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Invisible Inheritable Urban Biomimicry: How to Re-discover and Evaluate It

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Features of natural systems, simulative modelling, urban biomimicry, urban theories.

Abstract

The contemporary built environment, the primary human habitat, contributes significantly to global environmental challenges, such as biodiversity loss and climate change. Consequently, there is an increasing focus on reconnecting urbanism with nature through biomimicry, an approach that draws inspiration from natural systems to design sustainable, self-sufficient, and resilient urban environments. This research explores the hypothesis that natural system principles are inherently present in many contemporary urban development theories, even if not immediately visible, and can support the creation of sustainable urban spaces. By analyzing theories such as new urbanism, smart growth, the 15-minute city, and others, this paper seeks to determine their alignment with biomimicry principles. The research employs both quantitative and qualitative approaches, combining theoretical analysis of natural systems and urban theories with the search for possibilities to apply simulative modelling to assess the specific applicability of biomimetic approaches. The findings of the research highlight that several urban models and theories, including New Urbanism and Alexander's pattern language, can support biomimicry application, thus allowing us to speak about the inherited urban biomimicry as a phenomenon and look for inspiration not only in nature but also in the urban structures of the past. The conducted analysis also reveals that if the degree of expression of urban biomimicry principles in cities is analyzed, then it is not enough to use qualitative models – quantitative models should be employed for this purpose. The possibility of using Space Syntax-based simulative modelling for the analysis of inherited biomimicry in urban structures is discussed and demonstrated.

Introduction

Relevance of the research. Contemporary cities and other built-up areas require large amounts of energy for construction, maintenance, and operation, directly and indirectly causing global environmental issues, such as loss of biodiversity and climate change through greenhouse gas emissions. According to the researchers, urban areas are responsible for 70 % of global carbon emissions and are also the cradle of major current social problems [1], [2]. It can be noted that contemporary urbanization is mainly going against nature. Because the built environment is a driver of many causes of negative climate and biodiversity changes, because it is the primary habitat for humans, and because a focus on the built environment presents potential opportunities for change [3], cities and urbanism are gradually turning back to nature. The majority of the world's cities have some natural elements, and some of the cities even boast abundant green areas and biodiversity. Currently, as a consequence of the above-mentioned challenges and growing worldwide commitment to nature conservation and to preserve and enhance the quality of living environments, efforts are being made to further enhance these green elements and features of our living and work environments [4]. However, reconnection and learning from nature are not limited to greening efforts, rainwater management or the development of biomorphic elements in buildings or public spaces. The approach of urban biomimicry – learning from nature and applying the principles of natural systems for self-sufficient, engineerable urban design [5] is the main focus of this research. This research is developed around the hypothesis that the principles of natural systems may be inherent in some urban development approaches, even if not visible from the surface, and could contribute to the development and maintenance of sustainable, resilient urban environments.

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The aim of the research is to conduct an analysis of the most important contemporary urban development theories, like new urbanism, tactical urbanism, smart growth, transit-oriented development, sustainable urbanism, acupuncture urbanism, Ch. Alexander's pattern language, landscape or conservative urbanism, participatory urbanism, inclusive urbanism, and 15-minute city from the point of view of inherent presence and expression of features of the natural system in them and to determine which of these theories could be considered as tools for biomimicry urbanism.

The methods of research include quantitative and qualitative analysis of literature and theoretical research in order to determine the main features of natural systems and their expression in selected urban theories and the possibilities to apply simulative modelling for quantitative analysis of biomimicry in urbanism and for the selection of the most appropriate approaches for particular cases. The manuscript is organized as follows: first of all literature analysis of urban biomimicry in the context of other nature-focused solutions is presented, and the main features of natural systems are determined as a result of this analysis; then, the most relevant selected contemporary urban theories are presented and analyzed in the light of biomimicry urbanism, and the presence of features of natural systems in them; the evaluation of urban theories is followed by discussion of possibilities of quantitative analysis of biomimicry in urbanism and by conclusions.

I. Theoretical Review of Urban Biomimicry in the Context of Other Nature-Focused Urban Solutions

There are several movements focused on nature in contemporary urban planning and design, including biophilic design and biophilic urbanism, nature-based solutions, biomimicry or biomimetic urbanism, etc. The concept of the biophilic city and the principles of biophilic urbanism were introduced by T. Beatley [6]. Meanwhile, the concept of nature-based solutions (NBS) was first mentioned in 2008 by the World Bank [7]. Biomimicry was popularized by scientist and author J. M. Benyus in 1997 [8]. Nature-based solutions in urbanism are generally defined as solutions to societal challenges that involve working with nature [9]. T. Beatley [10] defines biophilic cities as "those that are abundant in nature (trees, greenery, animals, gardens) and in opportunities to connect with and experience this nature". According to him, the recognition of the innate human affiliation with nature and the need to put contact with nature at the center are the basic premises of the biophilic urbanism approach [10]. G. Pohl and W. Nachtigall [5] define biomimicry as "learning from nature for self-sufficient, engineerable design". These concepts seem to be recent developments in urbanism; however, it is necessary to note that biomimetic, biophilic and nature-based features have appeared in environments designed by humans since antiquity.

The interconnections of the above-mentioned nature-focused approaches to urbanism – nature-based solutions, biophilic urbanism, and biomimicry – are evident: common focus on nature, employment of nature to solve societal challenges, inspiration by nature, etc. Y. Uchiyama et al. [1] even view biophilic design as a subcategory of biomimetic design. According to them, biophilic urbanism can be understood as a biomimetic application aiming at human well-being. However, biomimicry can be seen as a part of biophilic urbanism, which focuses on the discovery and application of geometry and patterns inherent in nature in the built environment [11]. This research focuses on biomimicry applications in urbanism in connection to other nature-focused approaches.

According to numerous researchers, biomimicry is a design framework with an increasing interest in sustainability in architectural and urban design practices [12]. It has been proposed that the biomimetic approach can address sustainability and climate change challenges [1]. M. Pedersen Zari [3] has analyzed the possibilities of the application of biomimicry in urban design for climate change adaptation and mitigation. M. Pedersen Zari's research focuses on cities as a medium for mitigating the causes of climate change. Specifically, how the built environment can adapt to climate change impacts while concurrently responding to the degradation of ecosystems and the loss of biodiversity through emulating or mimicking ecosystems themselves. This demonstrates that biomimicry can be successfully integrated with other approaches and contribute significantly to urban sustainability.

However, a quantitative literature search using the keyword "biomimicry" in the Web of Science scientific literature database has revealed limited interest in biomimicry: it has revealed 2313 results (compared to 450 683 results using the keyword "sustainability"). The distribution according to the research areas of the search results is the following: engineering – 741, materials science – 723, architecture – 59, urban studies – 26. The analysis of the use of terms in the publications focusing on biomimicry (Fig. 1) [13] has also revealed the relative lack of research on biomimicry applications in the built environment. The cluster analysis of term distribution reveals no clearly distinguished cluster of terms related to architecture and urbanism, and built-environment-related terms appear at the fringe of the cluster focused on product design. This relative lack of research on biomimicry applications in urbanism and the promising character of such research justify the focus of this research.

