balance in enhancing the living environment through both green and blue infrastructures. This could involve developing indices for the influence and accessibility of various types of blue spaces – such as seas, rivers, lakes, and ponds – thereby ensuring a more comprehensive approach to urban quality of life.

If the qualitative models are considered, the proposed model offers a rigorous quantitative framework to assess multifunctionality and spatial configuration, it is essential to acknowledge that cities are not only networks of accessibility but also lived spaces shaped by human experience. As Gehl (2013) emphasizes through his 12 quality criteria, the social sustainability of urban environments depends on how spaces support protection, comfort, and delight, including opportunities for walking, staying, and social interaction. Quantitative metrics cannot fully capture these experiential and psychological dimensions. Moreover, as Johansson and Yahia (2011) demonstrate, the subjective perception of microclimatic conditions,

such as thermal comfort, also influences how urban spaces are used and perceived, thereby affecting overall sustainability. Thus, integrating quantitative simulations with qualitative assessments is crucial for a more holistic understanding of urban form and life between buildings. At the same time, the inclusion of spatially grounded quantitative indicators can enhance and operationalize qualitative urban design models, making them more applicable in planning and decision-making processes.

CONCLUSIONS

This research emphasizes the relevance of nature-inspired principles, particularly biomimicry, in modeling sustainable urban form, demonstrating how characteristics inherent to natural systems, such as multifunctionality and bottom-up self-organization, can guide urban sustainability analysis. By identifying and quantifying these biomimetic principles within Lithuanian cities, the study reinforces the potential of nature-inspired approaches not only as theoretical frameworks but also as practical tools for achieving urban sustainability goals. This research provides a quantitative, nature-inspired methodology that enhances understanding of multifunctionality, accessibility, and spatial hierarchy in urban systems, facilitating practical decision-making towards more sustainable and resilient urban development. However, the following shortcomings, which should be addressed in the future research, should be pointed out as well:

1. While the model successfully captures organic urbanization processes, it does not fully account for top-down interventions such as large-scale infrastructure projects, which can significantly alter accessibility dynamics. Future research should explore how planned developments influence street-based accessibility over time.
2. The proposed weighting metric, hull area squared divided by perimeter, offers improved robustness against irregular street densities; its sensitivity across different urban typologies warrants further investigation. Cities with fragmented structures

or dispersed centers may exhibit different accessibility behaviors that the current approach may not fully capture. Adjustments to weighting parameters or additional refinements in spatial data processing could enhance model precision.

3. Furthermore, the results reveal moderate correlations between accessibility and commercial functions, and weak correlations with public services. This suggests that while spatial accessibility is a strong predictor of urban vitality, other non-spatial factors, such as economic conditions, land-use policies, and municipal planning decisions, may significantly influence service distribution. Similarly, the weak or negative correlations with green space integration highlight the challenge of incorporating environmental factors into space syntax models. Green spaces often function separately from built environments, necessitating alternative approaches to assess their role in urban walkability.
4. Another limitation, which became clear while comparing cities, lies in the model's reliance on administrative boundaries, which may not fully capture functional urban zones that extend beyond or fall short of city limits. In some cases, official boundaries encompass vast peripheral or rural areas with little urban character, distorting average indicators and masking true urban dynamics. In other cases, essential parts of the functional city, such as commuter belts or integrated suburban districts, fall outside administrative limits, leading to underrepresentation of key urban functions. To address this, future research should explore methods for identifying informal or functional urban boundaries, such as using mobility patterns, built-up density, or morphological continuity.
5. In addition to boundary-related issues, the study faces several data limitations that affect the model's precision and interpretability. One challenge is the use of generalized land plot data, which may not reflect the actual distribution and footprint of buildings, a more precise indicator of urban intensity and function. Similarly, the classification of green and blue areas remains coarse, often aggregating ecologically and socially distinct

spaces such as forests, parks, wetlands, rivers, or ornamental lakes into single categories. This reduces the ability of the model to differentiate between areas with high ecological value and those with strong recreational potential. Improved classification schemes and higher-resolution spatial data could significantly enhance the model's accuracy and its responsiveness to real urban conditions. Moreover, the availability and quality of functional data (e.g., POIs, land use) can vary widely across regions, introducing inconsistencies in comparative analyses.

