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Bio-logic, a review on the biomimetic application in architectural and structural design

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ABSTRACT

Contemporary interdisciplinary design requires architects' knowledge and cooperation with such fields as construction, material engineering, fabrication methods, and knowledge in optimisation of the design process, production, and minimisation of used materials and energy. Following the example of other disciplines, contemporary architecture seeks inspiration from Nature on various levels. The development of modern tools and materials opens unprecedented opportunities for designers to shape free forms with precision, following sustainable development guidelines. The article presents the influence of biomimicry inspiration on shaping spatial structures of 20th and 21st-century architecture. The primary conclusion of the review indicates the need for further implementing bio-logic strategies into interdisciplinary, holistic building design.

1. Introduction

In the 21st century, biology is the best developing branch of science, which supports the development of other disciplines like physics in the last century. Evolving over millions of years, Nature has developed an infinite variety of materials, structures and systems. Understanding the principles that govern them allows technological development through bio-inspiration or biomimicry. This has contributed to a shift in design in the architectural environment and is observed in numerous inspirations of living organisms and biotechnical trends. Developing issues of interdisciplinarity in architecture, already in the last century, began to draw patterns from Nature [1]. A distinction must be made between the earlier references to Nature, found in Arabian ornamentation or shapes dictated by architectural orders and styles, and the contemporary inspiration by the logic of material used. This inspiration can be used on many levels simultaneously, from shape-ornament, through the search for an effective structural shape, to building system solutions. In interdisciplinary architectural and structural design, the search for structurally optimal conditions and materials is particularly needed. UNESCO's Engineering Report highlights the need for holistic thinking in Sustainable development, based on biomimetics, which "*links engineering and technology with natural life structures and systems*", which cannot be achieved without "*the development of computer science and technology and new materials*" [2]. Research into the use of biomimetic patterns has noted that optimisation of structures must be carried out in parallel with material optimisation [3], improvement of their performance, and the search for new conglomerates [4]. Still, the most significant barrier is the simultaneous use in structures of materials of homogeneous form, formed into complex systems such as, for example, the structure of the magpie skull bone, the shell of the beetle wing, or the bone of the cuttlefish [5]. This review illustrates the fundamentals for recognising specific examples of biomimetics, their current use. The paper provides a possible perspective on the challenges of biological and bioinspired structural behaviour and materials and their application in contemporary and future designs (see Fig. 1).

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1.1. Contemporary interdisciplinary design

In contemporary Architectural Design and Architectural Engineering, designs of organic forms prevail; however, this is dictated not so much by the desire to achieve an affinity with Nature but by

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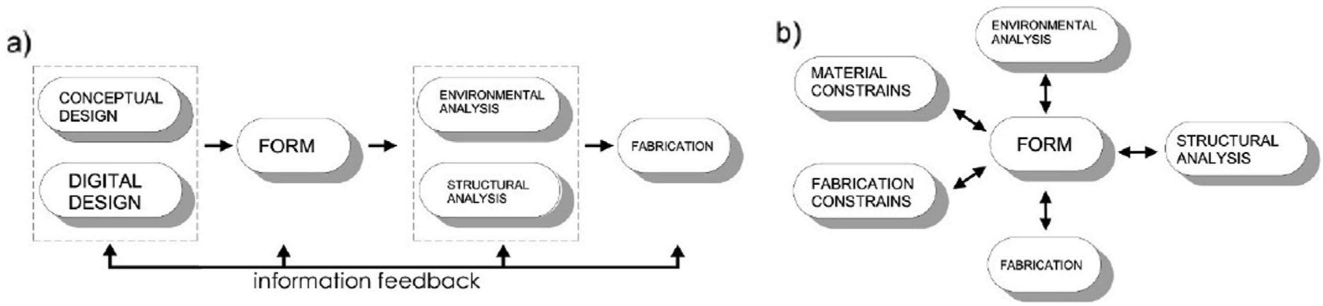


Fig. 1. a) current designing process, b) material-based design process [48].

