

# Urban Biomimicry Typologies: Ways of Learning from Nature and Locality

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## Abstract

In response to current urban sustainability challenges, biomimicry emerges as a promising approach for creating resilient contextually adapted urban environments. This research explores urban biomimicry through qualitative descriptive analysis and conceptual mapping, identifying the main typologies based on organism, habitat, ecosystem, and abstract natural principles. It further examines urban biomimicry approaches by their degree of bio-integration (from inspiration to ecological integration) and implementation strategies (top-down versus bottom-up), while considering their implications for local ecological and cultural contexts as well as aesthetic expression. Additionally, a graph-based analysis identifies conceptual relationships between biomimicry and New Urbanism (NU), revealing integrative concepts essential for interdisciplinary nature-inspired sustainable urban development.

## Introduction

*Relevance of the research.* As urban challenges intensify, expectations for what cities should achieve have grown. The sustainability paradigm of minimising harm and doing “less bad” is increasingly seen as insufficient. A shift is underway from sustainability toward regeneration in urban planning and design [1]. Regenerative design goes beyond reducing negative impact; its goal is to enable natural and human systems to actively heal, renew, and thrive together [2]. This approach takes inspiration from living systems, as in ecology, where regeneration is a fundamental feature [1]. As Blanco et al. [2] observe, a new urban design paradigm is taking shape – one that seeks to reconnect cities with natural ecosystems and enable social-ecological co-evolution: cities should function as integrated parts of the Earth’s life support system, continuously renewing the resources and ecosystem services they depend on.

One promising way for realising regenerative cities is urban biomimicry – the practice of learning from and emulating nature’s forms, processes, and ecosystems in the design of urban environments. Despite its promise, urban biomimicry remains an emerging field with significant gaps in theory and practice. Most applications of biomimicry to date have been at the building or product scale [3]. At the urban scale, examples are fewer and often lack a

unifying framework. Researchers note that the field still lacks a clear theoretical conceptualisation and typology [2]. Di Carlo and Papeschi [4] observe that without a clear framework, biomimicry risks being applied superficially or inconsistently, hampering its transformative potential. The literature calls for developing typologies to classify what is being mimicked (organism, ecosystem, or abstract natural principle) and how it is applied in urban contexts. There is also a need to integrate social and cultural dimensions into biomimicry theory. Urban biomimicry, as currently discussed, focuses heavily on ecological mimicry; yet cities are socio-ecological systems. A research gap exists in reconciling biomimicry with local cultural narratives, aesthetics, and community engagement. Considering this, the following research questions were formulated:

- What to mimic in urban biomimicry? Different levels of or approaches to biomimicry (organism, behavioural, ecosystem) may yield different outcomes, and a clearer typology is needed.
- How to connect biomimetic urban design to place: how can urban biomimicry be local and context-specific? This involves connecting with local ecosystems as well as local culture and heritage. The question may be raised: how can biomimicry ensure designs resonate with the ecological character of the region and the identity of local communities? This also includes

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considering traditional knowledge or biomimetic principles already present in vernacular architecture and urban forms.

- Should urban biomimicry be legible and aesthetically communicative? If a city mimics nature, does it matter if people can see or recognise it? Some argue an emergent “sustainability aesthetic” is needed to inspire and educate citizens [5]. Others suggest that function is the most important and that biomimicry can remain largely invisible as long as it performs. It is important to consider whether making biomimicry visible in the urban landscape benefits public engagement and environmental awareness or local identity.
- How can urban biomimicry approaches conceptually relate to and potentially reinforce sustainable urbanism principles, tools, and structural models, and what roles do biomimetic concepts play within such interdisciplinary theoretical networks? New Urbanism (NT) is chosen in this study as representative of sustainable urbanism due to its explicit emphasis on compactness, mixed-use development, pedestrian-oriented communities, ecological resilience, and preservation of local heritage, all of which are fundamentally aligned with sustainability and regeneration goals pursued through biomimetic design.

*The aim of the research.* The study seeks to clarify the concept of biomimicry in urban planning by establishing a typology of biomimetic approaches, examining how these can be grounded in local ecological and cultural contexts, and exploring their conceptual relationships with sustainable urbanism approaches through a systematic graph-based analysis.

*Research methodology.* The research first of all employs a qualitative methodology suitable for exploratory, conceptual inquiry. Its core is a narrative-descriptive literature review that draws on interdisciplinary sources from urban studies, ecology, and biomimetic design. Sources include peer-reviewed journals, conference papers, book chapters, and foundational theoretical works. The review process has been iterative, ensuring comprehensive coverage from the fundamental concepts to recent advancements. Complementing this qualitative theoretical exploration, the study employs a systematic graph-based analysis to visualise and clarify conceptual relationships between biomimicry approaches and NU principles. This analytical method identifies integrative concepts and highlights theoretical intersections, thus supporting interdisciplinary knowledge synthesis and guiding future research and practice.

## I. Typology of Urban Biomimicry

Biomimicry offers a methodology for aligning urban systems with the wisdom of nature, treating nature not

just as a supplier of goods but as a mentor for design [3]. This approach represents a shift from controlling nature to working with it, as EcoLogicStudio’s researcher and designer Pasquero emphasises [6]. Urban biomimicry can be conceptualized across multiple scales: at the micro-level, mimicking individual organisms, at an intermediate or meso-level, emulating habitats or collective dwellings, such as nests of social insects [3], which represent structured micro-environments shaped collectively by multiple organisms, and at the macro-level, replicating entire ecosystems [2] or abstract natural principles [7], such as diversity, integrity, redundancy, fractality etc., or even fundamental patterns or mathematical principles inherent in nature, such as logarithmic spirals and double-helical trajectories, which govern how natural forms and structures spontaneously emerge across different scales and contexts [8]. Crucially, urban biomimicry in cities is not limited to form; it’s about function and process [5]. According to the researchers and urban biomimicry proponents, this approach holds the potential to transform the built environment “from a threat to climate stability and biodiversity to a showcase for a regenerative world” [9], to “...design resilient cities that use their size and collective energy to create refuge for both humans and displaced wildlife, that promote the emergence of positive microclimate, that replenish depleted water sources and that restore degraded terrains, pushing back on processes such as desertification, land erosion and contamination” [10].

Typologies play a crucial role in framing urban biomimicry as a coherent field of study. This section reviews major classifications from literature subdivided into two categories: 1) the main key typology (biomimicry by scale distinguishing organism, habitat, ecosystem, and principles of nature), and 2) the relevant secondary approaches potentially influencing the key typology: degrees of bio-integration (inspiration, imitation, integration, top-down vs bottom-up biomimicry, modes of biomimetic design (form, process, performance, and material), and ethical aspect of urban biomimicry (nature as a normative principle vs nature as a technical model).

### A. Biomimicry by Scale: Organism, Habitat, Ecosystem, and Principles of Nature

At the most granular scale, a design can mimic a single organism or a specific natural structure. Organism-level biomimicry is widespread and is exemplified by design solutions that imitate the morphology or physiology of a single species. The goal is often to harness an individual organism’s adaptation and apply it to a human design challenge. This level is well-documented and aligns closely with traditional biomimetics and bionic approaches focused on form and function at the organism scale [11]. Such an approach treats nature as a library of “products” or

strategies, each organism providing a model for a specific design solution. Between single organisms and whole ecosystems lies the habitat or colony scale, for instance, the communal structures created by social insects or other animals. At this level, designers draw inspiration from nests, hives, mounds, or other built environments of organisms. Such habitats are the collective result of many organisms' behaviours, and thus offer analogies for architecture and small urban systems. Termite mounds, beaver dams, bee hives, and ant colonies are frequently cited as models. They represent natural constructions that regulate the environment and resource flows at a micro-ecosystem scale. Mimicking these can inform building complexes or neighbourhood layouts that self-regulate heat and moisture or that optimise space. For example, the nests of social insects have inspired passive cooling and ventilation strategies in architecture [3]. Dicks et al. [3] discuss insect nests and tree habitats as analogies for cities, noting that these models offer rich inspiration but must be scaled appropriately to inform urban design. At the broadest biological scale, the structure, processes, and relationships of the entire ecosystem become the inspiration for urban biomimicry. Here, urban designers emulate the ways in which communities of organisms interact with each other and with soils, water, and climate. An ecosystem-level biomimetic approach might, for instance, model an urban water system on a forest watershed [2]. Blanco et al. [2] argue that this level of biomimicry is especially relevant for sustainable urbanism, since it tackles the complexity of cities by treating them as analogues of living ecosystems. The ecosystem level is inherently systemic and lends itself to regenerative design principles: the city not only reduces harm but actively regenerates ecological health by operating like a native ecosystem [2].