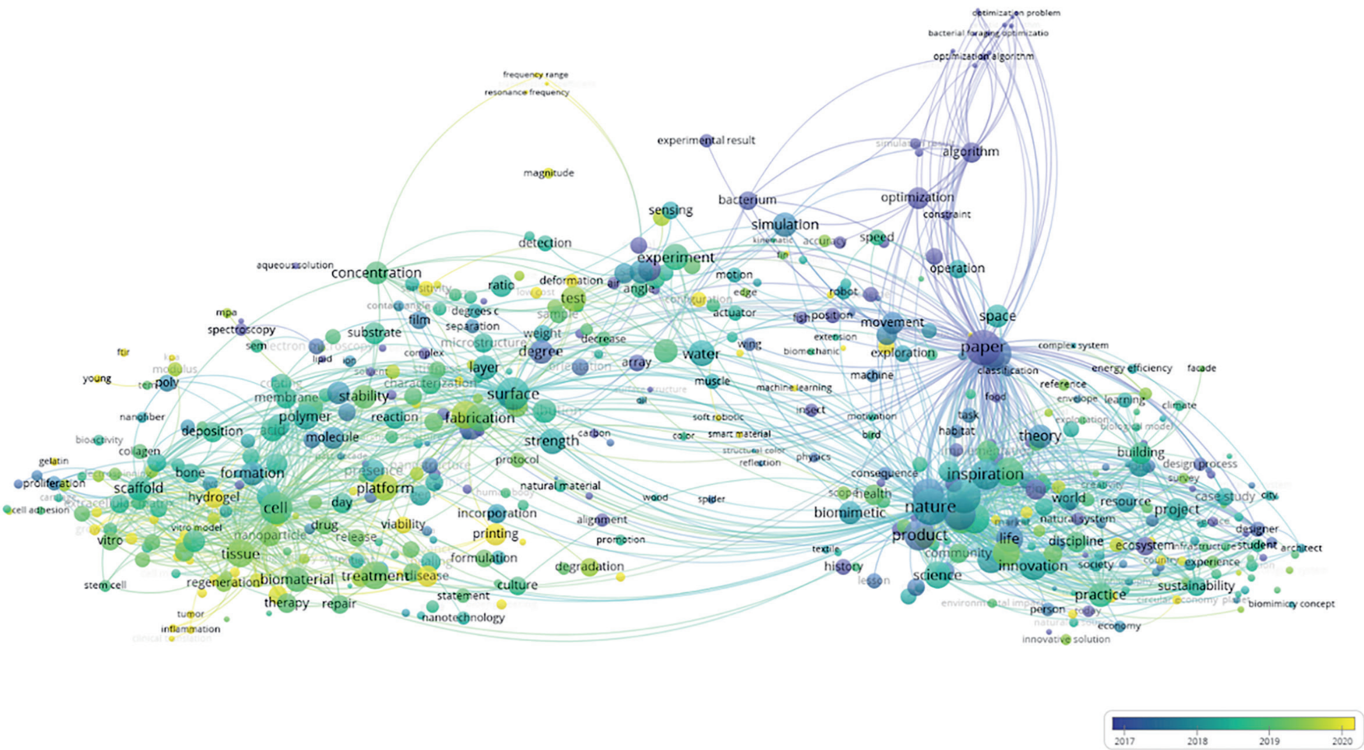

Fig. 1. Graphical analysis of the distribution of terms [13] in the publications focused on biomimicry based on the Web of Science database search (search date 26.06.2024) using the keyword "biomimicry".

Living organisms and the natural world are regarded as the key source of ideas for the functional design of sustainable built environments [1]; however, a structured and systematic approach is needed in order to understand and apply successfully these features of nature. According to A. Quintero et al. [2], organism, behavior, and ecosystem can be the objects of biomimicry – can be analyzed, imitated, and interpreted in engineering and design, including architecture and urbanism. Additionally, they distinguish five dimensions, which can occur either in organism, behavior, or ecosystem biomimicry: form, material, construction, process, and function. Other authors [8] and [14] distinguish the characteristics of natural systems and analyze how they can be applied.

J. M. Benyus [8] suggests looking at nature as a model, measure, and mentor [15]. For example, nature designs and constructs its forms to serve a specific function, resulting in efficient and sustainable structures [14]. In urbanism, the form-fits-function biomimicry principle can ensure that urban forms are functional, sustainable, and responsive to the needs of their inhabitants. According to Y. Uchiyama et al. [1], nature has inspired built space since antiquity, when natural proportions were borrowed for aesthetic purposes; however, currently, the focus is less on aesthetics and more on mimicking functional aspects of living systems. When analyzing the existing urban structures, this principle can be reflected in the correspondence between certain spatial configurations and their functionalities; for example, more dense urban morphology corresponds to higher functional diversity, city center or higher inhabitant density, etc.

In natural systems, the principle catalysis of cooperation is evident in symbiotic relationships, where different organisms work together to achieve mutual benefits, for example, mycorrhizal fungi and plant roots exchanging nutrients [16]. In urbanism, this principle reflects the kind of added value created by urban space for certain functions that bring/attract them together. This can promote a sense of community, resource sharing, and collaborative problem-solving within the urban environment.

According to M. B. Yassine and A. Razin [15], the morphology of organisms is perfectly adapted to the environment in which they live; this can be referred to as local contextuality. H. Mansour [14] notes that nature cooperates to fully use the habitat materials in the site; it utilizes local expertise and thus remains in balance with the biosphere. The local contextuality principle partially corresponds to behavior biomimicry in design, as it mimics how organs or organisms behave in the larger context. However, it can be expressed in other ways, too. In urbanism, this principle can be expressed as correspondence to local/cultural distributive and correlative codes and can be purposefully applied by designing buildings and city layouts that consider the local climate, culture, and geography, such as using local materials for construction, incorporating climate-responsive design features, and respecting existing topography and cultural heritage. This ensures that urban development is sustainable, resilient, and harmonious with its surroundings.

Natural systems can be characterized by the seamless flow and interconnectedness of ecosystems in space and time. This can be identified as continuity as nature does not have restrictions, as H. Mansour [14] notes. In natural habitats, food chains and nutrient cycles are uninterrupted, promoting biodiversity and ecological stability. According to M. B. Yassine and A. Razin [15], the goal of biomimetic architecture is not only to shape and measure space but also to develop synergistic relationships between the building and its environment in space and time. In urbanism, this principle can be reflected by designing continuous and interconnected green corridors, such as linear parks, greenways, and urban forests. These green spaces can link neighborhoods, provide wildlife habitats, mitigate urban heat island effects, and offer recreational opportunities, fostering a more sustainable and resilient urban environment. Additionally, continuity in urban design can promote walkability, cycling, and public transit, reducing dependency on cars and enhancing overall urban connectivity and livability.

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

According to M. Pawlyn [17] and Y. Uchiyama et al. [1], a characteristic of ecosystems is the tendency to optimize themselves and self-organize [5] for the good of the whole (total optimization) rather than for individual parts while maintaining the diversity of elements [1], this can be referred to as the integrity and self-organization of ecosystems. Thus, integrity and diversity are simultaneously present in the ecosystems. In urbanism, this principle can be applied by ensuring that all elements of the city, including infrastructure, public spaces, and services, are integrated and function cohesively and that urban structure would present itself as not broken urban structure without missing parts of large gaps. This can involve comprehensive urban planning that promotes seamless transportation networks, interconnected green spaces, and cohesive community services, ensuring that the city operates as a unified, efficient, and resilient system. Self-organization principles in urbanism can be applied to design cities that allow for decentralized decision-making and adaptability, enabling urban areas to evolve naturally in response to local needs. This can be achieved through flexible zoning, community-led initiatives, and modular infrastructure that adjusts over time based on human and environmental interactions.

Natural systems are characterized by the presence of multiple species or processes that serve similar functions, providing backup and enhancing resilience, such as various pollinators ensuring plant reproduction or multiple pathways for nutrient cycling – this is referred to as the redundancy of natural systems. When applying this in design and searching for inspiration in natural systems, N. Taylor Buck [18] recommends looking at organism "families" that face and solve the same problem in slightly different ways. In urbanism, this principle can be reflected as the existence of alternative choices for the same function, e.g. movement, and achieved by designing redundant systems for critical infrastructure, such as multiple transportation routes, backup power sources, and decentralized water management systems. This ensures that the city can continue to function smoothly in case of failures or disruptions, enhancing overall resilience and reliability.

According to M. Pawlyn [17], ecological systems are distributed and diverse, panarchically self-regulating. In urbanism, this principle of decentralization can be expressed as a heterocentric spatial structure and applied by creating a decentralized urban structure with multiple, self-sufficient neighborhoods that have their own amenities, services, and infrastructures. This reduces dependency on a central core, enhances local resilience, and promotes more balanced and sustainable urban growth.

In natural systems, elements serve multiple roles, such as wetlands providing habitat, water filtration, and flood control, or trees offering oxygen production, shade, and habitat. When applying the principle of multi-functionality in design and searching for inspiration in natural systems, N. Taylor Buck [18] recommends looking at organisms or systems with single solutions that solve multiple problems simultaneously. In urbanism, this principle can be expressed as mix of various functions in the same territory and applied by designing spaces and infrastructures that serve several purposes, such as green roofs that offer insulation, stormwater management, and recreational space, or public parks that provide social areas, environmental benefits, and spaces for physical activities. This maximizes the utility and efficiency of urban areas, making them more adaptable and resource-efficient.

According to H. Mansour [14], nature optimizes rather than maximizes, using the least materials and energy for optimal structure and function. As M. Pawlyn [17] notes, ecological systems run on current solar income. According to Y. Uchiyama et al. [1], energy-use optimization has been a central subject in biomimetic architecture. In urbanism, this principle of less energy consumption can be applied by designing energy-efficient buildings, promoting public transportation, and integrating renewable energy sources. Urban planning can also emphasize transit-oriented development and compact, walkable neighborhoods to reduce the need for long commutes, thereby lowering overall energy consumption and enhancing sustainability.