integrating form with the supporting structure. Today's construction sector is responsible for the effective use of natural resources, which minimises material consumption. Interdisciplinary research leads architects to look less at the aesthetics of the "sculptural object" and more at the rational use of repetitive elements. Designing according to the logic of Nature can be seen in definitions such as biomimicry-material science, biomimetics or bionics. All these definitions differ slightly etymologically, but today they are used as synonyms by many researchers, as in this article. The structures of organisms found in Nature are very different from the structures built by humans. However, the purpose of implementing bionic shapes in architecture is not the great complexity or the use of many advanced and expensive energy-consuming materials that make these solutions far from being ecological - close to Nature and the guidelines of sustainable development.

The increased interest in bionic design in the 21st century is mainly due to computer capabilities. Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) tools aided the speed of innovation and digital fabrication in the 20th century. However, it was not until computer-aided design, introducing morphogenic and evolutionary algorithms derived from Nature, that significantly changed the way of designing [6]. Previously impossible curvilinear, complex geometries are no longer a barrier to innovation and fabrication [7,8] thanks to the shift from form designing to form finding [9] and computer-aided design and the development of modern structural computing.

Algorithm-based models support form and structure development by differentia growth according to given parameters, without human interactions. Computer-aided design allowed the transcription of the design into a digital record and the ability to process the input and create new databases based on boundary conditions. The designer asks research questions, provides context and resource constraints of material, time or budget. The implementation of digital technologies allows for an interdisciplinary exchange of information that supports the development of research into optimising architecture as a project and the process of creating and operating a building.

Therefore, the use of bionics is coupled with the possibility of using modern computer programs. The apparent differences in structural design and those produced by Nature are evident in the degree of complexity of living organisms. Significant differences in living organisms and man-made structures indicate the need for a deeper understanding of the systems occurring in Nature. Minimising the material used and the energy required for its construction are the main aspects necessary to enter the generative design, which is also factors of sustainable development [10]. The philosophy of using biomimicry in the building sector stems from the need to design according to sustainable development guidelines. Nature can be an inspiration to reduce natural resources and the carbon footprint [11,12]. The paper attempts to address the issue of evolving technologies' influence on structural designing and how designers perceive and relate to biomimetic inspirations at an early stage of interdisciplinary architectural designs. The paper provides a possible perspective on the challenges of the biological and bio-inspired structural behaviour and materials and their applications in contemporary and future design.

2. Literature review. Bionic forms as an inspiration to architectural designing

2.1. Historical background of biomimicry

Architectural inspiration from Nature has been evident since the beginning of human construction. Like the modern hanging roofs of today, tents are an example of man's technical structures [13]. References to acanthus or lotus leaves, visible in the ancient order, became a model of harmony and proportion identified with the concept of beauty [14]. According to Aristotle, Nature is the first source of all human creations, including the artistic aspects of designing [15]. Biodiversity prompts us to search for optimal solutions in architecture and construction. The most famous researcher who sought to use patterns found in Nature was Leonardo da Vinci, who based his design of flying machines on bird observation. In modern times it can be seen that this search was too close to repeating shape rather than *functioning principles* [16]. Actual examples of the following inspiration from animate Nature include Leonardo da Vinci's the flying machine (1452–1519) [17] and the invention of the Wright brothers, thanks to which in 1903 man took to the air for the first time [14,18].

The beginning of research into the use of bionic patterns by humans can be seen in zoologist D'Arcy Thomson, who in a book published in 1917 describes the phenomenon of the formation of the shapes of living organisms, describing mathematically and physically the parameters affecting their development [19].