6. The applied weighing procedure should be improved in the future: greenery should include not only tree cover, but the low-growing woody plants (bushes, shrubs) and permanent herbaceous from Copernicus land cover data; weighting should be differentiated between different types of greenery and water bodies. Weighting of commercial and public functions in buildings should be based not on information on land plot functions, but on exact data on buildings when such information will be available. Public functions should be analyzed by dividing them into separate groups, e.g.: everyday and episodic use; local neighbourhood or wider importance, etc.
7. To strengthen the model, future development should focus on integrating more detailed building-level datasets, refining the typologies of open spaces, and incorporating dynamic or time-sensitive data such as population flows or microclimatic patterns. Additionally, testing the model in different cultural, climatic, and morphological contexts is essential to evaluate its generalizability and adaptability. Cross-cultural validation would not only reveal universal patterns but also highlight context-specific spatial configurations that require tailored sustainability strategies.

Overall, this study advances theoretical discussions by bridging the gap between abstract sustainability principles and empirical urban analysis. The proposed model not only provides a robust methodology for quantifying sustainable urban form while focusing on its multi-functionality, but also enhances the the-

oretical understanding of how accessibility, multifunctionality, and spatial hierarchy interact within complex urban systems. Future research should refine this approach by incorporating additional socio-economic variables and exploring how different planning interventions influence spatial dynamics over time.

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ANNEX

Full analysis of weighted accessibility and its hot spot analysis in Vilnius, Kaunas and Klaipėda.

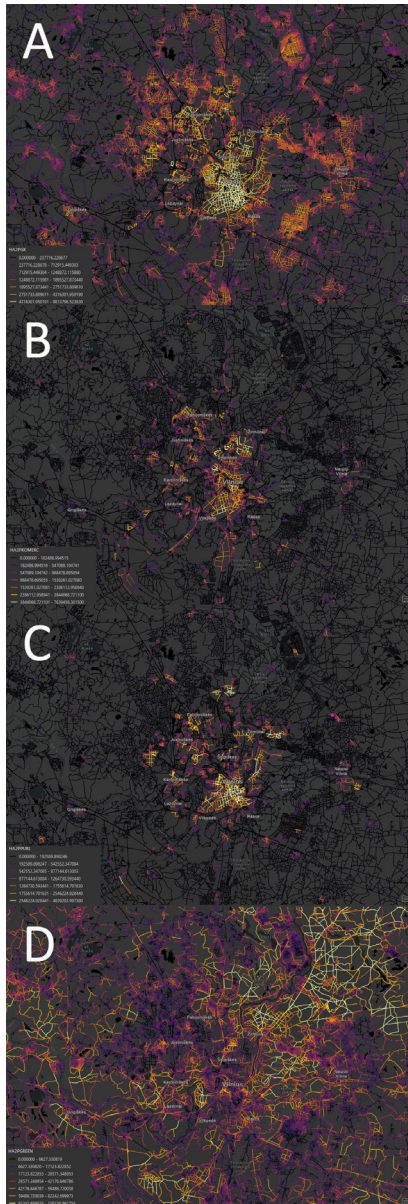


Fig. 14. A.1. Weighted accessibility of Vilnius with warmer colors showing better accessible and bigger quantities of weights. A) weighted by buildings that potentially support street culture; B) weighted by commercial area; C) weighted by area of public buildings; D) weighted by green areas

Source: own elaboration.

