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TOWARDS RESILIENT CITIES: BIOMIMETIC STRATEGIES FOR URBAN ADAPTATION

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ABSTRACT

Biomimicry, as an evolutionary strategy drawn from nature, has emerged as an essential framework for the built environment within the context of sustainable urban development geared towards resilience. By covering the various aspects of human technology, this inventive concept simplifies design processes in all fields, particularly in architecture. It offers adaptive solutions to emerging urban challenges, by providing engineers, architects and urban planners innovative tools to draw inspiration from natural ecosystems.
This paper discusses the fundamental principles of biomimicry and its practical application to architectural design and urban sustainability. It presents a holistic biomimetic methodology that uses living organisms as references to develop effective responses to address the critical effects of climate change and enhance the resilience of urban systems. To this end, the study presents a selection of natural inspirational models, with strategic characteristics suitable for sustainable urban environments design; more adapted to hot and arid climates conditions.
Learning from nature, this research highlights the transformative potential of biomimetic approaches to improve the resilience and adaptation in cities. By strengthening the harmony between built environments and natural ecosystems, these strategies make it possible to design cities that are more sustainable, balanced and in symbiosis with their environment.

KEYWORDS

Biomimicry, Urban Forms, Sustainable Development, Biomimetic Design, Hot and Arid Climate

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1. Introduction

"The architect for the future will build imitating nature, because it is the most rational, sustainable and economical method…" (Gaudi, 1889). His insight rings true, as nowadays, cities are facing a big batch of problems. Rapid urban change has been a key factor behind the severe development of ecological footprints impacts and environmental related vulnerabilities that need to be reconsidered in the city sustainability concept (Liu et al, 2023). as well as an increasing number of major cities in the world are struggling with problems such as heatwaves, flooding, and resource depletion, innovative approaches are needed to make cities more resilient (keho, 2023). One of the most effective solutions is to use biomimetic strategies, where nature is used as a model, mentor and guide.

According to Radwan and Osama (2016) Biomimicry offers an endless number of complex designs and strategies adopted by living organisms in the world around us. For millions of years, living organisms have successfully developed effective solutions to adapt to environmental challenges without affecting ecosystem integrity (Raza et al, 2023). Studying and learning from these organisms allows architects and urban planners not only to design in response to climate challenges, but also enhance sustainability and biodiversity by making cities more ecological and resilient (Cobbinah, 2021). The study of termite mounds has given rise to innovative concepts of passive cooling., as well as the composition of spider silk, which has prompted the production of new materials combining lightness and strength, Those and an infinite potential of nature's geniuses that have been a source of inspiration for human innovation.

In fact, as urban environments have to adapt to manage fluctuating climatic conditions that continue to increase over time, the concept of resilient cities returns strongly to biomimetic approaches. To face these challenges, cities will need not only to resolve the impacts of climate change, but also to ensure a resilience and harmonious co-existence with the natural world. In other words, this means that we need to rethink the urban planning process by mimicking coexisting systems, notably in terms of resource management, temperature regulation and energy efficiency, in order to create urban ecosystems that promote human well-being while preserving at the same time the ecological balance. To this end, the paper will investigate the question of how biomimicry could be effectively gain entrustment into urban planning, to create cities that are harmoniously adapted to their ecological contexts, more particularly in hot and arid climates. This discussion seeks to identify viable, practice-based solutions that can improve the resilience of cities as well as the well-being of their inhabitants, within the ecosystems they belong to. The adoption of biomimetic solutions offers a promising innovative approach that facilitates the creation of highly adaptive cities, integrating mechanisms and strategies that, like other ecosystems, evolve harmoniously with nature's rhythms while solving such critical issues. In this way, cities will not only survive the climate change, but will also ensure a sustainable future.

2. Methodology

This study pursues a scientific research framework to investigate the conceptual foundations of biomimicry, drawing from a comprehensive analysis of a diverse array of scientific papers. The selected literature ranges over architecture, sustainability and biomimetic design, providing a multi-dimensional analysis of the study's subject. Key areas of focus include biomimicry; urban design; sustainable development; biomimetic principles; strategies for hot and arid climates; sustainable approaches to the built environment; and the dynamic involvement of humanity and nature.