The concept of being inspired by Nature's designs is found in many different fields under names such as "*Bio-life*", "*mimesis-to imitate*", "*Biomimetic*", "*Biomimesis*", "*Biognosis*", "*nature and technology*", "*biology and innovation*" or "*Bionic*". Pushing research towards developing more technologically advanced ways of optimally producing human creations through "*Learning from nature*" [20]. The term Biomimetic was first used in 1957 by Otto Schmitt, describing it as "*the transfer of ideas and analogues from biology to technology*" [21], and Bionic in 1960 by Jack E. Steele of NASA, mainly about material science. In 1997, Janine M. Benyus published her book Biomimicry, in which she described the phenomenon as: "*conscientious emulation on nature genius*" [22]. Benyus emphasises that biomimicry plays the leading role in technological development, copying natural material properties and understanding algorithmic design behaviour and ecosystem levels. At the same time, Gruber defines biomimicry as "*delivering identi-*

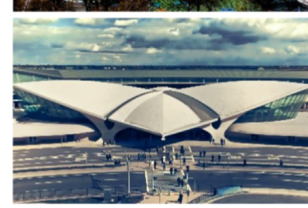
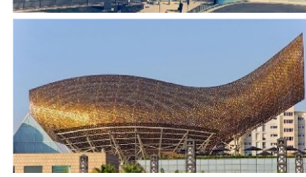
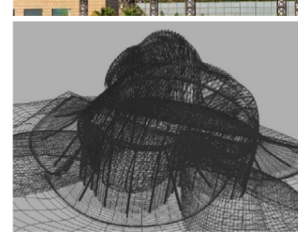
fication of new and innovative fields together with a method of transferring ideas from nature's phenomena to architecture" [23].

The search for bionic inspiration in structural logic is mainly evident in the 20th century searching for architects and constructors. The shift in design from purely aesthetic sculptural design, which allows free forms to be achieved without any attempt at material optimisation, to the use of algorithms to shape bionic structures, has become a ground field of the search for bio-logic. The table shows how the inspiration of patterns found in Nature changed in the 20th century (Table 1).

Contemporary trends in interdisciplinary design are characterised by a search for inspiration in the characteristics of materials found in Nature and the structural logic achieved by combining lightweight and strength.

Biomimicry has contributed to a shift in design, not only following free aesthetic forms, but above all, minimising natural resources and carbon footprint, and thus sustainable architecture, meeting the "shift from an industrial age to the ecological age of humankind" [4]. The early inspiration in biomimetic forms was visible in new architectural trends such as zoomorphism (the structure looks like the animal form) and biomorphism (embracing natural patterns in architectural form), mimicking the shapes found in Nature on a geometry level. Examples of Biomimicry-compliant design, shown in Table 1, indicate the trend of shifting

Table 1
Examples of the use of bionic inspiration in the 20th century.

Period/date	Representations	Inspiration description	Example Building	Photo
Art Nouveau 1890–1910	Hector Guimard Victor Horta Antoni Gaudi	Sculptural use of aesthetics and bionic ornamentation in architecture	1911-Hector Guimard, door and portals ornaments	
Modernism	Frank L. Wright	Embedding the building in Nature, organic architecture [24,24]	1964-Fallingwater house	
Modernism	Frei Otto Buckminster Fuller Heinz Isler	Use of shell structures, the introduction of the concept of form-finding on physical models, membranes and rod structures	1972- Frei Otto, Munich Olimpic Stadium	
Modernism	Eero Saarinen Jorn Utzon Niemeyer	The use of form-finding and free surfaces in reinforced concrete structures	1962- Eero Saarinen, JFK Airport	
Deconstruc-tivism	Frank Gehry	Advance digital design and fabrication tools, zoomorphism	1992-Golden Fish	
1990	Greg Lynn	Morphogenetic, incorporating biological growth and mutation based on animation software	1990-The visualisation of Embryologic Housing, from IT Revolution in Architecture	
1997	Santiago Calatrava	As the architect and structural engineer, Calatrava created his unique style based on recreating the natural structures: Biomorfizm	1997- The Quadracci Pavilion, Milwaukee Art Museum	

from pattern mimicking to the logic of Nature in shaping load-bearing structures. They become the vestibule of research works that herald a new design era- emerging computational technologies.