Beyond concrete organisms or ecosystems, designers can mimic abstract principles and strategies that recur across nature. At this level, nature is not a single model but a source of general "design wisdom" in the form of patterns and rules tested by evolution. Examples include principles like self-organisation, cooperation, diversity, modularity, circularity, or fractal hierarchy. These are not tied to one species or ecosystem but are overarching "ways nature works." In recent research [7], several such features of natural systems – local adaptivity, continuous evolution, decentralisation, redundancy, and resource efficiency – that could guide urban planning were distinguished. The Biomimicry Institute's Life's Principles is the framework that compiles many of these guidelines, for example, "evolve to survive," "integrate development with growth," "be locally attuned", etc., which could serve as normative urban design checkpoints drawn from nature's common operating principles [12]. It is necessary to note that this abstract approach often requires translating qualitative ecological wisdom into design metrics, which is an

ongoing area of research. The most theoretical end of the spectrum considers the mimicry of fundamental physical or chemical laws that underlie natural phenomena. In this case, designers look to basic natural laws, such as those in thermodynamics, geometry, or mathematics, that also govern biological structures. Based on the research of Parker and Jeynes [8], it can be suggested that biomimicry can extend to principles like fractal scaling laws, the Fibonacci sequence in growth patterns, or energy laws (minimisation of energy, entropy dynamics) as inspiration for design [7]. This category blurs the line between "bio" and "physics," treating deep operating laws of nature as models for human systems. However, some scholars caution against uncritical adoption of supposed "laws of nature" in design [13], noting that claiming a design is sustainable because it follows a "law of nature" can be misleading if that law is randomly selected or interpreted ideologically. Whether at this level or the more concrete levels mentioned above, matching design interventions to the appropriate scale of natural analogy is crucial, as Dicks et al. [3] note. Mismatches in scale can lead to "disparities in translation," as noted by Dicks et al. [3] when comparing insect nests versus forests as city models. Thus, this multi-level typology could help designers be explicit about what level of nature they are emulating and to remain mindful of the opportunities and limits at each level.

#### B. Degrees of Bio-Integration: Inspiration, Imitation, Integration

Another way to classify biomimicry is by the degree of integration with living systems, ranging from superficial inspiration to full ecological symbiosis. Gerola et al. [14] propose a three-tier typology of biomimetic design reflecting an increasing depth of bio-integration described as *inspiration*, *imitation*, and *integration*. In the case of *inspiration*, nature provides the idea for design, but the translation into the design is relatively general. Terms like "bio-inspired design" often fall in this category. In this mode, biological knowledge serves as a stimulus rather than a blueprint [14]. Cohen and Reich [15] define inspiration as the transfer of "ideas or general design principles" from nature to technology without delving into detailed biological models. The key point is that nature influenced the concept, but the design does not directly replicate a specific natural mechanism. This approach tends to be non-symbiotic as the resultant design, while nature-inspired, does not necessarily interact with or benefit actual ecosystems. The role of nature here is largely conceptual. *Imitation* is a deeper form of biomimicry in which designers study a biological model in detail and abstract its key functional principles for direct application [14]. This aligns with what is traditionally called biomimetics or bionics: nature is treated as a technical model, and the goal is faithful replication of function if not

form. *Imitation* requires understanding the science of how a natural system works: imitation “transfers more detailed knowledge, including models and exact parameters,” from nature to design [14]. Here, the biomimicry is more literal: specific features of the biological model are reproduced, even if with some abstraction, in the design. Imitation still generally yields a human-made, non-living artefact rather than integrating living organisms. Thus, it tends to remain bio-inspired rather than bio-integrated. Many current biomimetic innovations fall into this category: they provide sustainability benefits but do not inherently establish a symbiotic relationship with the environment; nature is teacher and template, but not a direct participant in the finished design [14]. *Integration* is the most profound level, where the boundary between the designed system and natural living systems begins to blur. In this case, designers incorporate living organisms or processes into the design, or, conversely, embed the design back into an ecosystem, in order to closely co-function with nature [14]. This approach is truly symbiotic biomimicry: nature is not only imitated but also engaged as an active component of the design. There are two strands within integration: biodesign and ecological integration. Biodesign actually uses biological materials, microbes, or plants in a design to leverage their capabilities; for example, integrating algae into building facades to generate energy. Meanwhile, in ecological integration, design is deliberately woven into an existing ecosystem to support and enhance; for example, wastewater treatment wetlands, green roofs that become habitat, or urban layouts that allow wildlife corridors and nutrient cycling similar to wild ecosystems. In such cases, the measure of success is not just a human performance metric, but also an ecological one: e.g., does the project restore biodiversity or ecosystem health [14]? Pedersen Zari et al. [16] describe this as designing with nature to yield net-positive outcomes for the environment. Integration thus implies a deep partnership: human and natural systems function together, each contributing to the other's resilience, and this is symbiotic by definition. As cities seek to become more than just inspired by nature – to become truly reintegrated into the web of life – the emphasis should be moving toward the Integration end of this Inspiration, Imitation, and Integration spectrum. Inspiration and Imitation by themselves do not guarantee environmental synergy; meanwhile, designs that fully integrate with local ecosystems would likely yield the most transformative sustainability outcomes, but they also demand the greatest shift in design approach and stakeholder collaboration, including non-human stakeholders.

### C. Top-Down Versus Bottom-Up Biomimicry

Biomimicry can also be classified by methodological approach – essentially, how the biomimetic idea is arrived at and implemented in design – which often correlates

with top-down vs bottom-up processes. In one sense, this distinction can refer to the design workflow: a top-down (or “technology-pull”) approach begins with a human-defined problem and then searches for a fitting biological solution, whereas a bottom-up (“biology-push”) approach starts with a fascinating biological discovery and tries to find or create a problem/use-case to solve with it [17]. Both routes are employed in bio-inspired innovation. In urban planning and architecture, this translates to two complementary workflows.

Beyond the design workflow, top-down vs bottom-up can describe the mode of implementation and governance in urban projects. A top-down biomimicry implementation is typically driven by central planning, experts, or a hierarchical decision process. City officials or lead designers impose a biomimetic concept onto the urban fabric. This can ensure a cohesive vision and the allocation of resources at scale. Geddes and other early town planners metaphorically described cities as organisms and attempted comprehensive, top-down organic planning [18]. However, top-down approaches have been critiqued for potential inflexibility and lack of local fit. In biomimicry, a purely top-down imposition might risk misreading local ecological conditions: forcing a template onto a place rather than growing from the place. In contrast, a bottom-up biomimicry implementation could be characterised as decentralised, participatory, and emergent. In this case, local stakeholders, smaller design interventions (such as urban acupuncture [19]), or even spontaneous community actions drive the bio-inspired changes, which then accumulate into larger patterns. This approach mirrors how nature itself builds complexity: through self-organisation and adaptation from the ground up [20]. Di Carlo [20] argues for a bottom-up, evolutionary approach to sustainable city design, drawing on complexity theory and self-organising processes in nature [20]. Importantly, top-down and bottom-up biomimicry are not mutually exclusive; the projects may integrate both. For instance, a city government might set a general biomimetic goal (top-down vision), but implement it via community-led pilots in each district (bottom-up execution), adjusting the plan as emergent feedback comes in – a process akin to hierarchical yet adaptive control seen in some ecosystems. Di Carlo [20] notes that modern sustainable city design is moving toward recognising self-organisation and “non-linear” processes as crucial, after decades of mostly top-down schemes [20]. This shift parallels a philosophical change: rather than viewing nature as something to replicate in form (which top-down often does), designers are viewing nature as something to emulate in process. For example, instead of rigidly designing a bioinspired neighbourhood all at once, planners might establish conditions for it to grow like an ecosystem – setting initial “seed” projects and connectivity, then allowing incremental development and succession. Such bottom-up biomimicry can be seen in movements

like tactical urbanism with green infrastructure, or the embrace of modularity and decentralisation in city systems (small-scale solar, local water harvesting), which then network together.