As H. Mansour [14] notes, nature uses an ordered hierarchy of structures. M. Pawlyn [17] distinguishes such features of hierarchical structure as the capability of growth and self-repair, environmental responsiveness, environmental influence of self-assembly, growth by adaptive accretion, and separate control of stiffness and fracture. In urbanism, this principle can be expressed as strongly expressed patterns of center and periphery at different levels and applied by structuring cities with clear, functional hierarchies, such as central business districts, secondary commercial areas, residential zones, and local neighborhoods. This hierarchical organization ensures efficient resource distribution, easy navigation, and effective management of urban growth and services.

Self-similarity of patterns repeating at different scales – fractality – is often underlined as an important principle in natural systems that can be employed in designing artificial environments [11], [12]. Researchers encourage exploring natural growth patterns and their application in architecture [1]. According to A. Gertik and A. Karaman [12], cities that are designed with fractal form play an important role in ensuring the continuity of urban space and the interrelationships of urban parts. In urbanism, this principle can be reflected by demonstration of similarity to fractal structure in terms of variety of scale, porosity, etc. and achieved by designing city layouts and structures that exhibit fractal-like characteristics, where smaller-scale elements like street patterns or building designs echo larger-scale patterns in the city's overall layout or architectural style. This can create visual coherence, optimize land use, and enhance connectivity across different scales within the urban fabric.

According to G. Pohl and W. Nachtigall [5], technology is nothing other than the continuing of natural evolution with other means. Thus, according to this outlook, technology is not something principally different from nature. G. Pohl and W. Nachtigall [5] note that aside from pragmatic needs for differentiation, there are no compelling reasons why nature and technology should then be considered opposites, as has occurred in the past. Considering this approach and based on the analysis of literature presented above, 12 features of natural systems applicable in the biomimetic urbanism – form fits function, catalysis of cooperation, local contextuality, continuity, diversity, integrity, redundancy, decentralization, multi-functionality, less energy consumption, hierarchy, and fractality – were distinguished. In Table I, each feature is presented as it appears in natural systems and its possible applications in urbanism.

TABLE I

Features of Natural Systems [14], [18], [15], [17], [1], [12] and Their Potential Biomimetic Applications in Urbanism

Catalysis of cooperation	Symbiotic relationships, where different organisms work together to achieve mutual benefits	Added value created by urban space for certain functions that brings/attracts them together. Designing spaces that foster community interaction and cooperation, such as mixed-use developments that combine residential, commercial, and recreational areas, or public spaces like parks and community centers that encourage social interaction and collective activities.
Local contextuality	Organisms and ecosystems adapting to their specific local environments	Correspondence to local/cultural distributive and correlative codes. Designing buildings and city layouts that consider the local climate, culture, and geography, such as using local materials for construction, incorporating climate-responsive design features, and respecting existing topography and cultural heritage.
Continuity	Seamless flow and interconnectedness of ecosystems is space and time	Evolutionary development of urban spatial structure in space and time. Designing continuous and interconnected green corridors, such as linear parks, greenways, and urban forests. These green spaces can link neighborhoods, provide wildlife habitats, mitigate urban heat island effects, and offer recreational opportunities, fostering a more sustainable and resilient urban environment. Promote walkability, cycling, and public transit, reducing dependency on cars and enhancing overall urban connectivity and livability.
Diversity	A variety of species and ecosystems, which enhances resilience, adaptability, and ecological balance, such as the biodiversity of a rainforest contributing to its stability and productivity	Diversity of functions and/or spatial codes. Creating diverse land uses, housing options, and public spaces, promoting a mix of cultural, social, and economic activities.

Continuation of Table I

Integrity	Cohesion and stability of ecosystems, where each component, from organisms to processes, works together to maintain balance and health, such as the interconnected roles of plants, animals, and microorganisms in a forest	Ensuring that all elements of the city, including infrastructure, public spaces, and services, are integrated and function cohesively and that urban structure would present itself as not broken urban structure without missing parts of large gaps. Comprehensive urban planning that promotes seamless transportation networks, interconnected green spaces, and cohesive community services, ensuring the city operates as a unified, efficient, and resilient system.
Self-organization	Species, resources, and environmental factors naturally balance each other, creating stable yet adaptive systems	Urban design that allows for adaptable, decentralized, and resilient cities, where elements like transportation, energy, and infrastructure evolve in response to local needs and conditions without centralized control.
Redundancy	Presence of multiple species or processes that serve similar functions, providing backup and enhancing resilience, such as various pollinators ensuring plant reproduction or multiple pathways for nutrient cycling	The existence of alternative choices for the same function, e.g. movement, achieved by designing redundant systems for critical infrastructure, such as multiple transportation routes, backup power sources, and decentralized water management systems.
Decentralization	Distributed control and functionality across various organisms and processes, such as ant colonies operating through local interactions without a central authority or the widespread root networks of plants distributing nutrients and support	Heterocentric spatial structure applied by creating a decentralized urban structure with multiple, self-sufficient neighborhoods that have their own amenities, services, and infrastructures.; Reducing dependency on a central urban core, enhances local resilience and promotes more balanced and sustainable urban growth.
Multi-functionality	Elements that serve multiple roles, such as wetlands providing habitat, water filtration, and flood control, or trees offering oxygen production, shade, and habitat	Mix of various functions in the same territory. Designing spaces and infrastructures that serve several purposes, such as green roofs that offer insulation, stormwater management, and recreational space, or public parks that provide social areas, environmental benefits, and spaces for physical activities.
Less energy consumption	Efficient energy use and resource optimization, such as birds migrating using thermal currents to conserve energy or plants maximizing sunlight absorption through optimal leaf arrangements	Designing energy-efficient buildings, promoting public transportation, and integrating renewable energy sources. Emphasize transit-oriented development, compact, walkable neighborhoods to reduce the need for long commutes, thereby lowering overall energy consumption and enhancing sustainability.
Hierarchy	Organized levels of structure and function, such as ecosystems being organized into species, populations, communities, and biomes, each level interacting and supporting the others	Strongly expressed patterns of center and periphery at different levels. Structuring cities with clear, functional hierarchies, such as central business districts, secondary commercial areas, residential zones, and local neighborhoods in order to ensure efficient resource distribution, easy navigation, and effective management of urban growth and services.
Fractality	Self-similar patterns repeating at different scales, such as the branching patterns of trees mirroring the patterns of their branches and twigs	City layouts and structures that exhibit fractal-like characteristics, where smaller-scale elements like street patterns or building designs echo larger-scale patterns in the city's overall layout or architectural style in order to create visual coherence, optimize land use, and enhance connectivity across different scales within the urban fabric.

II. Present Urban Theories and Models which Could Be Used for Urban Biomimicry

A mix of various urban models, concepts, and ideas are used by urban planners nowadays depending on the local situation, actualities, political decisions, or even personal preferences. Some of them are applied more at the level of strategic planning and some at the scale of urban design. Few models could be used together and create either positive or negative synergies. Without claiming to present an exhaustive list of urban models, the following could be mentioned as the most often employed by planners:

- *New Urbanism* focuses on mixed-use development and sustainable communities. It promotes compact design, green spaces, and community interaction. To describe and manage urban spatial structure, it employs the concepts of neighborhood as compact, walkable, and diverse communities that foster a strong sense of place and social interaction; specialized district based on the neighborhood model, and corridor as a linear urban center [19]. It is important to point out that New Urbanism turns back to traditional, pre-modernistic urban forms as their sources of inspiration.