2.2. Modern use of biomimicry

The development of research into the use of biomimicry in architecture represents new perspectives in the way we design, with its characteristics enabling the production of sustainable architecture across the board (cradle-to-grave or even cradle-to-cradle). The innovative use of computer models has enabled contemporary architects and researchers to design independently and achieve specific digital models optimisations. In contrast, modern materials engineering and advanced digital fabrication enable more efficient and rational execution with unprecedented precision [25]. The biomimetic approach changes the perception of design, detaching separate design elements like form, function structure and material selection. Copying Nature's evolutionary models, the interplay of geometric principles and biological knowledge allows these elements to permeate, co-solidify and connect [26].

A significant increase in the use of biomimetic solutions and structures has been seen in recent years, particularly in numerous research-based optimisation analyses on small pavilion objects. In 2005 and 2008, it was estimated to be around USD 1.5 trillion, while in 2025, it has risen to USD 1 trillion, creating over 1.6 million new jobs in the US alone [11]. According to the World Economic Forum, improving efficiency and global productivity in the Architecture, Engineering and Construction (AEC sector by 1% could save as much as $100 trillion a year [27,28]. The unique manufacturing scale affects the difficulty of adapting new manufacturing technologies available in other industries [29], mainly because of insufficiently skilled professionals [30].

The search for optimum structures in the first industrial revolution was based mainly on the research for overcoming hitherto unachievable surfaces (the palace of machines) and the large-scale development of steel structures in the industry. The possibilities of fast erection of buildings in skeletal systems forced designers to optimise the known construction materials: concrete, steel, reinforced concrete, wood and diaphragm materials.

The second industrial revolution, triggered by the rapid development of science and technology, introduced further industrialisation of production, introducing unification of construction solutions. The scientific and technical process resulted from the computerisation of work, improving science and production technology. The current progress of digitalisation can also be seen in how building elements are designed and manufactured. The term "*tectonics*", which emerged in the mid-nineteenth century, fits into the mode of contemporary interdisciplinary architectural optimisation, as "*not only indicating structural and material integrity but also the poetics of construction*" [31]. Access to advanced computer programs based on evolutionary algorithms and key to evolving digital fabrication methods allows for achieving individualised construction solutions that result in visible savings in production time, natural resources, and waste minimisation.

The organic shapes found in Nature are beautiful and inspire the search for efficiency. As the biologist points out: "*Materials are expensive, and shape is cheap*" [4]. Living organisms are the most economical creations, using the minimum amount of material available in the environment and the physical characteristics of that material in shaping a corresponding final form. In the search for efficiency in shaping load-bearing structures, modern tools open up the discussion of morphogenesis and evolutionary design [32]. Collaboration early in the design phase allows deeper analysis and more accurate use of patterns found in Nature [33]. Topological optimisation allows for interdisciplinary research, already in the initial design phase, using a generation-to-application approach [34].

The search for inspiration in living structures is carried out, among others, in the research of the new structuralism, which "*turn away from formalism and towards a material practice open to ecological potential*" [33]. Biomimetics does not mimic Nature by using the same materials or functions but instead captures principles that can be used to optimise technological aspects of design [16]. Topological optimisation, form-finding, morphogenesis or intelligent evolutionary algorithms have become the main development directions.

Increasingly, research aimed at finding tools for precision manufacturing, minimising the generation of carbon footprint, cost (cost-effective), and more optimal (efficient) forms focus on biomimetic architecture as means to achieve the most optimal shapes. Contemporary computation design opens up new possibilities and discussions on morphogenetic and evolutionary approaches [10,31]. Biologically inspired morphogenesis differs from the traditional architectural design process. In biomimetic algorithmic design, form-finding is led by a dynamic process concerning product materialisation in time [35]. As "*Morphogenesis is the creation of forms that evolve in space and over time*" [36]. Computational design, based on parametric and generative algorithmic scripting, together with the possibility of mass production of extraordinary quality, allows the exploration of geometry in holistic terms. In architecture, morphogenesis (also described as "*digital morphogenesis*") is understood as the use of generative tools such as emergence, self-organisation and form-finding, to obtain the form and its further transformations [37,38]. Understanding the morphological diversity used in the computational design process is possible by understanding the totality of environmental conditions affecting the emergence of natural forms.