#### D. Modes of Biomimetic Design: Form, Process, Performance, and Material

Literature often distinguishes what aspect or mode of nature is being emulated, for example, form, material composition, processes, functional performance [21]. These four modes – *form*, *process*, *performance*, and *material* – are not mutually exclusive, but they offer a useful classification of how designers direct and focus the influence of nature. In the context of urban design, these categories help interdisciplinary teams communicate: an engineer might ask for a biological process to solve a recycling issue, while an architect might be more interested in form inspiration for aesthetics and structure, and a sustainability officer might emphasise performance metrics like energy use matching natural benchmarks. Biomimicry of form, for example, emulates the shapes and structural forms found in nature. The idea is that nature's forms often optimise strength, flexibility, surface area, etc., thus adapting them in design can yield efficient designs. This aspect of biomimicry includes using mathematical forms prevalent in nature (fractals, hexagonal packing, catenary curves) to achieve performance similar to that of the natural analogue [22]. Biomimicry of form is perhaps the most visually apparent type and has a long history in architecture. The process of biomimicry emulates or imitates natural processes (biochemical, ecological) or behaviours. Process biomimicry tends to improve the way something is manufactured or managed by borrowing nature's recipes. For example, in cities, the hydrological process of a wetland can be emulated to design a wastewater treatment facility. Performance biomimicry focuses on achieving the same functional performance that nature attains, possibly by different means. In this mode, the end goal is to meet a benchmark set by nature, for example, in efficiency, resiliency, etc., even if the method or form is not an obvious copy of a specific organism. For example, mangrove forests naturally filter water and buffer storm surges. A performance-mimicking approach might not recreate a mangrove's exact form, but could design an urban water management system that achieves equivalent filtration and surge protection as a mangrove [21]. Performance biomimicry is somewhat abstract: it treats nature as the standard of what is possible (e.g., zero waste, full closed-loop recycling, ultra-lightweight strength) and then engineers toward that goal. Benyus [23] referred to this as taking nature as a "measure" of success. Biomimicry of materials involves copying or deriving inspiration from materials that nature produces, including their microstructure and composition. Nature's materials often

exhibit exceptional properties, such as high strength-to-weight ratios, self-healing, and biodegradability. Material biomimicry can involve developing new synthetic materials that emulate these properties or directly using natural materials in innovative ways [21]. In construction, material biomimicry might mean using mycelium (mushroom root networks) as a grown insulation material [24], or bio-bricks produced by bacterial mineralisation instead of firing clay. It also covers bio-sourced and biodegradable materials as replacements for conventional ones. This mode connects strongly with materials science. Barragan [21] underlines that a holistic biomimetic approach ultimately seeks to harmonise geometry, processes, performance, and materials biomimicry, so that a city or building is deeply aligned with natural principles on multiple levels.

#### E. Ethical Aspect of Urban Biomimicry: Nature as a Normative Principle vs Nature as a Technical Model

Behind many of the above-presented typologies, it is possible to find a fundamental divergence in how biomimicry practitioners view the role of nature: is nature the ultimate standard of good design, or is it primarily a provider of technical solutions? Gerola et al. [14] observe that "nature" is a "normatively loaded and contested concept" in these discussions. This can be framed as nature as a normative principle vs nature as a technical model. Benyus [23, 25] original formulation of biomimicry clearly advocates for nature as a standard of good design. She famously stated that in biomimicry, "nature is model, measure, and mentor" [14]. Here, nature as a model means the technical aspect, looking to nature for design ideas, although nature as measure means that the designs should be evaluated against nature's criteria for sustainability, and nature as mentor implies even broader ethical guidance where nature is approached with respect and as a teacher, not just an instrument. Proponents of this view see nature's 3.8 billion years of evolution as containing not only clever mechanics, but also implicit wisdom about what works in the long run for life on Earth. Thus, nature's principles (such as building diversity, recycling materials, using sunlight for energy, etc.) carry normative weight – they are benchmarks of sustainability that designs ought to meet. In the literature, this strong interpretation is sometimes called the "strong sustainability" concept of biomimicry [14, 26]. For instance, Biomimicry 3.8 (the consulting group co-founded by Benyus) emphasises creating cities that function like ecosystems in quality, not just in mechanism, under the assumption that ecosystems embody an optimal balance that is worth striving for morally and functionally. In this framework, nature is conceptualised as a normative principle on which to measure the appropriateness and integrity of designs [27].

On the other hand, many practitioners in bio-inspired engineering and architecture adopt a more pragmatic,

technical and morally neutral view of nature – nature as a toolbox of solutions. This perspective values nature's models for their utility, without necessarily implying that following nature's way is inherently the right thing to do. In fields like biomimetics, bionics, or bio-inspired product design, the usual goal is innovation and performance rather than explicit sustainability or ethics [14]. In other words, the conceptual imitation can be very sophisticated and apply deep biological knowledge, but the normative stance is weak: there is no obligatory requirement that the outcome benefits the environment. This "nature as model only" approach has been described as the weak concept of biomimicry (or simply bioinspired design in the narrow sense) [26], [27]. In fact, some critics from this camp warn against idealizing nature: while nature is effective, it is not always efficient or benign in ways we would want – e.g., natural systems can be brutal or wasteful from a short-term perspective, and not every natural strategy is appropriate to emulate (some might even be undesirable if taken out of context) [27].

Contemporary urban biomimicry would benefit from the convergence of normative and technical perspectives: the most resilient and sustainable outcomes likely require treating nature as both model and measure. This means combining the technical solutions emulated from biology with the normative goals of sustainability science. For example, a city plan might imitate water retention of a forest (technical model), and use the condition of a forest as a normative by asking: Does the city manage water as prudently as an intact forest watershed would? This dual perspective is evident in concepts such as "ecological performance standards" for cities, where designers quantify how much carbon sequestration, water filtration, etc. a local ecosystem does and then design the urban environment to meet or exceed those standards [2].

## II. Context and Aesthetic Expression in Urban Biomimicry

The analysis of typologies has demonstrated that urban biomimicry can take different forms, scales, and approaches. In order to understand better how different trends of urban biomimicry interact with local context (ecological and cultural) and with aesthetic legibility (is it visible or invisible urban biomimicry), this section first of all focuses on the key typology of urban biomimicry identified in the literature – biomimicry by scale distinguishing 1) organism, 2) habitat, 3) ecosystem, and 4) principles of nature biomimicry. For each category in this typology, two questions are asked: 1) How can biomimetic design be context-specific, grounded in local ecosystems, culture, and heritage? 2) Should urban biomimicry be visibly expressed and communicative, or is functional performance alone sufficient? Further the discussion is elaborated on how other approaches to urban

biomimicry distinguished as secondary in this research – 1) degrees of bio-integration (inspiration, imitation, integration, 2) top-down versus bottom-up biomimicry, 3) modes of biomimetic design (form, process, performance, and material), and 4) ethical aspect of urban biomimicry (nature as a normative principle vs nature as a technical model) – can potentially affect connections to place and aesthetics of the categories of the key typology.

### A. Organism-Level Biomimicry

Organism-level biomimicry, which draws on a single organism or species for inspiration, in terms of local context, can connect to place if designers choose native or culturally significant species as models. Emulating a species endemic to the region can celebrate local biodiversity and heritage – effectively tapping into the local ecological and cultural memory. However, organism-level biomimicry is not inherently context-sensitive: in principle, designers might copy an organism from anywhere without regard to the local biome. Critics argue that biomimicry sometimes abstracts nature's models without fully accounting for the dynamic, interconnected systems in which they evolved, meaning that transplanting strategies into new contexts without understanding local environmental complexity can produce unsustainable or ineffective outcomes [28, 29]. The aesthetic legibility of organism-level biomimicry can be high and have a visible bio-inspired form. If the design is inspired by or imitates the morphology or pattern of a particular lifeform, it can produce recognisable motifs. On one hand, clearly biomorphic designs may cultivate public fascination and environmental awareness. A prominent example is the often-cited suggestion to "imagine a building like a tree, a city like a forest" [30]. Such imagery, if manifest in real projects, creates an explicit ecological narrative that citizens can read in the urban landscape. Di Carlo [5] argues that an emergent "sustainability aesthetic" is needed to inspire and educate, suggesting that the success of urban biomimicry may rely on engaging the senses and emotions of people, not only on engineering performance. A visually communicative biomimetic form can signal a commitment to the nature of the city, become an icon of local identity, and even evoke biophilic responses that improve psychological well-being [31]. On the other hand, form-level mimicry can risk superficiality if disconnected from function [5]. Nonetheless, organism-scale biomimicry remains potentially the most legible mode: it inherently lends itself to aesthetic expression, which, when done thoughtfully, can strengthen local cultural connections and affiliation with nature and serve as an educational symbol of urban sustainability and resilience. The Deep Green Urbansphere project by ecoLogicStudio exemplifies organism-level urban biomimicry through its direct inspiration from the slime mould (*Physarum Polycephalum*). This biological model provides a sophisticated algorithmic

logic for optimising urban infrastructure networks, demonstrating clear organism-level biomimicry where a specific organism's behaviour guides urban design processes. However, its connection to place and locality varies, as the trained algorithm must deliberately incorporate local ecological data and context to achieve true site-specific relevance [10, 32, 33]. Aesthetically, this approach translates the intricate, networked patterns of slime mould growth into speculative urban forms, creating visually distinct and expressive urban scenarios that simultaneously function as communicative tools for promoting sustainability awareness.