- *Modernist Urbanism* is based on the ideas of Le Corbusier and emphasizes mono-functional zoning, high-rise buildings, and the separation of living, working, and recreational spaces. It most often prioritizes car travel and large infrastructure projects [20]. Even though the anonymity of public spaces and transformation of a street into a road by modernistic urbanism was criticized in the Charter of New Urbanism, it still is used by planners either as a model for specific districts within the concept of New Urbanism (e.g. University campus) or even at a whole city scale. A lot of urban territories which still function today are planned based on it.
- *Tactical Urbanism* involves small-scale, temporary changes to urban environments, like pop-up parks or pedestrian plazas, to test ideas and improve public spaces before permanent solutions are implemented [21]. Quite often, Tactical Urbanism is identified with Acupunctural Urbanism: both models focus on local scale interventions, but the second one points out the strategic importance of selected spots and grounds its ideas on some biomimicry ideas. The first one aims at relatively quick improvements, while the second one focuses on long-term results, etc.
- *Smart Growth* is a theory in urban planning and transportation that emphasizes concentrating development in compact, walkable urban areas to prevent urban sprawl. It promotes land use that is dense, transit-accessible, pedestrian-friendly, and supportive of cycling. This approach includes features like local schools, streets designed for multiple modes of transport, and mixed-use developments that offer diverse housing options. The term “smart growth” is widely used in North America, while in Europe, especially in the UK, similar principles are often referred to as the “compact city” model [22]. It looks similar to New Urbanism, but while Smart Growth focuses more on policy and regional planning, New Urbanism emphasizes the physical design and form of neighborhoods and communities.
- *Transit-Oriented Development (TOD)* focuses on high-density, mixed-use development around public transportation hubs to reduce car dependence and enhance accessibility [23]. The TOD approach is quite often used for the renovation of either urban suburbs or modernistic districts. It could be easily combined with Acupuncture Urbanisms or other models.
- *Sustainable Urbanism* is a very wide concept that “focuses on promoting long-term viability by reducing consumption, waste and harmful impacts on people and place while enhancing the overall well-being of both people and place” [24]. It points out ecological, economic, social, and cultural aspects of city functioning. As the above-mentioned principles are quite general, various attempts to describe sustainable urban form are made, e.g. the Urban Scale Sustainability Compass [25]. It is a framework for sustainable urban development, focusing on four dimensions: social equity, environmental impact, economic resilience, and governance. The idea is that it should help cities balance human needs with ecological limits, guiding planners and policymakers toward more sustainable, livable cities while offering a list of more details aspects to be considered in planning (e.g. cultural identity, integration, quality of public spaces, perception, urban structure) and some quantitative criteria to describe them.
- *Acupunctural Urbanism* is inspired by an analogy between the human body, the city and the theory of Acupuncture from Ancient China. It focuses on small, strategic interventions in urban areas that catalyze widespread change, similar to how targeted points in acupuncture affect the entire body [26]. In essence, it could be combined with many other urban models and especially New Urbanism.
- *Christopher Alexander’s Pattern Language* makes a framework of design patterns that focuses on human-centered architecture and urban design. It emphasizes creating spaces that meet people's social, emotional, and cultural needs through repeatable, adaptable patterns [27]. It is important to point out that, according to Alexander, patterns are interconnected in a fractal or network way: bigger ones contain smaller ones. The actuality of this fundamental concept, which was presented in the 80th of the 20th century, could be confirmed by the recent continuation of this idea by Mehaffy while adding 80 new patterns with the aim to reflect “… to expand the capacity of pattern language in support of a hopeful new era in support of open-source, human-centered, life-enriching technology” [28]. Despite the more frequent application of pattern language in research than in urban planning, some examples demonstrate good possibilities to do it [29].
- *Landscape or Conservative Urbanism* suggests that landscape, rather than buildings, should be the organizing principle of urban planning. It emphasizes the integration of natural systems and open spaces into the urban fabric [30]. In this case, urban structure is defined and adapted to natural situations. This urban model, if applied at a more conceptual level, looks at a city as a collection of landscapes: “The city of the future will be an infinite series of landscapes: psychological and physical, urban and rural, flowing apart and together. They will be mapped and planned for special purposes, with the results recorded in geographical information systems (GIS), which have the power to construct and retrieve innumerable plans, images, and other records” [31].
- *Participatory Urbanism* should be seen as a paradigm in urban planning that states that the engagement of citizens in the design and planning process is crucial for

ensuring that urban development reflects the needs and desires of the community through collaborative decision-making [32]. Many methodologies are suggested for this purpose, such as semi-structured interviews, participatory mapping and modelling, timelines and trend and change analysis, daily time-use analysis, oral histories and ethno-biographies, e-mapping, etc. [33].

- *Inclusive Urbanism* seeks to create equitable urban environments that serve diverse populations, addressing issues of social justice, accessibility, and affordable housing: "People are at the heart of smart, livable cities. However, many cities are not properly planned and built to serve their diverse populations, with women and girls, people with disabilities, older persons, and children left vulnerable and marginalized" [34]. In essence, as a more strategic aim, it can employ tools of Inclusive Urbanism or be seen as an umbrella for New Urbanism designs, etc.
- *The 15-minute city concept* envisions urban areas where all essential services and amenities are accessible within a 15-minute walk or bike ride from home. This approach aims to reduce reliance on cars, enhance local economies, and improve quality of life by promoting convenience, sustainability, and community engagement. The term was coined by Carlos Moreno [35] and was and is easily translated from theory into urban policy and into political programs that resonate with wider urban society. Besides that, even if it could be seen as a form of New Urbanism, the 15-minute city concept catalyzed the actualization of walkability analysis and modelling while using GIS and other recent analysis and design technologies.

After the presentation and short review of the most popular urban models, the next question arises: Are they compatible with the earlier-named principles of biomimicry urbanism?

TABLE II

The First Part of the Matrix Representing Synergies Between Biomimicry Principles and Urban Models Deep green color – strong support for the principles; light green – support; orange – not natural support, but could be depending on specific design solutions; red – rather no support)

	New Urbanism	Modernistic Urbanism	Tactical Urbanism	Smart Growth	Transit-Oriented Development	Sustainable Urbanism
Form fits function	Supports. Creates walkable, mixed-use neighbourhoods enhancing social and functional needs.	Often does not support. Emphasizes form over functional integration.	Supports. Uses small-scale, adaptable projects to address specific needs.	Supports. Promotes compact, efficient land use that supports various functions.	Supports. Aligns high-density development with transit access.	Supports. Integrates environmental and social functions into urban form.
Catalysis of cooperation	Supports. Promotes mixed-use spaces that integrate various functions depending on neighbourhood or district type.	Most often does not support. Separates functions, disrupting natural integration.	Strongly supports. Uses flexible, temporary projects to enhance function-space interaction.	Supports. Encourages compact development that balances functions and space.	Supports. Integrates high-density development with transit infrastructure.	Supports. Harmonizes environmental, social, and functional aspects.
Local contextuality	Generally supports local contextuality with walkable, human-scale neighbourhoods that often reflect traditional local design, though it may apply uniform principles.	Largely ignores local contextuality by favouring standardized designs that overlook specific local characteristics.	Supports local contextuality with small, temporary interventions tailored to local needs and contexts.	Can support local contextuality by considering local culture and geography but may sometimes apply broad principles that lack local adaptation.	Partially supports local contextuality by focusing on transit hubs, though it may lead to standardization rather than reflecting local specifics.	Generally supports local contextuality by integrating environmental and social sustainability into local conditions, though global goals can sometimes overshadow local nuances.
Continuity	Supports continuity with traditional, mixed-use, walkable neighbourhoods but may sometimes apply designs that disrupt historical continuity.	Does not support continuity due to radical, functionalist designs that break with historical and spatial contexts	Partially supports continuity through temporary, flexible interventions, though these may not always integrate long term.	Supports continuity by promoting compact, mixed-use developments that integrate with existing infrastructure and enhance sustainability.	Supports continuity by linking growth with transit systems, though heavy focus on transit hubs may disrupt older areas.	Supports continuity by aligning development with existing environmental and social conditions for long-term sustainability.

Continuation of Table II

	New Urbanism	Modernistic Urbanism	Tactical Urbanism	Smart Growth	Transit-Oriented Development	Sustainable Urbanism
Diversity	Supports diversity with mixed-use, walkable communities but may sometimes limit typological variety with nostalgic designs.	Does not support diversity well due to functional zoning and uniform styles, leading to reduced social and functional variety.	Supports diversity with flexible, small-scale interventions, though its temporary nature may limit long-term diversity.	Supports diversity through compact, mixed-use, and transit-friendly developments, fostering social and functional integration.	Supports functional diversity around transit hubs but may not fully support social or typological diversity.	Supports diversity by balancing environmental, social, and economic needs, encouraging a range of housing and functions.
Integrity	Supports integrity and cohesion with mixed-use, walkable neighbourhoods integrating residential, commercial, and recreational spaces.	Often hinders integrity and cohesion with functional zoning and standardized designs, leading to fragmented urban structures.	Supports cohesion with flexible, temporary interventions that connect different city areas, though its short-term nature may affect long-term integrity.	Supports integrity and cohesion through compact, mixed-use developments and efficient land use that integrate various functions.	Supports cohesion by integrating transit systems with mixed-use developments, enhancing connectivity.	Supports integrity and cohesion by balancing environmental, social, and economic factors for cohesive, sustainable growth.
Redundancy	Strongly supports redundancy with mixed-use developments where functions coexist closely, enhancing resilience.	Generally does not support redundancy due to its focus on functional segregation, reducing overlapping uses.	Strongly supports redundancy with flexible, temporary interventions that introduce multiple uses and adaptable spaces.	Supports redundancy through compact, mixed-use developments that integrate various functions in the same areas.	Supports redundancy to some extent with mixed-use hubs around transit stations, though it may prioritize transit efficiency.	Supports redundancy by integrating diverse functions into urban spaces, promoting resilience through overlapping uses.
Decentralization	Supports decentralization by promoting walkable, mixed-use neighbourhoods that create self-sufficient communities, reducing reliance on a central core.	Generally does not support decentralization due to its focus on centralized planning and functional zoning.	Strongly supports decentralization with small-scale, localized interventions that foster unique functions and uses in different city areas.	Supports decentralization by encouraging compact, mixed-use developments throughout the city, balancing growth and reducing central reliance.	Strongly supports decentralization with mixed-use hubs around transit stations, spreading functions across multiple nodes.	Supports decentralization by promoting diverse, self-sufficient neighbourhoods, reducing reliance on central infrastructures.
Multi-functionality	Strongly supports multi-functionality with mixed-use developments where residential, commercial, and recreational functions coexist in walkable neighbourhoods.	Generally does not support multi-functionality due to its emphasis on functional zoning and separation of uses.	Supports multi-functionality with temporary, flexible interventions that enhance multiple uses within spaces.	Supports multi-functionality with compact, mixed-use developments that integrate various functions within the same areas.	Supports multi-functionality by creating mixed-use hubs around transit stations, integrating different functions.	Supports multi-functionality by promoting diverse, integrated uses that balance environmental, social, and economic needs.
Less energy consumption	Supports less energy consumption with walkable, mixed-use neighbourhoods that reduce car travel and incorporate energy-efficient design.	Generally does not support less energy consumption, often leading to higher energy use due to reliance on cars and centralized infrastructure.	Can support less energy consumption with temporary, localized interventions that promote sustainable behaviours and reduce car use.	Supports less energy consumption with compact, mixed-use development that shortens travel distances and integrates sustainable infrastructure.	Strongly supports less energy consumption by focusing development around transit hubs, reducing reliance on personal vehicles.	Strongly supports less energy consumption through energy-efficient design, renewable energy, and sustainable practices.