For that rigor and inquiry, articles were selected on criteria set for research. The selection dealt mainly with some of the most recent works specifically outlining the multifaceted link of biomimicry with sustainability. The review also sought methodological and conceptual insights into how biomimicry can be applied innovatively as a design framework for addressing future sustainability challenges. The process was to identify biomimicry not only as a simple tool but rather as a "paradigm shift" that reorients our understanding of the connections between humans and their natural environment. It translates a whole field of literature into something that could be perceived to advance understanding of how biomimetic strategies could enhance resilience and sustainability in urban design practices, arising from current challenges in the contemporary environmental context. It is through this scientific investment that we intend to promote more profound and broader discussions on biomimetic applications, thereby contributing to the advancement of sustainable urban planning concepts.

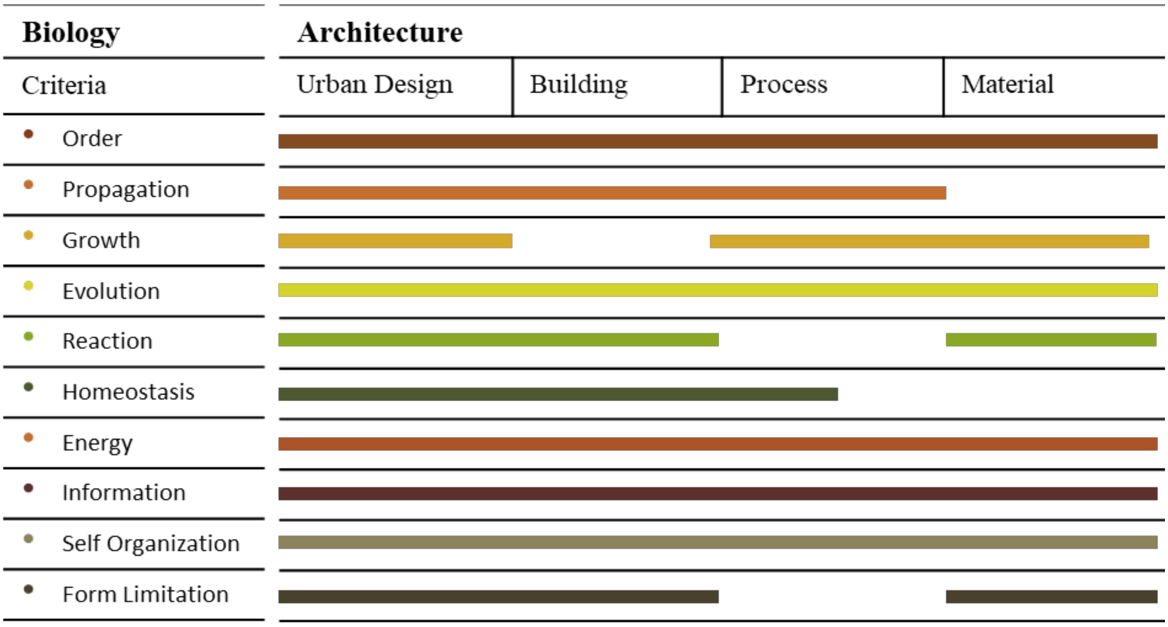
3. Literature Review

3.1. The influence of the biomimetic approach on urban and architectural design

The exploitation of biomimetic methods -or nature's mechanisms for overcoming human challenges- has emerged as a promising technique for architecture and urban planning. By integrating nature's principles into design processes, architects and urban planners are more able to create spaces that are more functional, sustainable and holistically in harmony with nature.

The biomimetic approach and bio-inspired design must therefore closely overlap to understand how this methodology influences the creation of our built environments. As Figure 1 shows, these interactions illustrate how strategies derived from nature are applied at various levels of our designs, in both architecture and urban planning. The diagram highlights the relationship between biomimetic principles and bio-inspired design concepts, and the possible synergies between them.

Table 1. Interactions between the biomimetic approach and bio-inspired design.
Adapted from "A Biomimetic Approach to Architecture and Design"by (Gruber, 2016).