#### B. Habitat-Level Biomimicry

In a local context, habitat-level biomimicry solutions can be in harmony with the place when they come from species that co-inhabit the region. For example, a coastal city might emulate a habitat structure of a coral reef for an artificial breakwater or urban reef park, directly tying design to the native ecosystem. The experience already exists, demonstrating how coastal cities can employ habitat-level biomimicry, specifically coral reef structures, not only to manage coastal erosion but also to rebuild local biodiversity and connect infrastructure with native marine ecosystems. For example, artificial spur-and-groove reef experiments in Hawaii have simulated spur-and-groove reef formations to design submerged protective structures that both break waves and promote coastal circulation and ecosystem functions [34]. Habitat biomimicry can also incorporate traditional knowledge: many vernacular architectures were essentially habitat-mimetic, working with local terrain and climate in ways analogous to “engineering of nature” [35, 36]. By integrating these analogies, designers ground new developments in a narrative continuity with the local natural history. Actually, both natural habitats and successful sustainable traditional land management and construction practices can act as both model and measure for urban design, meaning that they can offer ideas for structures that fit into the environmental flows. From an aesthetic point of view, habitat-level biomimicry might be less immediately iconic than single-organism inspired designs, although it can still be legible in design motifs or spatial configuration. A building or district inspired, for example, by a beehive [37] or an ant colony [38] could exhibit organic patterns like hexagonal grids and maze-like networks, etc. that signal a natural inspiration. Implemented examples and projects exist, demonstrating that organic spatial logics derived from social insect habitats can be translated into urban design in ways that are visually suggestive of their natural models [38]. Whether this is evident to the casual observer is uncertain, as the legibility often depends on explanatory interpretation. However, making the analogy intentionally visible or interpretable can enrich user's experience. There

is a growing view that urban sustainability efforts benefit from being transparent and didactic: showing people what is being mimicked and why can foster a sense of place and stewardship. For example, buildings with visible, interpretative sustainability features have been shown to raise occupant awareness, demonstrating the power of non-verbal environmental cues in enhancing ecological literacy and engagement [39]. The risk of invisibility here is if biomimetic functions are hidden underground or in infrastructure like bio-inspired water filtration systems.

#### C. Ecosystem-Level Biomimicry

Ecosystem-level biomimicry operates at the broadest biological scale and aligns closely with the vision of “a city like a forest” [3, 30], urging planners to design cities that function as dynamic, resilient ecosystems. Contextual sensitivity is arguably intrinsic to ecosystem-level biomimicry because any ecosystem model is inherently tied to a place. The main principle of this approach is local ecosystem mimicry: the city should emulate the specific ecosystem that would naturally exist in that location (often the ecosystem that was present before urbanisation) [3]. In this way, urban design can harness strategies encoded in local climate and geology, embodying the idea encapsulated in the “genius of place” concept that local nature embodies optimal solutions for that locale [3]. This is where traditional ecological knowledge can be highly valuable: local communities, especially indigenous ones, often understand the rhythms of local ecosystems and have cultural practices that align with them. Thus, urban biomimicry at the ecosystem scale can integrate such traditional knowledge – for instance, indigenous land and water management strategies like seasonal floodplain use, terraced agriculture, and sacred groves. In effect, ecosystem biomimicry extends beyond form into policy and process, requiring collaboration with ecologists and local stakeholders to ensure the city's metabolism (energy, water, material flows) approaches that of the native ecosystem. An example is the city of Lavasa, India, where planners working with biomimicry experts emulated ecosystem services of the region's deciduous forest, such as monsoon water capture, soil stabilisation, and evaporation cooling, directly in the urban design [40]. Regarding aesthetic expression, ecosystem-level biomimicry is often more process-oriented, performance-oriented, and systemic; as a result, such biomimicry might be largely invisible in a formal sense. A city functioning like a forest may just look like a green city, not necessarily a literal forest, unless designers choose to overtly symbolise it. The city's green infrastructure – parks, wetlands, green roofs, urban forests – could simply be appreciated as nature, not necessarily understood as a deliberate imitation of the original ecosystem. However, making the strategy legible could amplify its impact, as it was already mentioned above. The aesthetic dimension here may lie in an overall experience of ecological harmony:

when ecosystem biomimicry is successful, the city feels more integrated with its environment, with cleaner air, abundant greenery, and flowing water, which produces its own intuitive aesthetic pleasure for inhabitants. Di Carlo [20] even suggests that integrating urban habitats with local ecosystems yields environments of greater intensity and nuance, effectively a “new aesthetics” beyond static design.

#### D. Principles of Nature-Level Biomimicry

Abstract principles and laws of nature form the most theoretical category of urban biomimicry classification under analysis. The advantage for contextuality and place integration for this category is that some principles (like “adapt and evolve in place”, “be locally attuned” or “use waste as resource” [12, 25] are inherently about local fit. If planners and designers consciously apply such principles as normative guidelines, they will embody context-sensitivity in urban solutions from the initial design stages. However, working at the level of abstract principles can also become decontextualised as these rules, like Fibonacci sequences, fractal patterns, are universal in nature. This poses a threat that designers might be tempted to apply them as a universal formula, possibly overlooking local particulars and clashing with the “genius loci.” Critics caution against selectively picking laws or features of nature and claiming sustainability from them alone [41]. Therefore, while principle-level biomimicry can provide a powerful philosophical alignment

with natural law, it should be coupled with site-specific data and knowledge. On the positive side, this approach can integrate traditional ecological knowledge by recognising that many cultural practices encode natural principles (for example, sacred groves reflect principles of biodiversity preservation [42]). Thus, acknowledging these practices as aligned with the laws of nature can validate local heritage within a modern scientific framework. Aesthetically, abstract principles might manifest in subtle or hidden ways. A city plan based on, for example, decentralisation and network connectivity might not outwardly look biomorphic at all, as its biomimetic nature resides in its process and performance. Whether such designs should be made legible is a matter of debate. As it was already discussed above related to other categories, even when biomimicry operates at an abstract level, there is value in translating the invisible guiding principles into something people can see or feel, thus fostering an ecological consciousness. Based on Guattari [43], any truly ecological design discourse “must be aesthetic as well as ethical” to be meaningful: integrating principles of nature into cities is not just a technical task but a cultural one, where symbols, stories, and sensory experiences play a crucial role in sustainability.

To clarify how each biomimicry type relates to local ecological and cultural context as well as its potential for aesthetic expression, Table I summarises these dimensions along with strategies for enhancing legibility.

**TABLE II**  
**The Comparative Analysis of Cases [by the author]**

| Biomimicry type            | Connection to place (context)                                                                                     | Aesthetic expression                                                                                                                        |
|----------------------------|-------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Organism level</b>      | Potentially <b>strong</b> if local organisms are selected for mimicry, otherwise generic                          | Legibility: <b>High</b> , often iconic and recognisable                                                                                     |
|                            | Ecological: Should use locally endemic species to align with native ecology                                       | Aesthetic development strategies: Clearly reference local species and explain visually                                                      |
|                            | Cultural: Strengthened by the cultural or symbolic significance of chosen organisms                               |                                                                                                                                             |
| <b>Habitat level</b>       | <b>Strong</b> when habitats selected are local and culturally familiar                                            | Legibility: <b>Moderate</b> , recognisable through patterns or spatial arrangements                                                         |
|                            | Ecological: Design to integrate directly with local ecological habitats                                           | Aesthetic development strategies: Include visible ecological features, interpretative signs                                                 |
|                            | Cultural: Connect with vernacular habitat-like constructions                                                      |                                                                                                                                             |
| <b>Ecosystem level</b>     | <b>Very strong</b> , inherently tied to local ecological context and cultural identity                            | Legibility: <b>Low to moderate</b> , subtle, ecosystemic rather than iconic                                                                 |
|                            | Ecological: Explicit mimicry of functional and relational dynamics of local ecosystems                            | Aesthetic development strategies: Communicate ecological processes visibly, integrating abundant greenery                                   |
|                            | Cultural: Embrace traditional ecological knowledge and practices                                                  |                                                                                                                                             |
| <b>Abstract principles</b> | <b>Variable</b> , require deliberate localisation of universal principles                                         | Legibility: <b>Low</b> , typically subtle or invisible without interpretation                                                               |
|                            | Ecological: Apply locally-attuned principles such as “adapt and evolve in place,” “use waste as a resource”, etc. | Aesthetic development strategies: Explicitly demonstrate principles through educational signage, symbolic motifs, or explanatory narratives |
|                            | Cultural: Validate traditional ecological knowledge and local cultural practices through shared principles        |                                                                                                                                             |