Continuation of Table II

	New Urbanism	Modernistic Urbanism	Tactical Urbanism	Smart Growth	Transit-Oriented Development	Sustainable Urbanism
Hierarchy	Supports a clear hierarchy with neighbourhoods having distinct centres, edges, and transitions, creating organized public and private zones.	Supports a clear hierarchy through functional zoning and large-scale planning, though it can sometimes lead to rigid segregation.	Does not support a clear hierarchy; its flexible, temporary interventions can result in a less organized structure.	Supports a clear hierarchy with compact, mixed-use developments that create well-defined centres and neighbourhoods.	Supports a clear hierarchy by focusing development around transit hubs, structuring the urban framework into central nodes and surrounding areas.	Supports a clear hierarchy to some extent but emphasizes integration, which can blur hierarchical boundaries.
Fractality	Supports fractality by promoting walkable, mixed-use neighbourhoods with varied scales, though traditional patterns may limit fractal expression.	Does not support fractality due to its emphasis on large, uniform designs and clear functional separations.	Strongly supports fractality with small, flexible interventions that create diverse, overlapping patterns.	Supports fractality by encouraging compact, mixed-use developments with varied scales and functions, though not explicitly focused on fractal patterns.	Supports fractality by developing diverse activity nodes around transit hubs, creating a complex urban structure.	Strongly supports fractality with integrated designs that reflect natural systems and patterns.
Self-organization	Supports self-organization by promoting walkable, mixed-use neighbourhoods that adapt to local needs and conditions.	Generally does not support self-organization due to its top-down planning and strict zoning, limiting organic development.	Strongly supports self-organization with flexible, temporary interventions that adapt to local feedback and needs.	Supports self-organization by encouraging compact, mixed-use developments, though it includes some centralized planning.	Supports self-organization by creating adaptable, mixed-use hubs around transit nodes, with some planning involved.	Supports self-organization with designs that evolve in response to environmental and social changes.

TABLE III

The Second Part of Matrix Representing Synergies Between Biomimicry Principles and Urban Models (Deep green color – strong support for the principles; light green – support; orange – not natural support, but could be depending on specific design solutions; red – rather no support)

	Acupunctural Urbanism	Christopher Alexander's Pattern Language	Landscape or Conservative Urbanism	Participatory Urbanism	Inclusive Urbanism	15-Minute City
Form fits function	Supports. Targets specific issues with focused, functional interventions.	Supports. Designs are based on human needs and successful patterns.	Might support depending on the situation. Preserves natural and historical forms to meet environmental and cultural needs.	Supports. Ensures urban forms meet community needs through inclusive design processes.	Supports. Design spaces to be accessible and equitable for all.	Supports. Ensures most needs are met within a 15-minute walk or bike ride.
Catalysis of cooperation	Supports. Targets specific needs with precise interventions.	Strongly supports. Designs are based on human needs and behaviours.	Supports. Aligns functions and space with natural and historical contexts.	Supports. Reflects community needs and preferences in design.	Supports. Creates accessible and equitable spaces for all.	Strongly supports. Ensures daily needs are within a short walk or bike ride.
Local contextuality	Strongly supports local contextuality with targeted interventions addressing specific local issues and enhancing neighbourhood character.	Strongly supports local contextuality by using design patterns that arise from local needs and conditions.	Strongly supports local contextuality by preserving natural and historical contexts, integrating local characteristics.	Strongly supports local contextuality by involving residents in the design process to reflect local needs and identity.	Strongly supports local contextuality by addressing the needs of diverse groups and reflecting local social and cultural diversity.	Can support local contextuality by creating compact, self-sufficient neighbourhoods, though it may overlook unique local contexts due to its universal proximity focus.

Continuation of Table III

	Acupunctural Urbanism	Christopher Alexander's Pattern Language	Landscape or Conservative Urbanism	Participatory Urbanism	Inclusive Urbanism	15-Minute City
Continuity	Strongly supports continuity with small, targeted interventions that revitalize without large-scale disruptions.	Strongly supports continuity by evolving from traditional patterns, maintaining spatial and cultural integrity.	Strongly supports continuity by preserving natural landscapes and historical elements, integrating with the past.	Supports continuity by involving communities in planning, reflecting local histories and needs.	Supports continuity by creating spaces for diverse populations, promoting long-term social cohesion.	Supports continuity with compact, mixed-use neighbourhoods that evolve gradually, minimizing disruptions.
Diversity	Supports diversity through targeted interventions addressing local needs and fostering functional and social diversity.	Strongly supports diversity with human-centred designs that adapt to local needs, ensuring long-term variety.	Supports diversity to a limited extent by preserving historical or natural contexts, which may restrict typological change.	Strongly supports diversity by involving various stakeholders, reflecting the community's social, functional, and typological needs.	Strongly supports diversity by ensuring accessibility and equity, catering to various social groups and functions.	Supports diversity with mixed-use, self-sufficient neighbourhoods, encouraging a variety of functions and housing types.
Integrity	Supports cohesion with small-scale interventions that enhance functional integration without large-scale disruption.	Strongly supports integrity and cohesion with organic, human-centred designs that align with local needs.	Supports integrity by preserving natural and historical landscapes, though it may limit new, integrative developments.	Supports integrity and cohesion by involving the community in planning, ensuring urban structures reflect local needs.	Supports integrity and cohesion by designing accessible and equitable spaces, integrating diverse needs into a cohesive framework.	Strongly supports integrity and cohesion with compact, self-sufficient neighbourhoods where essential functions are within a 15-minute walk or bike ride.
Redundancy	Supports redundancy with targeted interventions that introduce multiple functions, enhancing adaptability.	Supports redundancy with designs that allow multiple uses within the same space, fostering flexibility.	May not support redundancy due to its focus on preserving existing landscapes, which can limit multifunctional spaces.	Supports redundancy by involving the community in planning, leading to designs with multiple functions and adaptable spaces.	Supports redundancy by creating spaces for various social groups and functions, enhancing adaptability.	Strongly supports redundancy by designing neighbourhoods with essential services close together, reducing reliance on long-distance travel.
Decentralization	Supports decentralization through small-scale interventions that enhance multiple decentralized areas.	Supports decentralization with designs that reflect local needs, promoting organic, decentralized growth.	May not strongly support decentralization, as preserving landscapes can reinforce centralization around historic areas.	Supports decentralization by involving community members in planning, creating multiple, locally-driven centres.	Supports decentralization by designing accessible spaces throughout the city, distributing functions and services.	Strongly supports decentralization by creating compact neighbourhoods where essential services are nearby, reducing central hub reliance.
Multi-functionality	Supports multi-functionality with targeted interventions that introduce diverse functions within specific areas.	Strongly supports multi-functionality with designs that incorporate various uses within the same spaces.	May not strongly support multi-functionality, as it focuses on preserving natural and historical landscapes, which can limit diverse uses.	Supports multi-functionality by involving community input, creating spaces that reflect diverse needs and functions.	Supports multi-functionality by designing spaces for various social groups and activities, promoting a range of uses.	Strongly supports multi-functionality with compact neighbourhoods where essential services and functions are integrated within short distances.
Less energy consumption	Supports less energy consumption with targeted interventions that improve local energy efficiency and sustainability.	Supports less energy consumption with designs that align with natural systems and include energy-efficient practices.	May support less energy consumption by preserving landscapes and promoting sustainability, though it may limit innovative measures.	Supports less energy consumption by incorporating community input for energy-efficient and sustainable urban spaces.	Supports less energy consumption with designs that include energy-efficient features and promote sustainability.	Strongly supports less energy consumption by creating compact neighbourhoods where essential services are within short distances.