2.3. Development of biomimicry research

The last 30 years have shown an increased interest in emerging biomimetic studies for civil engineering. Among structural objects being researched using algorithmic optimisations are small scale buildings such as foot bridges [39], towers, and pavilions [40]. Especially pavilions became the "vehicle for design-build projects" [41] in terms of finding the parametric designing and digital fabrication methods for bionic inspirations [42]. The search for biomimetic inspiration can be seen on three primary levels: [4,43]:

- Geometrical pattern level

This search contributed to using Delaunay triangulation or Voronoi diagram or Laguerre tesselation in architecture, derivatives of dragonfly wing patterns, giraffe skin colour patterns, or Turing's pattern, which can describe zebra or gecko skin colour patterns. The search for 3D prints can be seen, for example, in the use of foam cells or birds nests, on the scale of extensive sports facilities.

- Behavioural level

Depending on the specific environmental conditions, the load-bearing structures of living organisms have developed many models that are now an inspiration for designers. Designers find analogies to arboreal forms [44] are used, exoskeletons of underwater organisms or the distribution of material, as in a system of a bone or the bamboo [45].

- Ecosystem level

Research conducted on the way ecosystems functions in Nature and local ways of organising resource flows. Research in structural sustainability reached beyond the structural systems and focused on building performance, such as the inspiration of natural ventilation, wind energy, or water collection [46].

Each level of biomimetic inspiration requires different in-depth studies and a growing need for interdisciplinary research. Innovator designers look up to biomimicry to achieve efficient and effective products. Natural systems and their logic-based evolution hold the knowledge to survive and optimise energy, material, and labour. Presented architectural examples highlight the differences in three levels of biomimetic inspirations (Table 2).

2.4. Development of design support tools

The search for freeform in contemporary architecture is becoming a two-pronged task, combining the search for aesthetic expression and structural optimisation to select sustainable geometry in each project [47].

Generative and parametric design supports the development of biomimetic approaches in architecture, with the use of algorithmic patterns based on geometric relationships of forms found in Nature. Enabling computer simulations of infinite iterations and remodulating the algorithm allows architects to create algorithms that shape optimal structures in multivariate analyses without interfering with the final form. The ability to carry out such investigations at the initial design stage allows for minimisation of wear and tear and appropriate selection of materials, adjustment of structure dimensions and maintenance of architectural aesthetics (see Table 3).

Programs such as 3ds Max, Rhinoceros, Blender, Cinema 4D and similar, which enable to animate the transformation of an object in time-frame mode, provide the possibility to shape free geometries in architectural design. In parallel with graphics programs, BIM (Building Information Modelling) tools are developing to enable inter-disciplinary technical innovation, such as Revit, ArchiCAD and Vectorworks. The search for an interdisciplinary design that allows for interference, not only in the algorithm that shapes the form architecturally but also in the form-finding that enables the shape to be optimised structurally in real-time, is possible in Grasshopper, a plug-in for the already mentioned Rhinoceros.

Biomimicry in contemporary design is changing the way we design. The interdependence of boundary conditions, the interdisciplinary approach to the processes of shaping form requires a holistic understanding of the design processes, depending on the chosen materials, calculation methods, environmental guidelines

Table 2
Examples of the use of bionic inspiration in the 21st century.