Furthermore, a functional convergence between natural strategies and the requirements of urban and architectural design needs to be explored. By identifying key functions, it is possible to target more precisely the relevant biomimetic strategies drawn from nature. At this stage (see Table 1), a range of key functions have been identified in response to essential environmental objectives of natural ecosystems and buildings, highlighting common functions that meet these objectives. These functions form a crucial link between the challenges of adapting urban forms and solutions that are potentially transferable from nature. It is therefore essential to analyse in greater depth the way in which these specific functions are implemented by organisms and natural systems.

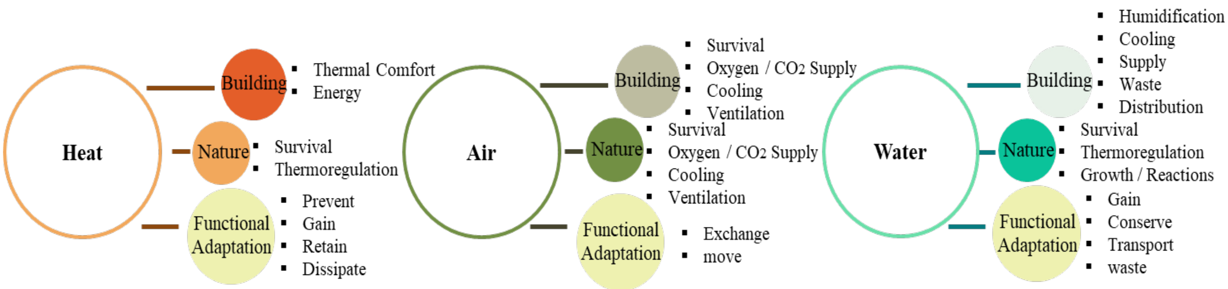


Fig. 1. Functional convergence to address environmental challenges:
Linking architectural needs and natural strategies (Badarnah, 2017).

3.2. Inspirational sources for the adaptation of urban forms

The adaptation strategies found in nature represent an extensive repository of knowledge that deserves to be explored and applied to design, particularly in the field of architecture (Badarnah et al, 2015). The evolutionary processes that shape animal architecture are driven by the pursuit of greater efficiency and sophistication. Structures created by animals exhibit remarkably adherence to stringent criteria for economy and efficiency, often minimizing the consumption of materials and resources. For example, some species, such as spiders and wasps, adopt behaviours that include consuming parts of their own construction to recycle and reuse building materials, thereby exemplifying sustainable that are deeply rooted in natural ecosystems (Hansell, 2005).

In this paper, we propose to study and investigate several biological patterns that present interesting properties and characteristics, with the aim of developing new bio-inspired urban forms that are more adapted to hot climates. More specifically, we will analyze the architectural efficiency of structures such as honeycombs, wasp's nests, and termite mounds. These designs of nature have developed advanced principles of thermoregulation and structural integrity, illustrating strategies for the optimal use of resources under harsh environmental conditions. Examination of these models will provide inspiration for the design of urban environments that not only improve the thermal comfort of indoor spaces, but also optimize the use of resources, thereby contributing to sustainable living. This bio-inspired approach could lead to innovative architectural thinking, rooted in natural principles, while responding to the specific challenges of the modern hot climate.

4. Analysis

To demonstrate and emphasis the fundamental role of biomimicry as a sustainable design methodology in hot and arid regions, we have structured our discussions through the analysis of three selected natural models: honeycombs, wasps' nests and termite mounds. Each of these natural architectural structures offers innovative solutions adapted to the challenges posed by harsh environmental conditions. Honeycombs, built by bees, illustrate an ingenious use of hexagonal shapes and materials, maximising volume and structural strength while minimising the weight and required space. Wasp nests, meanwhile, demonstrate a unique ability to create compact, solid structures by making efficient use of the materials available in their immediate environment.

Finally, termite mounds reveal particularly ingenious strategies for thermal self-regulation. These structures use passive ventilation principles to maintain a stable internal climate, even under extreme environmental conditions. These natural models offer valuable lessons on how living ecosystems can inspire innovative and sustainable approaches to the specific challenges of hot and arid environments.