#### D. Influence of Secondary Approaches

Other approaches to categorising biomimicry, distinguished as secondary in this research, also influence how primary scale-based biomimicry categories relate to the local context and what aesthetic expression they can gain in urban design. The conceptual scheme (Fig. 1) visually represents

the multidimensional interactions between biomimicry typologies and their contextual and aesthetic implications. Secondary approaches are shown surrounding the central horizontal axis, where the key biomimicry scale levels are positioned. Line thickness indicates how strongly each secondary approach influences context-specific integration and aesthetic outcomes for each scale of biomimicry.

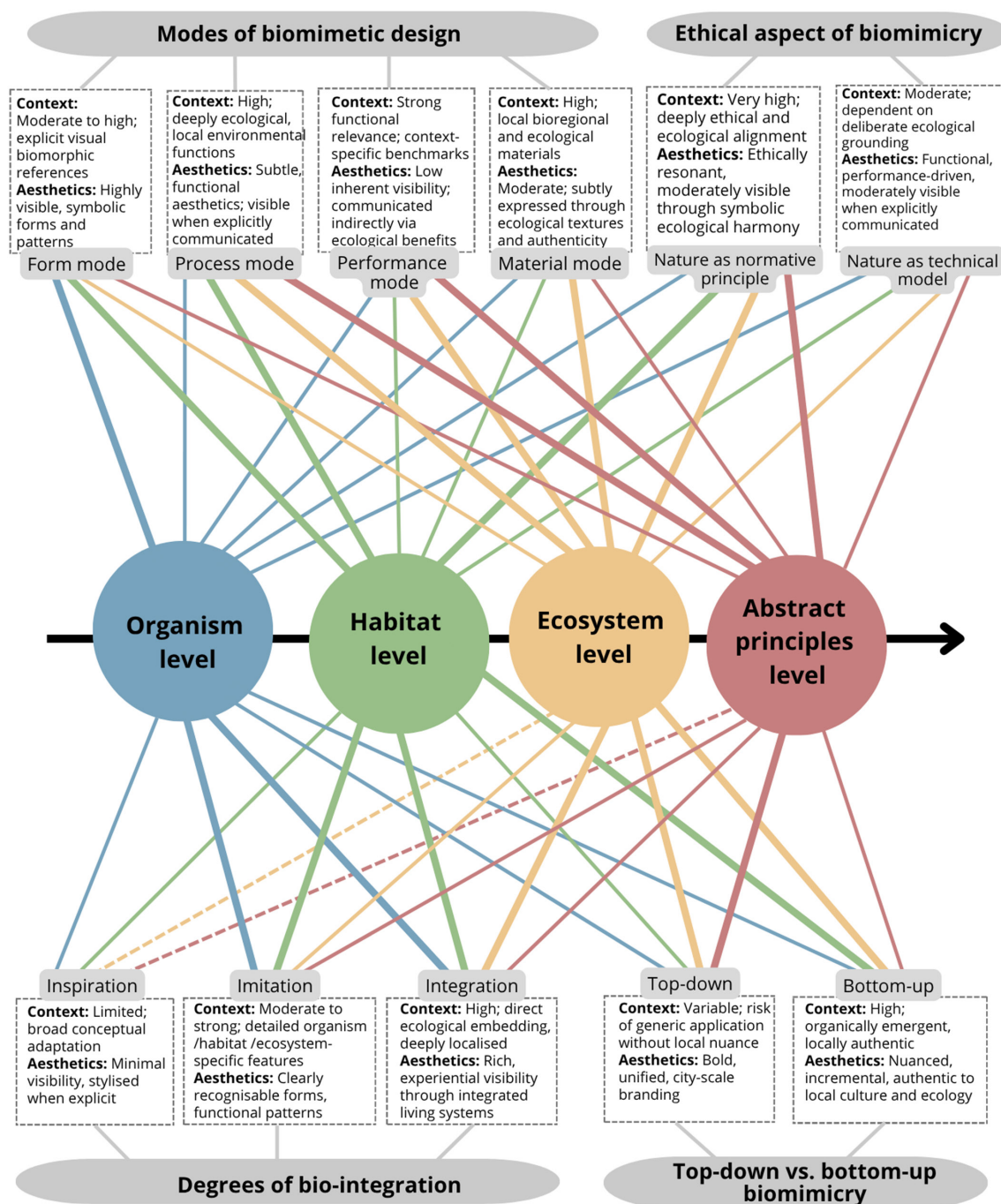


Fig. 1. Conceptual scheme illustrating how secondary biomimicry approaches (degrees of bio-integration, modes of biomimetic design, ethical aspects, and top-down vs bottom-up) influence the primary typology (organism, habitat, ecosystem, abstract principles levels) in terms of their contextual connections (ecological and cultural) and aesthetic expression. The thickness of connecting lines indicates the relative strength of these influences: thick lines denote strong connections, medium lines indicate moderate connections, and dashed lines represent weaker, more indirect influences (created by the authors).

*Degrees of bio-integration: inspiration, imitation, integration.* At the level of inspiration, biomimicry tends to offer broad conceptual ideas derived from nature, typically characterised by limited contextual specificity and minimal aesthetic visibility. In contrast, imitation approaches provide clearer and more explicit biomorphic forms, significantly enhancing visual legibility, though demanding meticulous adaptation to local contexts. Integration, representing the deepest level of bio-integration, engages directly with local ecosystems, embedding living organisms actively within urban environments. For example, the design of the Hamlet Waterfront in Vietnam explicitly chose to integrate the existing wetland habitat into the urban fabric [44]. This profound connection facilitates rich, context-specific aesthetics, allowing urban designs to visibly demonstrate ecological relationships and environmental authenticity.

*Top-down vs bottom-up approaches.* Top-down biomimetic strategies can successfully articulate bold, unified visions, prominently marking urban sustainability efforts. However, without nuanced localisation, these initiatives risk superficial application, potentially leading to a disconnect from local community, identity, and heritage. Conversely, bottom-up biomimicry inherently arises from local environmental conditions and community interactions. This organic emergence has the potential to incorporate naturally local ecological and cultural dimensions, producing authentic aesthetics that evolve incrementally and resonate deeply with community experiences and perceptions.

*Form, process, performance, and material modes of biomimetic design.* Form-based biomimicry can significantly influence urban aesthetics through the use of biomorphic structures and patterns, often becoming visual symbols of local identity and ecological commitment. In contrast, process-based biomimicry is deeply anchored in local environmental systems and ecological functions. Although its biomimetic characteristics may be less overtly visible, explicit communication and interpretation can reveal its inherent ecological logic. Performance-based biomimicry, defined by functional benchmarks derived from local ecosystems, ensures strong contextual appropriateness, although it can lack immediate visual identification without deliberate efforts to communicate its ecological basis. Material-based biomimicry emphasises context specificity through the use of regional and biomaterials, which may subtly yet distinctly alter urban aesthetics towards greater ecological and tactile authenticity.

*Nature as normative principle vs technical model.* Approaching nature as a normative principle positions urban design within ethical frameworks deeply aligned with local ecological standards, embedding sustainability as an intrinsic aspect of place identity. Conversely, interpreting nature primarily as a technical model tends to prioritise innovation and performance metrics. While this

can yield substantial technological advancements, it risks marginalising deeper cultural and ecological integration unless carefully and intentionally contextualised.

### III. Network-Based Analysis of Potential Relations of Urban Biomimicry Approaches to New Urbanism Models

To analyse the existing and potential influence of urban biomimicry on sustainable urban planning, the New Urbanism (NU)-based or related urban concepts and models were selected, as NU could be seen as the integrating theoretical network for many smaller sustainability-related urban models and concepts (e.g., transit-oriented development (TOD), walkability, 15-minute city, etc.). The idea was to view the whole set of theories and models as at least a potential network where one model could be supported by the other or borrow some elements from it. Based on a literature analysis [45, 46, 47], the following NU models were identified and grouped into three categories.