Date	Type of inspiration	Inspiration description	Building	Photo
2009	Pattern	Voronoi Diagram	Alibaba Headquarters, in Hangzhou, China, by HASSELL architects	
2007			Beijing National Aquatic Center	
2008		Birds Nest	Bejing Olympic Stadium, by Herzog and DeMeuron	
2003	Behaviour	Silica skeleton of sponge, as a lightweight material	30 St Mary Axe, London, by Foster and Partners	
2014		Water Spider web	ICD/ITKE Research Pavilion, by Nemesi&Partners	
2014	Ecosystems	Termite mound ventilation systems	HygroSkin	

Table 3
Non-standard materials in architectural design with the use of additive manufacturing.

year	Author	Building, location	Material Technology/algorithm	Picture
2020	Neri Oxman, Mediated Matter Group, MIT Media Lab	Silk Pavilion II, Museum of Modern Art (MoMa) in NYC.	Silk web the natural ability of silkworms to spin threads on the initially installed "structural threads."	
2017	Block research Group ETH Zurich, researchers	Institute of technology in Architecture, ETH Zurich	Sand-print Optimised through Thrust Network Analysis and Rhino VAULT, EXOne S-Max 3D sand printer	
2019	ICD ITKE	Research Pavilions, Stuttgart	Carbon and glass fibre-reinforced polymer composites The unique additive manufacturing methods concerning mechanical pretension structures [101,101]	
2019	TECLA/ WASP	Sustainable Habitats, Bolonia	Clay-based earth materials, based on surrounding materials availability, two-axis printing robot	
2020	ETH Zurich researchers. J. Flatt	Reinforced concrete column optimisation, ETH Zurich	Reinforced concrete with custom-made filament The fabrication with the use of the six-axis robotic arm of Universal Robots UR10	
2021	Joris Laarman, MX3D	Bridge, Amsterdam	3D Printed bridge with the use of stainless steel.	

or methods of execution. Architectural form in parametric and generative design becomes the result of a search and not, as before, a set of variants predestining a given historical style. In constructing scripts, algorithms, and interdependencies, the architect becomes a manager, not just a sculptor, choosing the aesthetics of bio-like structures. The following graphic, modelled by Pragya Bharati's study, shows the need to change how biologically optimised forms are designed.

3. Mechanical properties of biomimetic structures

3.1. Structural design

Biological inspirations in engineering design develop in various aspects, still challenging in the contemporary interdisciplinary environment [39]. Vincent [49] created a set of suggestions on the "Biomimetic Map" diagram between finding the solutions in biology and converting them into engineering. As a mathematical approach to best-performing solution finding, structural optimisation seeks highly efficient results in terms of material, stiffness, stress, or other related behaviour [50].

Structural design optimisation is commonly limited to a post-rationalisation of free-form architectural shapes. Focusing only on minor shape adjustments in the late-designing phase [51]. While modern possibilities of using multivariate optimisation allow already in the preliminary design phase, construct a statement, parameters for further modifications based on structural logic and generate multiple solutions to consider by the architect [52].

Numerical tools, and the availability of Finite Element Method (FEM) and Bidirectional Evolutionary Structural Optimization (BESO) optimisation methods, stimulate architects' audacity for free-form geometries researches [53]. Primarily used centrical shapes in the XXth century, such as domes or catenary models in concrete shells, cable nets of membranes mainly were used thanks to easy optimisation tools. Nowadays, thanks to the so-called "*Guggenheim effect*", the approach to complex forms emerges with structural buildings behaviour.

Digitisation of tools has allowed architects and designers to use generative tools to design the form and the supporting structure with Evolutionary Structural Optimisation [54,55] and Bi-Directional Evolutionary Structural Optimisation [6,56]. These involve the removal of redundant material during successive iterations of static calculations, making it possible to achieve smooth shapes of load-bearing forms. An example of evolutionary algorithms in architecture is the plug-in for Grasshopper: tOpos [57].

The search for optimal shapes is carried out by using, among other things, topological optimisation. Topological sensitivity changes are the most radical type of shape adjustment to selected boundary parameters than changes in individual aesthetic features, changes in geometry, or adjustment of element cross-sections. Topological optimisation can significantly impact cost-efficiency while being difficult to model mathematically [58,59]. However, structural topology is not often used in architectural scale because "mathematically formulating objectives and constrains is difficult or impossible in the design of buildings" [50]. Topological optimisation is most often accompanied by the BESO method, eliminating redundant material and adding it where needed. Although topological optimisation inspires designers to use bionic inspiration, it does not allow them to control and influence the final shape of the forms aesthetically or functionally [60,61].