- **The Honeycomb, the hexagon and its mysteries.**

Inspired by beehives, honeycomb structures have been widely applied in various fields, including in architecture. One of the main challenges in this field, is to understand the exceptional properties of these patterns, which reside in their geometry, scale and the materials used (Long et al, 2012).

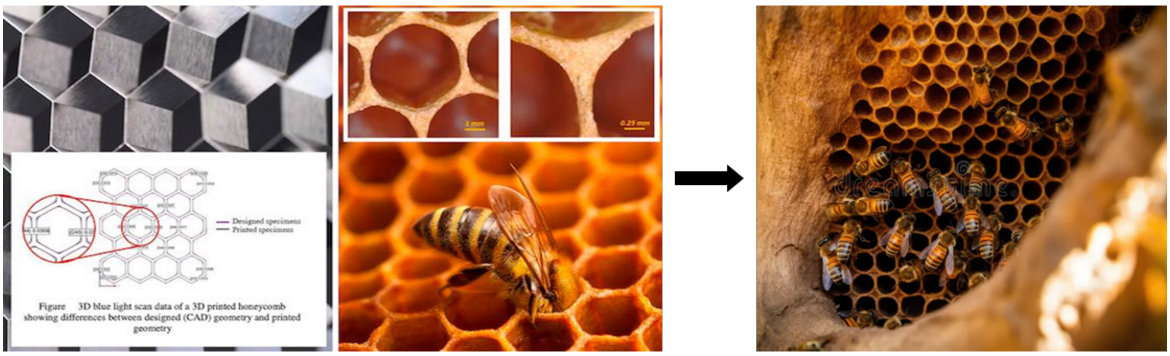


Fig. 2. Honeycombs are a typical example of biomimetic design.
Drawn from: Biomimicry and Bees: What (more) can we learn from honeycombs?, Oct 18, 2023.

Zhang et al (2015) state that the honeycomb structure minimises material waste and exposed surface area. It was a Greek mathematician who first formulated the enigma: in the 4th century, Pappus of Alexandria looked into what the history of geometry would call the "honeycomb conjecture". With a divine sense of strategy, Pappus says, the bees have chosen the hexagon, because this structure requires the least material. The enigma will then consist in mathematically demonstrating why the juxtaposition of hexagons corresponds to the most economical "paving of the plane". In other words, why the cells formed by bees make it possible to store as much honey as possible with as little wax as possible and without wasting any space? Not only Pappus will not succeed, but also for centuries, mathematicians will work on the subject in vain. Bees are therefore the authors of one of the most difficult problems in the history of geometry. Darwin also looked into the question, considering that the efficiency of hexagonal storage is due to natural selection: the bees that are the most economical in wax overtake their congeners (Fournier & Fourié, 2011).

Fortunately, we did not wait until the enigma was solved to imitate the geometric model invented by bees. The design of the cell has been imitated for centuries for paving (in the architectural sense, this time), storage or decoration. In addition, the cells represent a model of strength. In the mid-1980s, their imitation gave rise to a new type of innovations, called a "honeycomb structure" (Xiong et al, 2011). The theorem corresponding to Pappus' intuition has only been demonstrated in 1999, by the American Thomas C. Hales (Fournier & Fourié, 2011). In 2001, the mathematician demonstrated that "the honeycomb conjecture". He has shown that of all the divisions in the plan into parts of the same area, it is the regular hexagon paving that has the smallest perimeter. Since the cells house eggs of the same shape and volume, bees therefore optimize the amount of wax needed to build nests in an absolute way (Richard, 2006).

The honeycomb is truly one of the wonders of nature. The bees build successive layers of hexagonal cells, identical in size and shape, stacked with remarkable precision, as if they had emerged from a plan drawn on graph paper. But why do bees opt for hexagonal cells rather than square or circular ones? (Karihaloo et al, 2013). As previously mentioned, natural organization is economical, expending the least amount of material and energy to accomplish a task. As this is the most economical method of assembly, three-way junctions with angles of 120° are common in nature (Foy, 1983).