- Core principles of New Urbanism: Walkability, connectivity, mixed-use and diversity, mixed housing types, quality architecture and urban design, traditional neighbourhood structure, increased density, smart transportation, sustainability, quality of life.
- Tools and design approaches: The rural-to-urban transect, form-based codes, urban-to-rural transition management, complete streets, street trees and greenways, frontage design (e.g., stoops, porches, arcades), community charrettes (participatory design workshops), codes and covenants for shared space management, urban acupuncture (small interventions with systemic impact).
- Spatial scales and structural models: Region level – transit-oriented development (TOD), greenbelts, polycentricity; city level – compact city model, regional form-based planning; district level – neighbourhood unit, urban villages, mixed-use centres; block level – perimeter blocks, shared courts, human-scale grid; street level – slow streets, shared space, pedestrian boulevards; parcel level – building typologies, architectural pattern books.

Based on earlier presented literature analysis on biomimicry, the following approaches/models were taken: organism level biomimicry; habitat level biomimicry; ecosystem level biomimicry; principles of nature level biomimicry; modes of biomimetic design (form mode, process mode, performance mode, materials mode); degrees of bio-integration (inspiration, imitation, integration); top-down biomimicry; bottom-up biomimicry; ethical aspects (nature as normative principle, nature as technical model). While using ChatGPT [48], the database of keywords defining each model was created with 7 keywords assigned to each term.

For further analysis, the mathematical graph model was selected. In mathematics, a graph is a structure made up of nodes (also called vertices) and edges (links) that represent relationships between elements. Graph theory provides the formal framework for analysing such structures and is widely used to study systems where connectivity plays a central role. As Newman [49] notes, “Graphs are the natural mathematical representation of a system of relations.” In this study, graph theory was selected because it allows the conceptual relationships between biomimicry principles and NU models to be represented and analysed systematically.

First, graph theory can quantify the influence of individual concepts through centrality measures, identifying key integrators, bridges, and peripheral elements within the network. Freeman [50] observes that “centrality measures identify the most important vertices within a graph, according to structural position.” This is especially relevant for detecting bridging concepts, those that connect otherwise separate thematic clusters, using measures such as betweenness centrality [50]. Graph metrics like clustering coefficient and modularity further reveal thematic communities in the network, where related concepts group together [49]. Graph theory also supports multi scale analysis, from local patterns such as the number of triangles around a node to global properties such as average path length [51]. This makes it possible to explore both the micro level interactions between specific concepts and the macro level organisation of the conceptual system. An additional advantage is that graph structures can integrate qualitative semantic similarity

data with quantitative structural metrics, bridging text analysis and network science [52]. Graph based methods are well established in urban studies, with tools such as space syntax demonstrating how spatial systems can be systematically represented and compared [53]. Furthermore, the visualisation capabilities of graph models are particularly valuable, as they make complex relational data more intuitive for interpretation and communication [54]. Importantly, graph theory is domain agnostic; it applies equally well to biological, social, or urban systems, making it ideal for integrating two distinct conceptual domains such as biomimicry and NU [55]. Finally, modelling the full network structure allows for the detection of emergent property patterns that arise only from the whole system and cannot be inferred from individual elements alone [56].

Each concept was treated as a node of the graph, while similar keywords defining the concept were interpreted as undirected edges of the graph, meaning that certain ideas or concepts could be transferred or related between models in both directions. As various synonymous terms could be used in literature, the semantic proximity of the keywords and names of the model nodes was analysed using *spaCy*'s *en\_core\_web\_md* [57] model for Python to compute semantic similarity between keywords. The Python NetworkX tool [58] for creating the undirected graph was used in PyCharm, where each node is either a biomimicry principle or an NU model; each matching keyword pair forms a separate edge. Graph data was imported into Gephi [59] for further centrality calculations and visualisations. The workflow scheme is presented in Fig. 2.

#### Methodological workflow: semantic graph creation

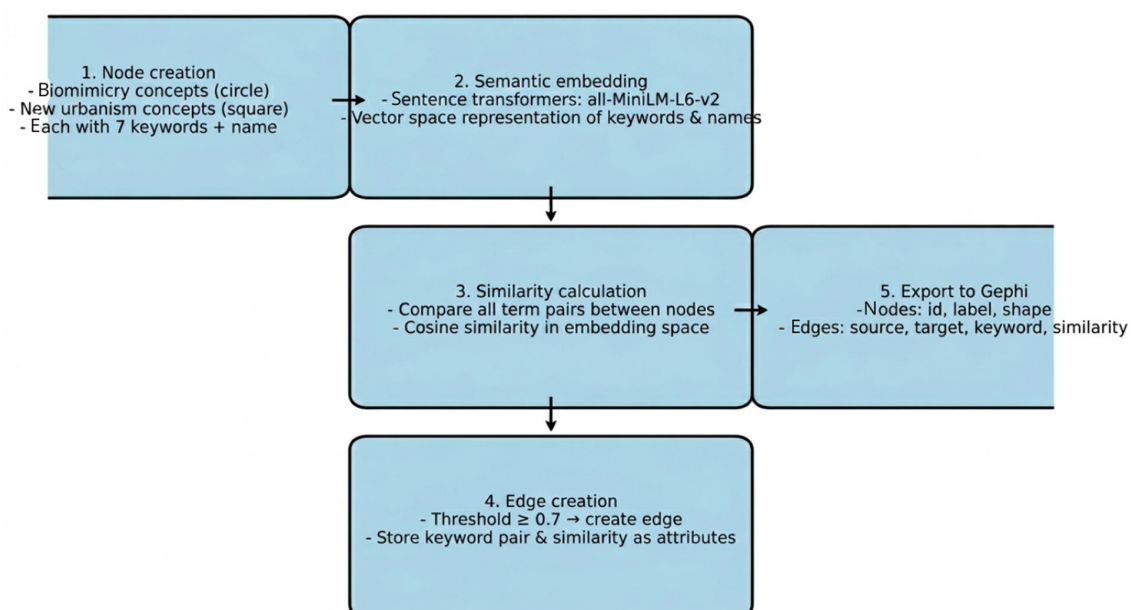
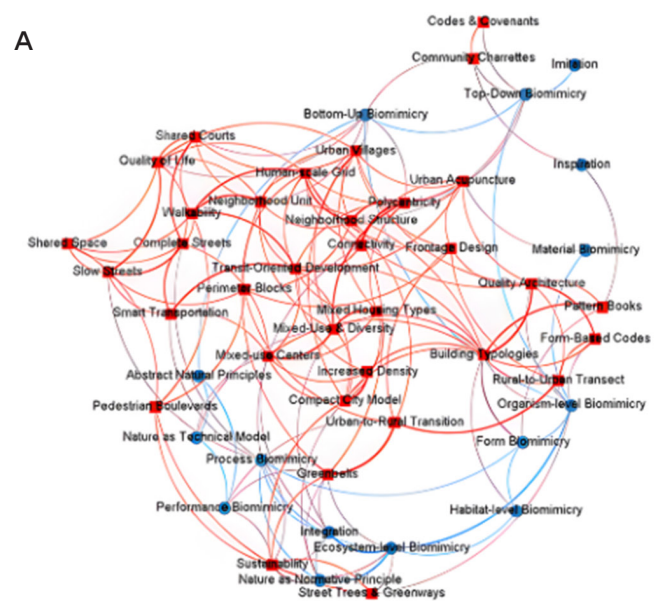


Fig. 2. Methodological scheme of the graph-based model analysis [created by the authors].



where  $N(v)$  is the set of neighbours of  $v$ . In the presented investigation, it measures how many direct semantic connections a concept has.



Fig. 3. Graphs representing the theoretical framework of the biomimicry approaches and NU concepts: B – degree centrality [created by the authors].

$$Closeness(v) = \frac{n-1}{\sum_{u \neq v} d(v, u)},$$

where  $n$  is the number of nodes in the graph,  $d(v, u)$  is the shortest topological distance from  $v$  to every other node  $u$ . High closeness indicated that the concept can reach all others quickly via semantic links and could be considered a good conceptual integrator. Low closeness identifies a remote thematic region.



Fig. 3. Graphs representing the theoretical framework of the biomimicry approaches and NU concepts: C – closeness centrality[created by the authors].