3.2. New technology implementation

3.2.1. Experimental optimisation

Biomimicry has an undoubtful impact in creating double-curvature buildings, such as free-form transparent canopies, concrete shells, material membranes or masonry vaults [62]. Most of those structures cover important areas without additional supports, creating an open space concept interiors.

While form-finding is a process used mainly by architects, it also improves the mechanical properties of structures. Mechanically constrained shapes such as those used in the form-finding approach have a strong relationship between the form and the structural forces, ensuring stable static equilibrium. The most popular prestressing methods were a physical model based form-finding delivered by Frei Otto and Heinz Isler [63], based on dynamic relaxation and force-density methods [64]. Modern paradigms using numerical methods of form optimisation, such as dynamic relaxation, force density method, or particle spring systems, allow optimisation of pre-determined forms by the architect [64,65]. Prestressed structures such as the membrane of concrete shell structures demand the equilibrium state, which finds an analogy to minimising the area content, such as in the film soap analogy [66,67]. The search to minimise the use of support material based on compressive or tensile forces and minimise bending moments has made it possible to experimentally design concrete shell structures that effectively achieve thin shells at significant spans. The research search involving chain systems was quite challenging to use in FEM due to substantial displacement, only using modern computing power and iterative solvers.

The search for structurally optimal shapes using form-finding is particularly evident in the design of long-span roofs and lightweight systems.

The search for modern technologies for the production of durable and versatile materials, on the one hand, and require low energy and technical sophistication has led to traditional construction being dominated by concrete, steel and wood. These materials, combined with conventional construction, whose main objective was repetition and maximum unification, work very inefficiently, such as cantilevers with constant cross-sectional thickness. Inspired by the logic of using materials in bionic structures, the recent search to optimise the use of natural resources strives for "*elegant strategies that fulfil a variety of not only mechanical but also functional needs*" [68]. The hierarchical structure of organisms to form supporting skeletons can be seen throughout the natural world. While the search for the optimal shape is becoming possible, using computer-based tools, fabrication of load-bearing structures is still a challenge in the ACE sector [69]. The use of cellular structural materials, such as honeycomb, cancellous bone, cuttlebone inspirations, typically lightweight materials with optimal strength, load-bearing and lightweight structures [68], become the new direction in material optimisation.

Top-quality architecture has been enhanced by developing new technologies in the design of forms and materials [70,71]. Investigating the dependence on new materials and producing them is becoming a growing need in light of sustainable design requirements [72]. These are visible in interior design [70] and the search for complex structural forms carrying considerable loads. Their chemical composition dictates that the search for bio-materials that meet the increasingly stringent standards is more straightforward. The other performance, combined with their shaping characteristics, makes it possible to achieve benefits that are difficult to achieve, such as superwettability of lotus leaves [73,73], shark skin [74] or desert beetles [75], stimuli-responsiveness of hygroscopic plants [76], chameleon changing colours based on tension on its skin [77], or lightness combined with the extreme strength of cuttlebone [68]. Research is also being conducted based on biomimetic studies of the characteristics of biological materials such as *Ammophila areanaria* grasses and their commonalities with materials such as bimetal [78].

3.2.2. Fabrication design

The development of computer-aided design has significantly influenced the selection of bespoke solutions for both design and execution. The engineering-assisted design and form-finding design described above have highlighted the need for more accurate solutions at the architectural scale. A new field of research has risen in the contemporary AEC sector, and the latest digital modelling considers form, material properties and 3D printing properties [79,80].

Bio-inspired designing in a sustainable approach transforms science to "regenerate" and "enhance". Current strategies for material optimisation bring new technologies such as Additive Manufacturing, Computer Numerical Control (CNC) machines and computer-based algorithms for robotic manufacturing. Recent projects refer to robotic fabrication in architecture as craft engaging different materials [81,82]. Mass customisation (MC) as a new approach to delivering wetter tailored with competitive price production also becomes a viral aspect of architectural design. Automation design enables the shift in the fabrication and assembly process, from make-to-order to engineering-to-order products [83,84].