- **The Wasps: Did the wasps teach us how to build?**

The wasp is a builder insect, which builds nests of paper. It is a predatory insect or parasite, living in colonies, with morphology close to bees. According to Pallasmaa (1995), three animals in particular have developed the ability to create paper independently. Paper wasps, for example, use small particles of used wood from trees and wooden poles, which they mix with their hardening saliva. The diversity of wasps is also reflected in the construction of their nests. Some species modify existing cavities, while others build nests, either underground or in the open air. A nest may contain one or more individual brood cells. The most commonly used building material is mud, a mixture of earth and regurgitated water, although many species opt for chewed plant material.

Fig. 3. Exterior view and interior design of the wasp nest.
Drawn from: What to do about a wasp nest and what do they look like? Jun,3, 2024

Mason Wasps (or potter wasps):

Not all wasps build paper nests: mason wasps use clay or mud. This is an ideal material for protection from heat, when it is controlled, like wasps and ventilation systems., some claim that the houses built of clay (or adobe) by the Pueblo Indians were inspired by mason wasps (Fournier & Fourié, 2011).

Who are the Mason Wasps?

The term mason-wasps refers to several species of hymenoptera that live alone and build earthen nests. These insects are also known as "Pottery Wasps"(Hansell, 2005).

Why masons?

Mason wasps are so named because of their ability to build nests from materials such as earth material, clay or sand. Depending on the species (Hansell, 2005). The wasp uses a kind of cardboard, made of wooden pulp impregnated with saliva, to build its nest. As for the mason wasp, it uses mud mixed with saliva to build its "shelter", which has the shape of a small amphora. They instinctively take into consideration the strength requirements of their building materials while building their nests–and they do so with ingenious simplicity (Tributsch, 1982) .

Nests are built in different places and in different ways. Some attach their nests to the stem of a plant, others in a wall crack, and others dig cavities on the ground. Some mason wasps even block the entrance to the cell with a stone (Hansell, 2005).

- **Termites: The passive ventilation.**

Termites., Social insects living in hierarchical colonies and organized into castes, building big nests in chewed soil, termites.

(a) (b)

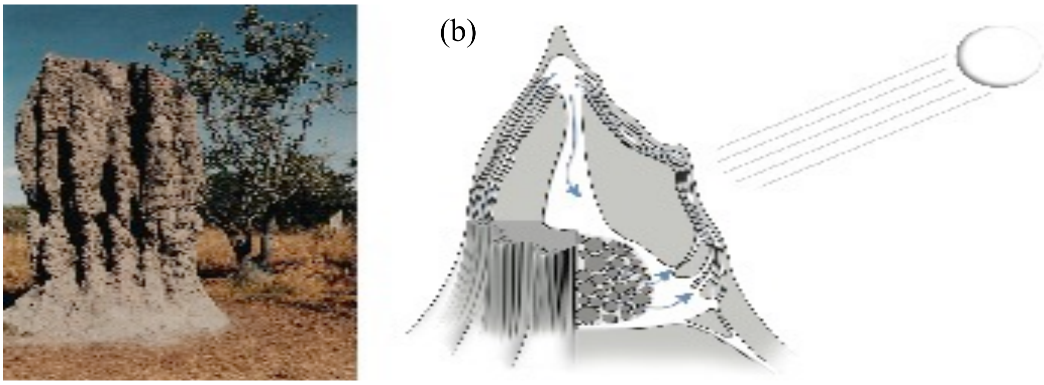


Fig. 4. (a) the numerous ridges of the cathedral mound, photo by Karen Sullivan.
(b) mound cross section showing the airflow inside the mound induced by external radiation (Badarnah & Fernandez, 2015).

Could we build cities like termites?

Is it possible to build an underground city where two million inhabitants live and work, raising their offspring, storing their food, a city that would be perfectly protected from sunlight and bad weather and where a constant temperature prevails? If we cannot at the present time, termites master this construction perfectly. In tropical regions, termites called "superior" (as opposed to their congeners that nest in wood) build clay houses, termite mounds, which can reach heights of 6 to 8 metres and measure up to 30 metres in diameter (Fournier & Fourié, 2011).