*Betweenness* (Fig. 3 D) is counted as the fraction of shortest paths between pairs of nodes that pass through a given node [50].

$$Betweenness(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}},$$

where  $\sigma_{st}$  is the number of shortest paths from  $s$  to  $t$  and  $\sigma_{st}(v)$  is the number of those paths passing through  $v$ . High betweenness identifies the model/node as a semantic bridge between biomimicry and NU clusters.

Fig. 3. Graphs representing the theoretical framework of the biomimicry approaches and NU concepts: D – betweenness centrality[created by the authors].

*The clustering coefficient* (Fig. 3 E) measures how connected a node's neighbours are [56].

$$C(v) = \frac{2e_v}{k_v(k_v - 1)},$$

where  $e_v$  is the number of edges between neighbours of  $v$ ,  $k_v$  means the degree of  $v$ , or simply the number of edges that are directly connected to the node. A high coefficient shows that the concept belongs to a tight-knit thematic cluster. A low coefficient says that the concept acts more as a potential connector between otherwise separate groups.

Fig. 3. Graphs representing the theoretical framework of the biomimicry approaches and NU concepts: E – clustering coefficient[created by the authors].

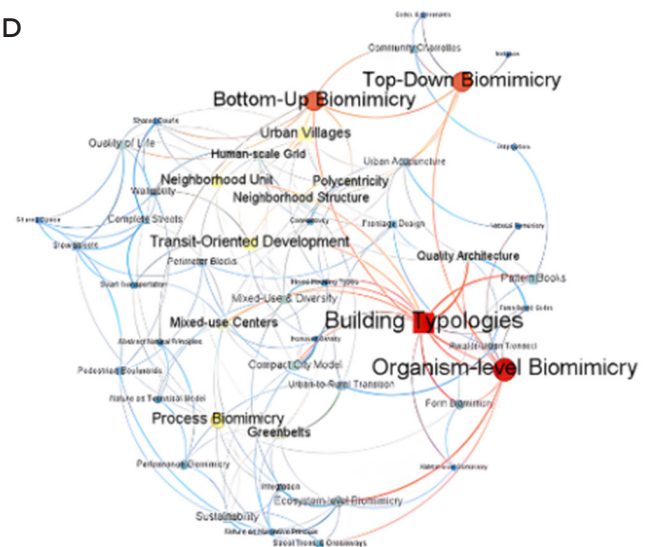
*The number of triangles* (Fig. 3 F) represents a count of triangles (3-node closed loops) a node participates in [56].

$$Triangles(v) = \frac{1}{2} \sum_{u, w \in N(v)} 1_{\{u, w\} \in E},$$

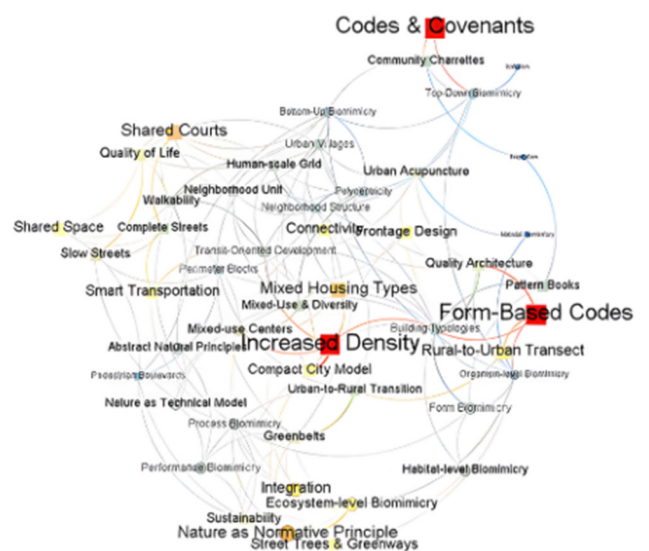
where  $v$  is the node for which we are calculating the number of triangles;  $N(v)$  means the neighbourhood of  $v$ , i.e., the set of all nodes directly connected to  $v$  by an edge;  $u, w \in N$  are two nodes chosen from the neighbourhood of  $v$ ;  $E$  is the set of all edges in the graph;  $1_{\{u, w\} \in E}$  is equal to 1 if  $u$  and  $w$  are connected, and otherwise it is equal to 0. More triangles equal more local redundancy and stronger thematic communities of the nodes.

Fig. 3. Graphs representing the theoretical framework of the biomimicry approaches and NU concepts: F – number of triangles[created by the authors].

D



E



F



*Eigenvector centrality* (Fig. 3 G) is a node's score that is proportional to the sum of the scores of its neighbours [60].

$$x_v = \frac{1}{\lambda} \sum_{u \in N(v)} x_u \text{ ,}$$

where  $v$  marks a specific node in the graph for which we are calculating eigenvector centrality;  $x_v$  is the eigenvector centrality score of node  $v$ ;  $N(v)$  marks the neighbourhood of node  $v$ , i.e., the set of nodes directly connected to  $v$ ;  $u \in N(v)$  means iteration through each neighbour  $u$  of node  $v$ ;  $x_u$  is the eigenvector centrality score of a neighbouring node  $u$ ;  $\lambda$  is the largest eigenvalue of the graph's adjacency matrix, as a normalisation constant derived from the eigenvalue, used so that the centrality scores don't grow indefinitely. In essence, the eigenvector centrality is recursive, as the score of  $v$  depends on the scores of its neighbours. As being connected to important concepts makes a particular concept important too, then high value means the node is part of the "semantic elite" of the network.

Fig. 3. Graphs representing the theoretical framework of the biomimicry approaches and NU concepts: G – eigenvector centrality[created by the authors].

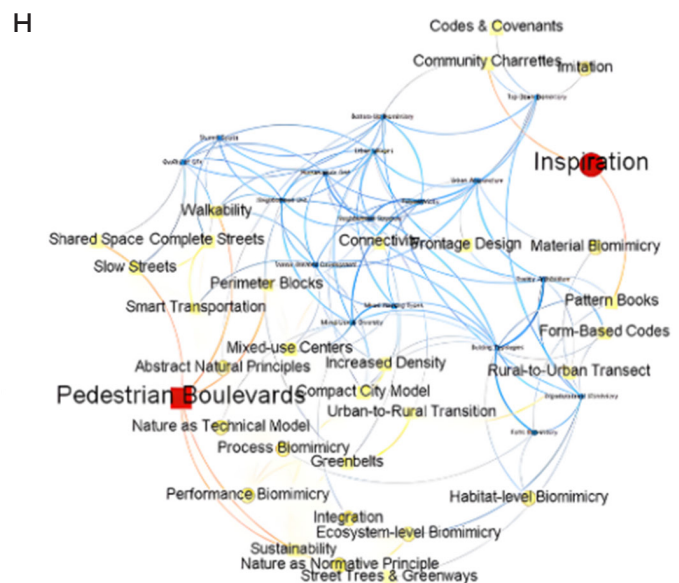


*Eccentricity* (Fig. 3 H) is counted as the maximum shortest path distance from a node to any other node in the network [61].

$$Eccentricity(v) = \max_{u \in V} d(v, u),$$

where  $d(v,u)$  is the shortest path length. High eccentricity means that the node is far from at least one concept or is more peripheral. Low eccentricity means the node is close to all others, indicating conceptual universality.

Fig. 3. Graphs representing the theoretical framework of the biomimicry approaches and NU concepts: H – eccentricity [created by the authors].



The graph-based analysis results are presented in Fig. 3. In Fig. 3 B–H, the red colour indicates high numerical values, while the blue indicates the small ones. The importance of the nodes of the graphs could be seen in Fig. 3 B–H, but in order to generalise the picture, only the centrality values with the biggest both positive and negative standard deviation values were finally analysed as representing really outstanding centralities. The results in the form of a table-heat map are presented in Fig. 4.