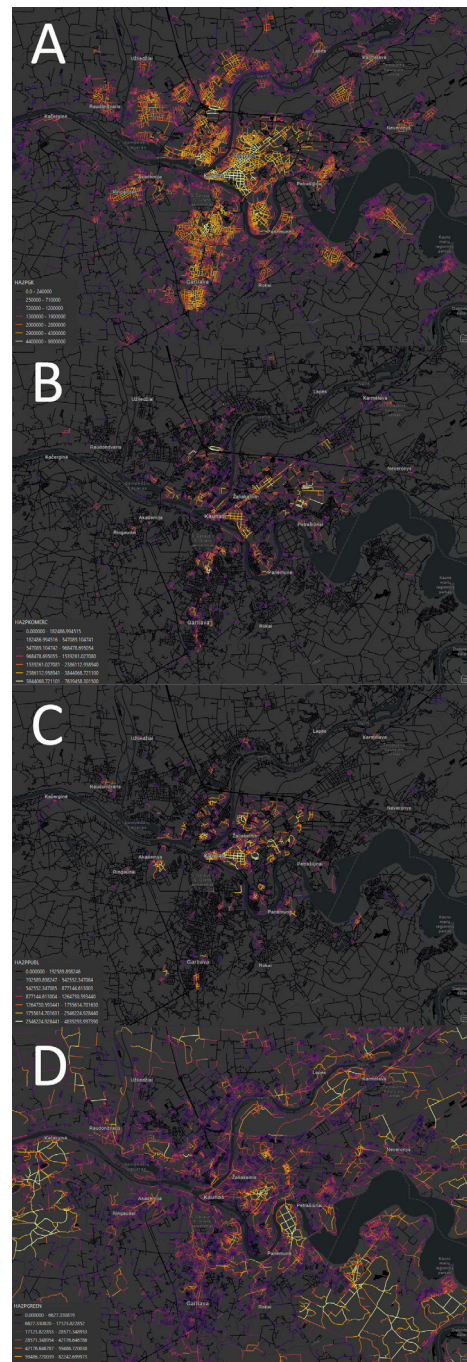


Fig. 15. A.1. Weighted accessibility of Kaunas with warmer colors showing better accessible and bigger quantities of weights. A) weighted by buildings that potentially support street culture; B) weighted by commercial area; C) weighted by area of public buildings; D) weighted by green areas

Source: own elaboration.

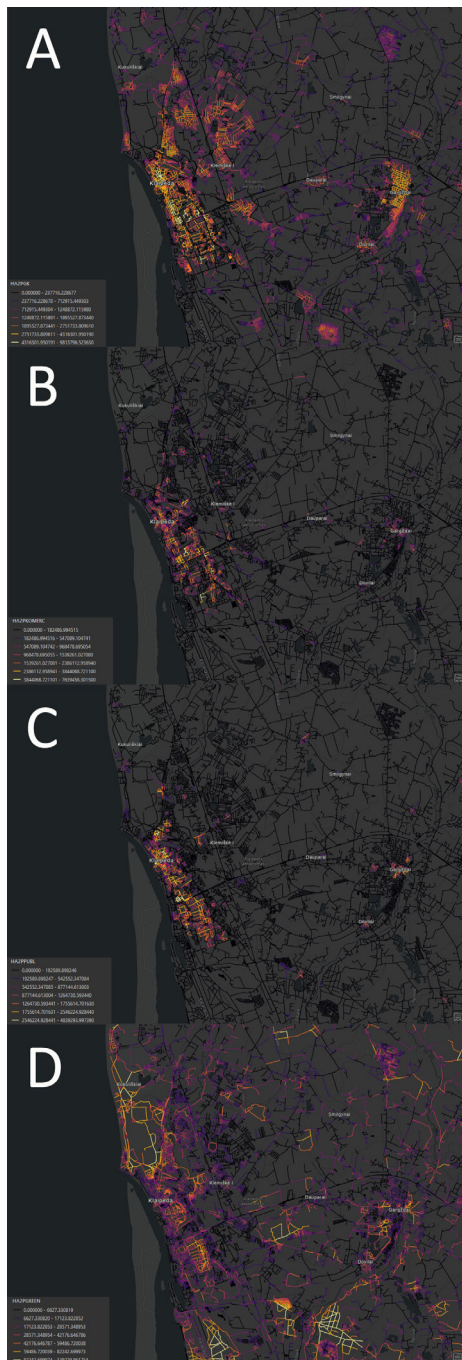


Fig. 16. A.1. Weighted accessibility of Klaipėda with warmer colors showing better accessible and bigger quantities of weights. A) weighted by buildings that potentially support street culture; B) weighted by commercial area; C) weighted by area of public buildings; D) weighted by green areas

Source: own elaboration.



Fig. 17. A.1. Hot Spot analysis of the weighted accessibility of Vilnius with warmer colors showing more than 90 percent confidence hot spots. A) weighted by buildings that potentially support street culture; B) weighted by commercial area; C) weighted by area of public buildings; D) weighted by green areas

Source: own elaboration.



Fig. 18. A.1. Hot Spot analysis of the weighted accessibility of Kaunas with warmer colors showing more than 90 percent confidence hot spots. A) weighted by buildings that potentially support street culture; B) weighted by commercial area; C) weighted by area of public buildings; D) weighted by green areas

Source: own elaboration.



Fig. 19. A.1. Hot Spot analysis of the weighted accessibility of Klaipėda with warmer colors showing more than 90 percent confidence hot spots. A) weighted by buildings that potentially support street culture; B) weighted by commercial area; C) weighted by area of public buildings; D) weighted by green areas

Source: own elaboration.