(a) (b)

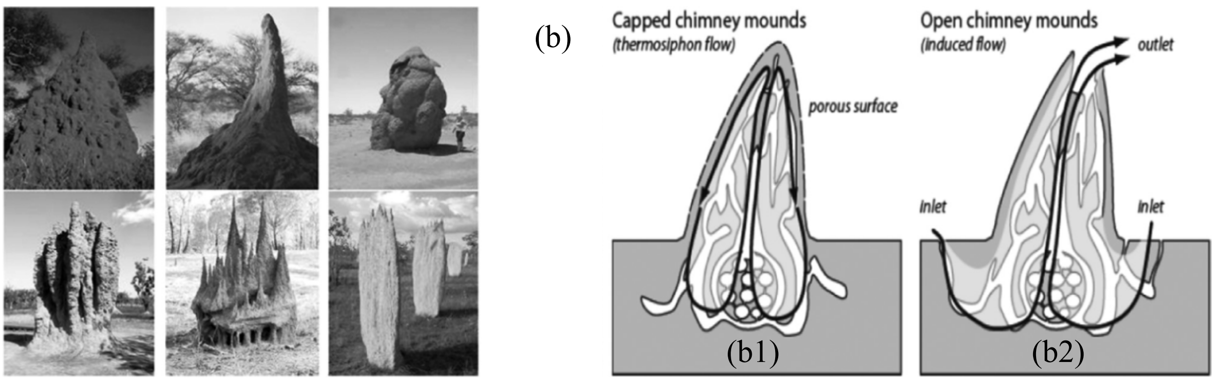


Fig. 5. Some termite mounds and its inner structure (Yuan et al,2017). (a) : The termite mound prototype; (b) : Ventilation air flow : (b1) Thermosiphon flow thought to occur in capped chimneymounds; (b2) Induced flow thought to occur in open-chimney mounds.

Insects build them by chewing clay: mixed with their saliva, it is dried under the heat of the sun, giving an extremely resistant material. These termite mounds are equipped with a formidable passive air conditioning system: in their galleries and rooms, a constant temperature never exceeds 23 °C in tropical regions where outside temperatures can reach twice as high (Luscher, 1955).

An example of Macrotermes Jeanneli nest mound, which illustrate the ventilation design. The mound is topped by a single chimney that rises several metres. All exhaust gases are vented through this chimney, while air enters at the base of the mound, either through the ground or through a multitude of small openings used for foraging (Darlington et al., 1997).

In addition to this thermal comfort, insects succeed in ensuring a stable humidity level in buildings often located in the middle of the desert. Termite mounds rise above the ground - sometimes very high - but have their foundations at depth. This circular base, which can sometimes go down to 2 meters underground (Scotte, 1994), sinks into wet ground areas. There, the termite mound obtains the humidity and freshness, which, due to a constant thermic exchange, will ensure the required temperature and hygrometry to the building. How? High chimneys that rise to the top of the termite mound evacuate the hot air: lateral air inlets allow the ventilation of these chimneys and the regulation of the temperature (Chayaamor-Heil & Hannachi-Belkadi, 2017). In addition, that is not all: this system is constantly improved by the intervention of the insects themselves, who block or open chimneys and open orifices that allow optimal ventilation, it is this constant interaction, which is obviously the most difficult to imitate in human buildings (Cohen & Reich, 2016).

3.3. Urban forms inspiration through a biomimetic approach

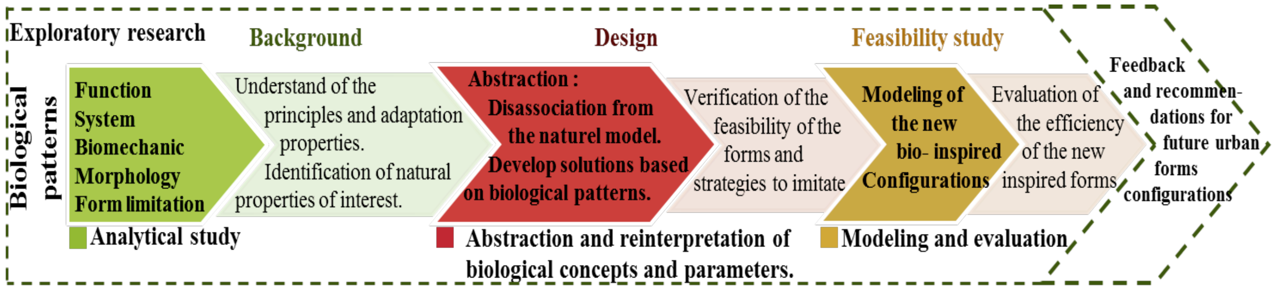


Fig. 6. Mick Pearce's approach, Adapted from "Innover Durable" by Estelle CRUZ, Biomimicry World Tour. Zimbabwe, September 2015.