Continuation of Table III

	Acupunctural Urbanism	Christopher Alexander's Pattern Language	Landscape or Conservative Urbanism	Participatory Urbanism	Inclusive Urbanism	15-Minute City
Hierarchy	Does not support a clear hierarchy. Its localized interventions can lead to a less structured, piecemeal approach.	Supports a clear hierarchy with designs reflecting natural patterns, creating a well-structured urban environment.	Supports a clear hierarchy by integrating historical and natural features into the urban structure.	Supports a clear hierarchy by incorporating community input, resulting in a structure based on local needs, though it may vary.	Supports a clear hierarchy by designing spaces for diverse needs, creating an organized structure with an emphasis on accessibility and flexibility.	Supports a clear hierarchy with well-defined centres and surrounding areas, organizing essential services and functions within a structured framework.
Fractality	Supports fractality through localized interventions that enhance and integrate with existing patterns.	Strongly supports fractality with designs reflecting natural patterns and recursive structures.	May not strongly support fractality, focusing more on preserving traditional landscapes.	Supports fractality by incorporating diverse inputs, resulting in a varied urban structure.	Supports fractality with designs that address diverse needs, creating a layered, interconnected urban fabric.	Supports fractality by creating self-sufficient neighbourhoods with integrated functions, though not explicitly focused on fractal patterns.
Self-organization	Supports self-organization through small-scale interventions that integrate with existing patterns, allowing for adaptive development.	Strongly supports self-organization with designs reflecting natural patterns and local needs, promoting organic growth.	May not strongly support self-organization due to its focus on preserving historical landscapes, which can constrain flexible development.	Strongly supports self-organization by involving the community in planning, resulting in urban structures that reflect local needs and evolve organically.	Supports self-organization by designing spaces that accommodate diverse needs, encouraging organic growth and adaptation.	Supports self-organization by creating compact neighbourhoods with integrated services, allowing for local adaptation and growth.

Evaluation of how biomimicry principles are supported or not by the discussed urban models is presented in Table II. It could not be seen as totally objective as it reflects the authors' experience and knowledge, so for sure, some smaller differences could appear if it were given to a bigger number of experts or based on a sociological survey. Nevertheless, we believe that the results represent some essential tendencies and possibilities of urban modelling while clearly stating that modernistic urbanism is least supportive of biomimicry, and all the other models could be seen as biomimicry-friendly and supportive of each other. The question can be asked: Can those principles be used effectively for the comparison of urban situations and projects? Table III presents three selected biomimicry urbanism examples, all of them at the urban level, relying on several of the elements found in nature. The use of water resources ("water urbanization") is often seen, as is the location of settlements next to areas of dense vegetation, such as forests or deserts. The analysis of the selected examples according to the principles of biomimicry is presented in Table IV.

TABLE IV

Biomimicry Examples at the Urban Level [36], [37], [38]

Biomimicry project title	**Biomimicry element(s) used**
Hammarby Sjöstad, Stockholm, Sweden	*Water cycles* The district has developed a system that simulates the natural processes of water purification and recycling. Collected rainwater is filtered and used as clean water for domestic use. *Ecosystem simulation* The district uses an efficient waste management system that resembles natural ecosystems where nothing is waste. Organic waste is recycled into biofuels and fertilizers. *Energy as an analogue of natural systems* The district uses an integrated energy production system where energy from waste, solar energy and biofuels are used together to create a closed energy cycle. *Different scale environments* The architecture and infrastructure of the district have been designed to integrate buildings and green spaces into the environment.

Biomimicry project title	**Biomimicry element(s) used**
Arcosanti, Arizona, United States of America	*Mimicking* The Arcosanti buildings have been designed to mimic natural ecological processes in order to maximize the use of solar energy. The buildings are oriented to receive maximum sunlight in winter and to be protected from excessive heat in summer. Natural phenomena The town uses natural wind management, similar to natural desert and forest ecosystems that regulate air flows. Wind flows help to cool buildings naturally and reduce energy demand. *Water* Arcosanti uses autonomous water harvesting and purification systems that mimic the natural water cycles in the desert. This system reduces water waste and optimizes resource use by mimicking the natural water treatment processes of ecosystems. *Natural materials* The buildings rely on natural materials, such as concrete and local minerals, which are efficient in storing and retaining heat. This is similar to natural methods where materials adapt to environmental conditions and optimize energy use.

Continuation of Table IV

Biomimicry project title	Biomimicry element(s) used
Waldstadt, Baden-Württemberg, Germany. The district was first referred to as Arbeitslosenwald ("forest of the unemployed").	*Imitation of natural energy* The design of the buildings mimics forest structures to optimize natural light and heat regulation. Similar to a forest, the orientation and design of the buildings are aimed at maximizing solar gain while naturally regulating internal temperatures. *Water and its filtration* The neighborhood employs systems that mimic the moisture regulation mechanisms of a forest. This includes rainwater harvesting and processing systems, akin to how a forest ecosystem naturally manages the water cycle. *Forest infrastructure* The urban layout and buildings integrate green spaces, similar to the role of vegetation and trees in a forest ecosystem. This integration helps maintain air quality and contributes to ecological sustainability. *Material and structural adaptation* The buildings use materials and structures that mimic forest textures and forms, ensuring aesthetic harmony with the environment while promoting sustainable energy use.



If the earlier described urban biomimicry principles are applied for analysis of the above presented three cases, it could be concluded that they all, as functional urban structures or systems to a certain degree, meet the principles "form fits function" and "catalysis of cooperation". Either directly or indirectly, they implement the principle of "local contextuality": the first project addresses urban local context more, while the second and the third address natural context. The projects seek to implement a "diversity" of urban spaces by combining buildings and nature. "Multi-functionality" could be named as addressed, at least in a similar way. "Less energy consumption" could be identified as quite a straightforward principle utilized in the projects through waste reduction, solar energy usage, modelling of water cycles, etc. Inclusions of nature and adaptation to its structure in the projects increase fractality in both visual spaces and the structure of functional spaces. "Self-organization" could be seen as assured, at least by a kind of ecocentric approach where natural spaces become an organizer of a whole structure, as in Conservative Urbanism. The same is true for the implementation of the "continuity" principle. It is hard to say anything precise about "integrity", "redundancy", "decentralization", and "hierarchy" without a more detailed study of the project, but such features probably exist in all of them as in many other urban structures.

As a result of the comparison of the urban models in terms of how they correspond to the principles of urban biomimicry and the short but illustrative analysis of three cases, the following conclusions could be pointed out:

- The analysis of the urban models demonstrated that modernistic urbanism is the least supportive of biomimicry, and all the other models could be seen as biomimicry-friendly and supportive of each other.
- As New Urbanism, which can demonstrate positive synergies with the other urban models, is looking for inspiration from the past, we can speak about a kind of inherited biomimicry and learn from nature and certain urban structures.
- Biomimicry principles are still described in quite general terms and, depending on selected urban samples, as it will be demonstrated further, it might be hard to compare them. In such a case, quantitative indicators that might describe the degree of expression of the biomimicry principles in an urban structure are needed.

III. Can Simulative Modelling be Employed for Quantitative Analysis of Biomimicry in Urbanism?

Why simulative models? As outlined in the introduction, the biomimicry perspective, when applied to cities, suggests viewing them as complex organisms. The modelling of such systems, as highlighted by R. Siegfried [39], necessitates specific simulation models that enhance understanding and provide predictive capabilities – crucial given the dynamic nature of cities as complex systems [40].

Urban planning employs three primary simulation models: agent-based modelling, cellular automata, and mathematical graph-based models. The last one is considered the most versatile across different fields and scales of application and can even serve as the foundation for other models, such as agent-based modelling. The introduction of the mathematical graph model for urban structures was led by several researchers starting in the 1980s. For instance, B. Hillier introduced the space syntax theory, which allows the analysis of urban structures by simulating human movement and examining visual connectivity using isovistas (visually perceived polygons of spaces) [41]. A. Turner later developed and released Depthmap software for public use in Space Syntax modelling [42].