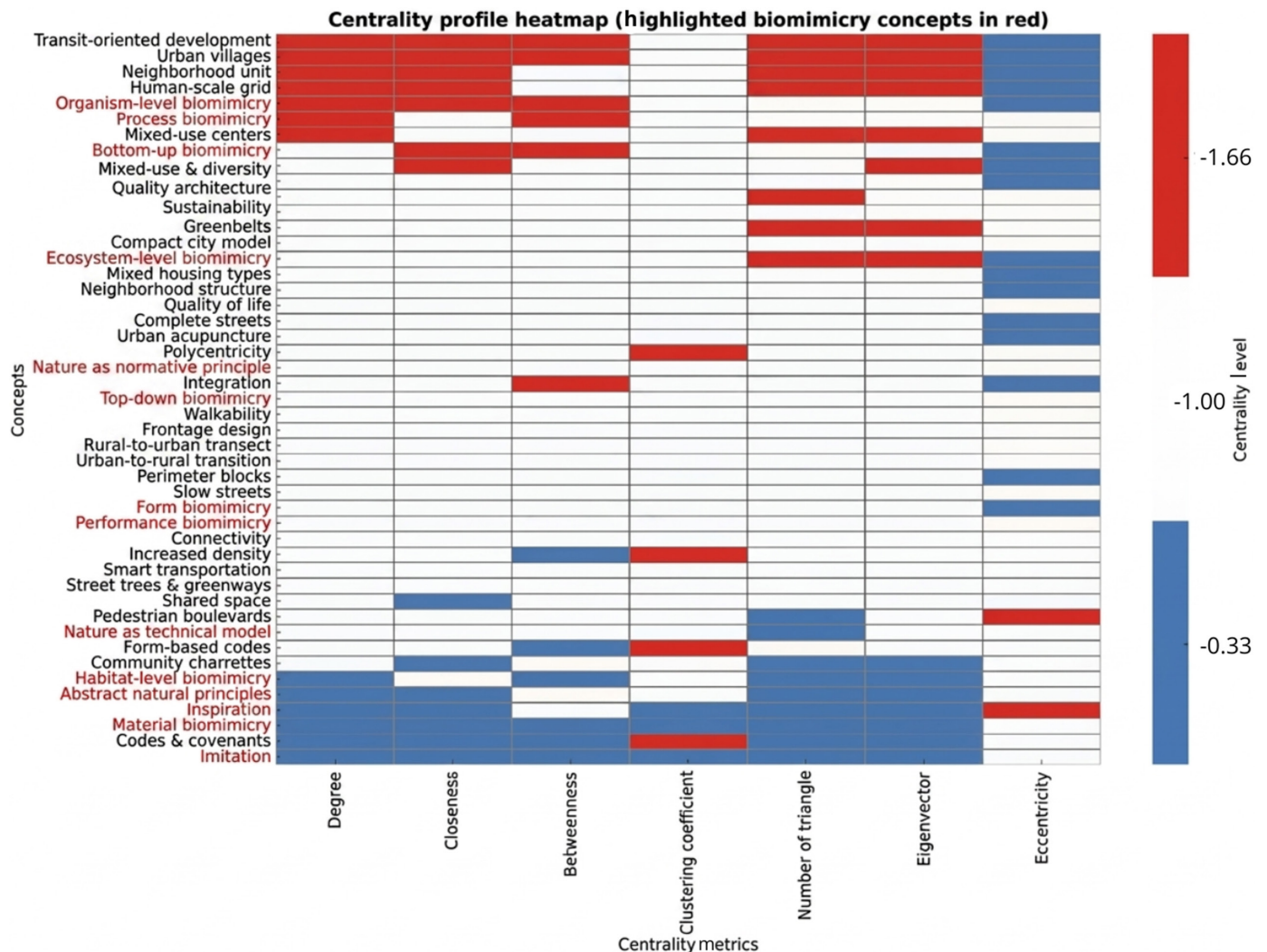


Fig. 4. Centrality profile heatmap based on the standard deviation analysis. The scale of standard deviation and values used for analysis are shown on the right [created by the authors].

Finally, based on Figs. 3 and 4, the results of the analysis could be generalised as follows.

- Most significant and influential concepts. Across multiple centrality measures, certain concepts consistently emerge as structurally important in the semantic network linking biomimicry and NU:
  - urban villages, transit-oriented development, neighbourhood unit, human-scale grid, and compact city model* appear repeatedly in high degree, closeness, betweenness, number of triangles, and eigenvector scores;
  - these nodes are both well-connected and centrally positioned, often acting as integrators between clusters;
  - many of them belong to NU spatial and structural models, which appear to provide a framework that is conceptually compatible with multiple biomimicry approaches;

- on the biomimicry side, *organism-level biomimicry, bottom-up biomimicry, and process biomimicry* are notable for their high *betweenness* and *closeness* scores, indicating they play a bridging role across domains;
- sustainability* and *mixed-use and diversity* also feature in high *degree* and *triangles* counts, confirming their role as broad, cross-cutting themes that link diverse concepts.

These high-centrality concepts function as “conceptual hubs”: widely linked, influential, and well-positioned to mediate integration between the biomimicry and NU frameworks. They represent promising anchors for cross-disciplinary planning strategies.

- Moderately significant but locally cohesive concepts. Some nodes do not score highest in *degree* or *betweenness* but have a high *clustering coefficient* or

*triangles*, indicating they belong to tight-knit thematic communities. Examples: *Increased density, form-based codes, codes and covenants, nature as a normative principle, mixed housing types, and shared courts*. These concepts may not bridge distant parts of the network but reinforce strong local conceptual groups. Their role is in strengthening internal coherence within specific thematic areas rather than mediating between domains. Such concepts are valuable for deepening connections within a given planning paradigm, even if they do not actively facilitate cross-domain integration.

3. Specialised or peripheral concepts. Repeated low centrality scores, especially in *degree*, *closeness*, and *betweenness*, mark a set of niche or isolated concepts:

- *imitation, material biomimicry, inspiration, habitat-level biomimicry, abstract natural principles, codes and covenants, community charrettes, nature as technical model, form-based codes*;
- many are biomimicry modes or principles that are conceptually rich but less directly embedded in the shared vocabulary between the two domains;
- high *eccentricity* values for *inspiration* and *pedestrian boulevards* confirm that some concepts are semantically distant from large parts of the network.
- These concepts may represent specialist knowledge or domain-specific tools that require intentional linking strategies to bring them into cross-domain discourse.

4. Bridge concepts. High *betweenness* without necessarily having the highest *degree* identifies strategic connectors:

- *top-down biomimicry, bottom-up biomimicry, and process biomimicry* act as semantic bridges, enabling thematic flows between biomimicry and NU clusters;
- these are critical for integration: removing them would likely fragment the network.

Bridging concepts should be explicitly addressed in interdisciplinary frameworks because they enable knowledge transfer across thematic boundaries.

5. Peripheral but potentially expandable concepts. Concepts with low *degree* and *closeness* but high clustering within small groups may be underutilised connectors: these could be expanded via strategic linkage to high-centrality hubs to strengthen the integration of niche approaches (e.g., habitat-level biomimicry, abstract natural principles). There is potential to deliberately weave these concepts into broader frameworks to diversify and enrich the discourse.

## CONCLUSION

The urban biomimicry typology developed and elaborated in this research highlights the multi-scalar nature of urban biomimicry, distinguishing between organism, habitat, ecosystem, and abstract-principles levels. This classification provides conceptual clarity, enabling practitioners to consciously select appropriate scales for biomimetic interventions and to recognise the theoretical nuances associated with each approach. Consequently, this systematic framework enhances the strategic application of biomimicry in urban planning by aligning design decisions closely with ecological and cultural contexts.

This analysis also reveals the critical importance of integrating biomimetic design within specific ecological, cultural, and aesthetic contexts. It demonstrates that distinguished secondary approaches, such as degrees of bio-integration, top-down versus bottom-up implementation, modes of biomimetic design, and ethical perspectives, significantly influence place-sensitivity and aesthetic legibility of the project. Acknowledging these interconnections assists urban designers in developing biomimetic solutions that are not only ecologically functional but also culturally resonant and aesthetically engaging.

The graph-based analysis reveals the conceptual alignment between urban biomimicry typologies and NU models, reinforcing the argument for their combined potential in sustainable urban development. According to the results of graph-based analysis, the relations between NU and biomimicry models could be summarised while identifying the following typologies of roles of the models:

- Core integrators, which include NU structural models and certain biomimicry approaches (esp. *organism-level, process, and bottom-up biomimicry*).
- Cluster stabilisers, which include NU-oriented planning tools and governance frameworks that keep thematic groups cohesive.
- Peripheral “specialists” which require deliberate integration to maximise network connectivity.
- Bridges or concepts that may not be the most connected but are strategically positioned to link otherwise distant thematic clusters.

These alignments suggest ways for urban planners to incorporate biomimetic thinking systematically into sustainable urbanism frameworks, enriching both ecological responsiveness and cultural resonance. Ultimately, the graph approach validates the theoretical typologies identified earlier, affirming their relevance as foundational concepts in future interdisciplinary urban sustainability research and practice.

## ACKNOWLEDGMENTS

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