In order to successfully adopt a biomimetic approach in the creation of urban forms, the design process should begin by an exploratory research on Nature, Biomimicry and the influence of this current on architecture and urban design, to understand the framework of this approach and to be able to determine the appropriate methodology to follow. Then we look for biological models that could serve us as inspirational sources, according to their formal or strategic characteristics appropriate to the adaptation of the urban forms.

Afterward, an analytical study could be carried out on the selected models that have interesting forms or particular adaptive properties that respond to the needs sought, to understand the principles underlying them, while deepening the study on all the characteristics that could serve us in the adaptation process.

After identifying the selected models, we pass to the abstraction of the solutions, characteristics and adaptation strategies drawn, to transfer them into the adaptation of the new forms, which involves the elaboration of a set of concepts and principles that could be adopted in the configuration process.

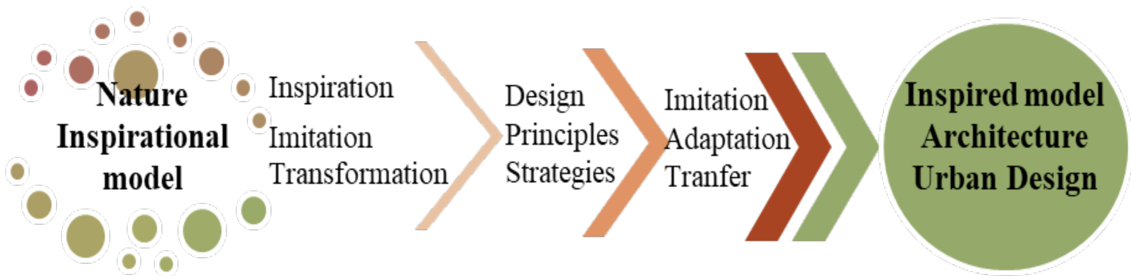


Fig. 7. Biomimetic approach process. Adapted from "A Biomimetic Approach to Architecture and Design" by Petra Gruber, NASA Biomimicry Summit., 2016.

Conducting a comprehensive feasibility analysis of the proposed modelled forms is essential for evaluating their efficiency and effectiveness. The analysis will serve at least two purposes: evaluating how viable such biological inspiration is as an addition to contemporary urban planning, and indirectly looking thoroughly at the modes of structural integrity, thermal performance, and resource utilization that could be examined for specific concepts and principles that need to be included in the adaptation of such new forms into urban structures. Furthermore, this feasibility analysis would make invaluable contributions to guiding future design.

Thus, an identification of strengths and weaknesses that the proposed models exhibit would invite prescriptive recommendations to promote sustainability and resilience in the cityscape (Zeng et al, 2022). These should prove priceless to architects and urban planners who are trying new and feasible ecologically. Finally, a thorough feasibility study will not only contribute to the better understanding of the proposed design but will also add to the discourse on sustainable urban development at a larger plane.

5. Results and discussion

Our investigation into honeycomb structures revealed that their hexagonal design significantly contributes to minimize material waste while maximizing exposed surface area maximizes exposed surface area. This geometric configuration, characterized by the inherent efficiency of hexagon, offers exceptional structural integrity while requiring significantly less material than other standard structures.

These characteristics are particularly relevant in architectural application, notably in hot climates, where maximizing volume and reducing exposed surface area are important. Indeed, the hexagonal structure of honeycombs promotes greater thermal efficiency by minimising direct heat absorption while optimising the exploitation of volume. According to the studies, the exact geometric configurations, the selection of materials and the and honeycomb scale have a significant impact on the physical characteristics of the structures.