Additionally, S. Porta and V. Latora advanced multiple centrality assessment models for urban analysis [43], [44], [45]. M. Batty, in his work *The New Science of Cities*, also promoted the mathematical graph model for urban planning [46]. A. Sevtsuk employed the same mathematical framework to analyze and model pedestrian movement in cities, developing a GIS-based tool for this purpose [47]. S. McElhinney further developed a visual graph analysis for Space Syntax with a specialized tool [48]. Additionally, C. H. V. Cooper and A. J. F. Chiaradia created sDNA, a GIS tool offering broader calculations for urban-scale modelling compared to Depthmap [49].

Despite the diversity of models and tools, all these approaches are grounded in the same mathematical graph model, where each spatial structure is viewed as a network of nodes and links. Depending on the scale and purpose, nodes and links are defined differently. For instance, Depthmap and Space Syntax represent straight axes, street segments, and visually perceived "cells" as nodes, with intersections and visibility serving as links [42]. Meanwhile, the Multiple Centrality Assessment Tool treats street intersections as nodes and street segments as links [50]. Similarly, Sevtsuk's UNAT tools view buildings as nodes and streets as links.

Despite these variations, all models share a common view of the city as a network of spaces or objects, facilitating social, economic, and cultural interactions – echoing Gabriel Dupuy's concept of Network Urbanism [51].

The mathematical foundation of graph theory focuses on calculating the importance or "centralities" of graph nodes. While the exact formulas and specific centralities will be discussed later, a basic explanation of three centrality types is provided:

- Degree centrality [52] measures the number of direct connections a node has. In urban spaces, this corresponds to the number of access points connecting one space to others, influencing visibility, accessibility, and openness.
- Closeness centrality [53] is the sum of distances from a node to all other nodes in the network. A lower sum identifies nodes that are more accessible, attracting more users and activities in urban contexts.
- Betweenness centrality [54] calculates how often a node lies on the shortest paths between other nodes. In urban analysis, it indicates spaces with the highest potential for transit and movement.

Could simulative models be related to the above-identified principles of biomimicry in principle? Before analyzing the possibilities of each principle to be reflected, the first question is if we have research that confirms that mathematical graph-based modelling, which most often uses only data of urban spatial configuration, is reflecting not only certain aspects of morphology but more complex urban functioning.

Marcus states that Space Syntax, as one of the mathematical graph-based models, is not only a configurational theory of architecture but an analytical, scientifically founded theory. While combining Space Syntax theory with urban morphology he points out that in Stockholm the most significant correlations are "…between integration (the most often used in modelling Space Syntax indicator or centrality) and movement of people; accessible building density and population; accessible plots and diversity indices such as the number of age groups and the number of business lines" [55]. Further on, he proposes that "… measurement of the variable's movement, density and diversity could be combined into a more general analytical theory of urban form" [55]. As a result, the concept of Spatial Capital is proposed while referring to the value or advantage a location or space gains from its position within the spatial configuration of a city or environment. In other words, Spatial Capital is the potential of a space to attract movement, social interaction, and economic activity based on its accessibility, connectivity, and integration within the larger network. Spaces with high spatial capital are typically well-connected, centrally located, and easily accessible, making them more valuable for commercial, residential, or social functions. Essentially, spatial capital highlights how the design and structure of urban spaces can contribute to their success and utility.

The natural movement theory developed by Hillier and his team [56] suggests and, based on empirical data, grounds the idea that pedestrian and vehicular movement patterns in urban environments are largely shaped by the spatial configuration of streets and pathways rather than by external factors like land use or signage. This states that people tend to move through spaces that are more integrated and connected within the overall street network, with busier routes naturally emerging from the layout itself. Thus, urban design influences how people navigate cities precisely and how cities function in general.

The theory of natural urban transformation is based on the theory of natural movement. It combines the analyses of three constituent elements of urban form (street network, building density, and land use functions) to produce a spatial classification system for various types of urban areas and reveal how they perform socioeconomically. "Applying this method to four Dutch cases has indicated how street network integration, building density, and degree of land-use mixture are interacting with one another.... An urban area's genotype is revealed by the way the space syntax method shows the hidden spatial logic of the street structure. The significance of this new classification method is that these spatial genotypes and phenotypes of urban areas can be quantitatively and independently analyzed in relation to socioeconomic data. As the results show, strong correlations are found between various spatial types and their socio-economic characteristics" [57].

Those three examples demonstrate that spatial configuration creates a kind of fundamental background for more complex urban processes and, in essence, could be used for quantitative analysis and description of the complex principles of urban biomimicry, which will be proved further while analyzing each principle separately.

The principle of "form fits function" in urban structure means that the physical design, layout, and organization of urban spaces are shaped by the uses or activities they are meant to support. This concept suggests that the structure of a city or neighborhood – such as its streets, buildings, and public spaces – should be tailored to meet the functional needs of its inhabitants, like mobility, accessibility to actual functions, and social interaction. In such a case, a simple statistical correlation between various mathematical graph centralities that describe the spatial configuration and data on urban functions, such as inhabitants' density, function density, etc., could be used. It would be logical to assume that such correlations differ from city to city, thus demonstrating how well the form fits the function. Can we find proof that such correlations are observed? There is a lot of research on this topic:

- Various studies have shown that the spatial configuration of a city's street and road net affects people's natural movement patterns and the distribution of shops and retail [58]–[61].
- Correlations were found between burglaries and various space syntax or mathematical graph-based indicators at the scale of visually perceived street spaces as topological depth, constitutedness, and local integration [62]. The same was confirmed earlier by Hillier based on Space Syntax analysis, where he states that "correlations between integration (one of the centralities of Space Syntax) values and observed movement or crime frequencies" were observed in London [63].
- Strong correlations between pedestrian movement and such indicators as integration and connectivity were found in London [63].
- Positive correlations between commercial density and integration, while negative correlations between integration and building density were found during the analysis and comparison of Boston, Lubbock, Pittsburg, and Salt Lake City [64].
- Etc.

Catalysis of cooperation in urban spatial structure refers to how city layout promotes collaboration and interaction among people, functions, and spaces. Well-connected spaces, accessible public areas, mixed-use developments, and informal gathering spots like cafes or parks encourage social and economic cooperation by facilitating movement and interaction. By shaping where and how people meet, urban design fosters opportunities for collaboration, community building, and shared activities. Graph-based simulative models, depending on which aspect of catalysis and at what urban scale we want to focus, can offer at least a few indicators tested in research:

- The research on connectivity between buildings and adjacent public spaces summarizes that simply higher density is not enough to catalyze interaction between people. "Microscale conditions are often neglected in the contemporary planning and design of urban areas. Urban project developers nowadays tend to build with high density or high floor-space index and propose large variations of urban functions (dwellings, offices, etc.) in these areas. However, the degree of interconnectivity and the shallow topological public-private interface is often forgotten. All these activities depend on how the spatial configuration is on the plinth or built-up street sides" [65].
- Investigation in Bialystok, besides the confirmation of the form fits function principle, based on correlations between various syntactic indexes densities of both inhabitants and points of interest from the Open Street Map at the regional district level, demonstrated the possibility of using mathematical graph-based simulation for in-depth analysis of multifunctionality of urban areas at various scales (whole city, neighborhood, etc.) based on the weighted calculation and the idea of overlapping gravity fields generated by different travel destinations [66].
- The synergy between local and global-scale urban centers was addressed by Hillier as "... the correlation of local and global interaction" [63].
- Strong correlations between metric reach or accessible length of street network and pedestrian movement, as a factor of social interaction, were identified in Atlanta [67].
- Etc.

Local contextuality could be addressed at least in a few perspectives while using graph-based models:

- Space Syntax, in essence, is focused on the investigation of urban genotype, which is defined as abstract rules underlying spatial forms in the field of space syntax. It is a transpatial concept that combines urban form and its contents [68].

- There is some Space Syntax-based research that is used in the investigation of urban development from a historical perspective, thus potentially addressing historical and cultural identity. "By facilitating the comparative study of urban form through time-space syntax, research has opened up several possibilities for exploring the relationship between urban transformations and social activity" [69]. The investigation of early industrial Sheffield Rockingham Street by Palaiologou is interesting by itself as it gave unique insights into the urban growth process, morphological histories, and spatial-locational histories, but it could be easily used for the identification of cultural heritage and monitoring of its transformations. It is important to note that such simulative models as Space Syntax not only allow us to better understand the past or present situation but also predict changes in the future. Historical investigation could help to establish certain boundaries or identity-based benchmarks of urban structure for urban planners.
- Simulative models could even be used for monitoring architectural changes in building facades, as the investigation in Kaunas demonstrates [70], based on Hillier's initial idea of such a possibility [71].

The continuity principle could be seen as either historical or spatial continuity. In the first case, it overlaps with the previously discussed principle of local contextualities. In the second case, Space Syntax offers the concept of fuzzy boundaries. Fuzzy boundaries are defined as the area boundaries arising from the way space is structured internally and how this relates to the external structure of space, and so maintaining inter-accessibility between the areas [72]. If an analysis of how fuzzy boundaries overlap with urban functions and densities is conducted, then it can be useful for the analysis of the sustainability of urban form in general [73].

The diversity and multifunctionality of urban structure should be seen in light of the urban diversity concept, which was introduced by Jane Jacobs and inherited by New Urbanism. According to Bobkova, it is related "to spatial capacity: the ability of spatial artefacts to carry categorical difference. The more such artefacts are divided into separate spaces, the more they create the opportunity to sort people, things, or functions into a greater number of categories" [74]. In such a case, diversity could be addressed by graph-based simulative models directly, as the following examples demonstrate:

- While incorporating morphological and functional diversity and multifunctionality in graph-based walkability modelling and comparison of walkability compasses of 8 cities – Tallinn, Riga, Vilnius, Kaunas, Malmo, Gdansk-Sopot-Gdynia, Bialystok, and Lublin [75].
- While modelling the multifunctionality of urban areas in the Bialystok regional district and comparing it to transportation needs [66].

Redundancy in urban structure refers to the presence of multiple alternative routes or spaces that serve similar functions within a city. If functional redundancy is considered, then the modelling of multifunctionality and diversity, which was discussed earlier, is valid here as well. Redundancy of movement was modelled and analyzed by Sevtsuk while employing mathematical graph-based modelling for the prediction of pedestrian flows in the San Francisco downtown area and validating it with GPS walking traces [76] and pedestrian flow modelling in Kendall Square in Cambridge [77]. Redundancy of the travel routes was represented there by detour ratio – "which enables trips between origin-destination pairs to be routed along all 'plausible' paths that are up to a certain percentage". The detour ratio in the quoted research is identified based on various empirical research as 1.15–1.20, meaning that up to 20 percent elongation of the path makes no impact on the human choice of the shortest route.

Interconnected qualities of decentralization, hierarchy, and fractality as a result of certain patterns of the spatial and functional organization of a city because "in consonance with space syntax theory, it was posited that this (urban) structure maintains a robust correlation with movement, wayfinding, behavioral patterns, and the overall functionality of any given spatial system. With this perspective in mind, it becomes strikingly apparent that urban morphology, as both defined and operationalized through the lens of space syntax, presents an exceptionally effective avenue for engaging in analytical, evidence-based design." [78]. In such a case, the only question is which specific syntax indicators show urban centers and which show peripheries. Integration is the most often used one for the first purpose as "integration is a normalized measure of distance from any space of origin to all others in a system. In general, it calculates how close the origin space is to all other spaces" [68]. The above-mentioned fuzzy boundaries identify urban peripheries. Normalized numerical values of both indicators, sizes of standard deviation, etc., could be used to evaluate the gravity power of the most reachable places at various levels and their diversity. It is worth mentioning that in many cases of validation of the syntactic model integrations, the best correlations with a density of function and objects, the previously mentioned Walkability compass model, could be taken as an example [75]. If a more complex understanding and modelling is needed, then the fundamental Generic City model should be mentioned. According to it, each city is made of foreground and background spatial structures. Maximal and mean numerical values of the indicators representing those two structures and correlations between them explain local peculiarities and regularities of the function of various cities, including strength of hierarchical segregation, multifunctionality, concentration of urban centers, and transit flows [79]. The other sophisticated model that further develops the concept of a generic city or supplements it is the idea of pervasive centrality. According to Hillier, the dominant urban models "emphasize clear hierarchies, regular geometries, and the separation of parts from wholes" [73]. As an alternative look, Hillier offers the concept of pervasive centrality where "intricate pattern of centers at all scales is potentially a vital component of spatial sustainability, for the very simple reason that it means that wherever you are, you are close to a small local center and not far from a much larger one" [73]. It could be seen in the context of foreground and background network interaction/synergy or measured as synergy between various centralities of the urban space network.

Less energy consumption related to urban configuration could be measured in the same way as the above-mentioned multifunctionality and diversity, as it means at least shorter communication routes, lesser CO2 emissions, etc. The idea of pervasiveness could be employed here as well. One more example of a straightforward usage of Syntactic modelling for transit-oriented development (TOD), which is an important aspect of energy consumption in a city as it relates to urban form, is TOD analysis and design proposals in Jakarta [80]. Basic indicators of Space syntax, such as choice or betweenness, integration within various radiuses, and based on correlation analysis evaluated synergy were used for this purpose.

The final biomimicry principle is self-organization. Space Syntax, like all the other simulative models, is focused on modelling bottom-up interactions between the "cells" of the model. In agent-based modelling, such basic elements are presented by the moving agents operating based on rules and elements of the environment that are described as simply as possible. In the cellular automata model, the "cells" are presented by small spatial units like land plots or buildings that react to changes in the neighboring "cells" based on described and test rules. In Space Syntax, various elements (street segments, visual axes, visually perceived entire spaces or parts of visual spaces) of the urban structure are modelled as mathematical nodes which are connected with the other nodes via graph links or edges. So, in essence, it could be said that Space Syntax is based on the idea of simulation and imitation of the self-organizing interaction of urban structure.

In essence, while summarizing everything that was said above, it could be stated that Space Syntax addresses the self-organization of urban structures by analyzing how spatial configurations naturally evolve and influence patterns of human movement, land use, and social interaction and putting the main attention to emerging local interactions between people, buildings, and streets.

IV. Discussion

The presented analysis of the most often used urban planning concepts, models, theories, and approaches revealed that in many cases, except modernistic urbanism, they do not contradict the principles of biomimicry urbanism, thus confirming that insight by Pohl and Nightingale that technology (of urban planning) could be seen as a continuation of natural evolutions just with the other measures and in other environments [5]. On one side, such a result suggests learning not only from nature but from urban, probably historical, examples of the ideas of New Urbanism and Ch. Alexander are considered. On the other side, the research demonstrates that the biomimicry principles, in essence, are quite general and suitable more for the identification of strategic or tactical directions in urban planning but not for precise analysis and comparison, thus calling for the need to search for quantitative indicators of the degree of biomimicry in spatial structures of cities. It should be agreed that there are many possible approaches to solving the problem of the quantitative description of biomimicry. The presented research has explored just one – based on simulative modelling. The main argument for such a choice was based on the fact that various complex systems, including the city, are successfully described and better understood, and their behavior is predicted based on simulative models that seek to identify the basic, the simplest, and the smallest elements of such a complex system. Space Syntax was chosen many times in various situations, validated, and quite well working model. Of course, it should be agreed that Space Syntax, as a mathematical graph-based simulative model, is only one option – agent-based modelling and cellular automata models could be considered for the same purpose as well. As the review of the modelling cases demonstrated, Space Syntax can offer a lot of indicators that could be related to the principles of biomimicry. The next challenge would be to make a more specific and grounded choice and test it in real urban structures.

The possible importance of such research could be illustrated by the potential role of Space Syntax in the urban planning process by Karimi, which could be used in various stages, starting from analysis of the present situation, continuing with a comparison of the alternatives and predicting results of design solutions, and ending with suggestions of quantitative parametric design indicators as Space Syntax provides "an analytical approach to urban design based on spatial configuration can provide a powerful vehicle to achieve a more enhanced urban design outcome. The proposed methodology is based on the Space Syntax theory, which treats space as an intrinsic entity to society, shaped through a series of relations and patterns or spatial configuration. The analysis of spatial configuration provides an efficient method of analysis to explore the functionality and efficiency of urban systems, which becomes an integral part of an analytical urban design process" [81].

CONCLUSIONS

1. The biomimicry approach can offer precise principles for urban planning that, in essence, can help to make our cities more sustainable, walkable, inclusive, etc.
2. New Urbanism, Alexander's Pattern Language, and other related models employed in urban planning do not contradict the principles of biomimicry, thus allowing us to speak about inherited urban biomimicry.
3. The idea of inherited urban biomimicry opens possibilities to search for biomimicry-based inspiration not only in nature but also in some urban structures. This possibility actualizes the need to look for the quantitative indicators of urban form, which could allow measurement of the degree of expression of the biomimicry principles. Such indicators, if offered, could be fruitfully used in various stages of urban design.
4. Space Syntax, as a mathematical graph-based simulative model of urban spatial structure, could be used for quantitative modelling of urban biomimicry.
5. Further investigation and testing of precise quantitative indexes of biomimicry should be based on analysis and comparison of real urban cases.

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