Based on their research, Zhang et al (2015) demonstrated that changes in these parameters can cause significant fluctuations in mechanical performance, such as resistance and energy absorption performance. Advances in honeycomb design knowledge are helping to optimize the energy performance of buildings and facilitate their incorporation into strong, lightweight construction systems capable of withstanding harsh climatic conditions while minimizing their environmental impact.

Moreover, the fascinating similarities between wasps and human building methods were brought to light by the study of wasp nests. Wasps employ their resources creatively by creating a paper-like substance from chewing wood fibers combined with saliva to build their homes. In addition to using locally available materials, this construction technique is an excellent example of resource management, which can significantly influence our architectural approaches.

The architecture of wasp nests, characterized by their layered structure and complex ventilation systems, showcases lessons on maximizing interior space while ensuring durability and resistance to environmental challenges. Morphological similarities between wasps and bees suggest that both insects have evolved good house-building techniques serving different ecological functions. The findings suggest that such designs in incorporation within buildings will enhance thermal and acoustic performance, giving designers a completely new angle towards developing environments that are functional and bring good responsiveness to the needs of the inhabitant.

Furthermore, the study of the habitats of termites provides insight into their sophisticated passive ventilation systems, which ensure that the internal temperature is stable irrespective of external variations. The termites build large mounds within which complex tunnel systems permeate for air circulation that effectively regulates the humidity and temperature. The study showed how such natural ventilation processes might suggest innovative designs for modern urban architecture-marvelous in hot, dry conditions requiring energy-efficient systems for cooling. A hierarchical social structure of termites directs toward a potential collaborative, community-based approach to designing buildings. As the termite collective constructs its nest, human architecture may benefit from devising collaborative techniques that would readily utilize the knowledge and skills of local communities in constructing sustainable buildings.

6. Conclusions

As a form of innovation, biomimicry involves imitating natural processes to develop new, researched designs or improve existing ones without compromising the environment. This approach has become one of the most promising paths to discoveries that promote sustainability. Releasing a whole world of fascinating forms and structures, covering an endless diversity of strategies and mechanisms of adaptation that living beings evolved over millions of years. The fact is that there is an infinite variety of techniques through which each species has carved out a place for itself in which it has evolved in harmony with its environment, offering invaluable insights for today's challenges.

In this study, an innovative approach was developed to mimic the adaptation strategies, formal features and materials used in biological patterns such as honeycombs, wasps' nests and termite mounds. Natural structures perfectly adapted to their environments offer valuable lessons for urban design, particularly in hot climates.

The results indicate a strong reason for considering the aspects and principles of animal architecture strategies into the processes of architecture and urban planning. Exploring their complexity, which reflects a combination of optimized forms, sophisticated adaptive strategies and ingenious materials management, provides a high potential for energy efficiency, rational resource management and multi-functionality and functionalities in human-made environments. Imitating these models not only improves the resilience and thermal comfort of urban forms, but also ensures better adaptation to the climatic constraints of hot environments, based on natural and sustainable solutions.

This analytical study highlights the importance of going back to nature and harnessing the genius of designs produced by living organisms to improve the creation of sustainable urban forms. The hexagonal geometry of honeycombs, in particular, demonstrates a unique optimization of structures and resources, providing concrete inspiration for the design of more efficient building materials and forms. Similarly, the ingenuity of wasps, which use locally sourced materials to build their nests, could significantly reduce the resource requirements and environmental impact, by promoting sustainable construction practices. In addition, the sophisticated passive ventilation systems of termite mounds, which exploit temperature and pressure gradients through their construction design, provide exemplary solutions for natural climate control. These principles are particularly relevant to meeting the growing demand for energy in cities, especially in hot and arid regions.

To design tomorrow's cities, it is essential to integrate these strategic solutions into conceptual frameworks, by adopting biomimetic approaches, future urban spaces could become more resilient, more adaptive and in perfect harmony with natural ecosystems. Restoring the link between built environments and nature. By drawing inspiration from biological world, it will be more possible to chart innovative paths towards ecologically balanced cities that promote both resilience and prosperity in natural systems.

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