Technology, which is developing at the intersection of many different fields, has become the focus of modern researchers. Until now, 3d printing technologies have been used in prototyping. In the 21st century, additive methods have become an independent technology, combining the optimal material and design method [85]. Because of its poof labour productivity, the AEC sector has experienced rather a stagnation than development over the last years [86]. Additive technologies primarily identified with cloth design, medical implants or vegan meat became in 20′s the separate technology branch. Also, using additive technologies to use eatable materials in architectural design is increasingly popular and appealing [87,88]. However, numerous attempts of houses 3D printing in real-scale have been made in multiple materials, such as concrete, soil, clay [89], and structural elements in such materials as sand-print, steel [90] and, carbon fibre [91], bamboo and wood-based materials [92,93].

The close relationships with crafting and material-oriented algorithmic design and architectural technology aim to more in-depth search for effective fabrication methods. A part of material-oriented research, self-assembly material-over-form investigations explore the use of prestressed textiles and 3D printed rigid elements [94,95]. 4D printing, i.e., standard 3D with the parameter of changing aspects over time, or with materials giving the possibility of changing according to parameters, is becoming a desirable technology, allowing modifications regarding form, properties, or functionality [96,97].

The possibility of using high-precision robotic arms allows for the free handling of additive materials and cutting or multi-axis machining. This changes the way traditional materials such as concrete, steel or wood are used. Additive manufacturing allows using unique features of materials, without restrictions, e.g. of shapes, which in the mass production of the last century forced straight walls and a straight angle [98]. Nowadays, quickly developing Assemble Additive Manufacturing, which combines origami shape design and additive fabrication, allows various shapes and angles in fabrication [99]. AM allows for adjustments in material usage and greater freedom of shape, reduces the proportion of labour involved in formwork preparation, and more stringent safety protocols [100–104].

Nature not only reduces human impact on natural resources [72]. The usage of timber in the AEC sector significantly rises, a renewable resource with a negative carbon footprint and low embodied energy [105–110].

Computer-aided design, the use of algorithmic construction of genetic codes, and the simultaneous possibility of using an infinite number of existing materials and those designed for specific objects have allowed designers to return to contact with the material and the use of its unique aesthetic qualities.

4. Discussion on contemporary research

Recent research on biomimetic structural designs Biomimicry in architectural engineering focuses on adaptive morphological structures on the one hand and the accessibility to unique mass production. Post-Fordism created the need for the individual output of elements well-tailored to their specific function. The potential of contemporary Computer-Integrated Manufacturing under Industry 4.0 advances towards intelligent and adaptive technologies. A feedback type of production based on fabrication and real-time sensor adaptation creates a new set of smart production. The most significant disadvantage of those techniques is a good quality environment around the sensors. Still, it improves human-robot interaction towards enhancing the precision of the final form. Machine Learning (ML) techniques, despite the limitations, is still difficult to ignore in the construction sector, allowing us to expect that increasingly smart robots will be aware of the surrounding and the human partner in Human-Robot Collaboration [102]. The use of human-robot interaction combined with biomimetic inspirations in structures and systems, functions and mechanisms and what is currently the most crucial material space and technique for its most optimal manufacturing opens up a new world of research fields for interdisciplinary designers.

We rely on access to developed programs, the computing power of computers is increasing, but this is not the key to solving the problem of overall design from the initial phase of the project. A designer brings together knowledge of architecture and construction to understand and implement the fundamental laws of physics and design requirements and the pursuit of beauty. Good design becomes an interdependence between architectural and structural decisions.

One of the most critical factors in contemporary design is a sustainable approach and its influence on structural and aesthetic optimisation [111–114]. Rapid industrialisation has resulted in environmental pollution [115–117]. Hence the need for more biomimetic-based structural and material optimisation is crucial in AEC Sector. Learning from natural-based evolutionary algorithms might be a way of improving technologies for the environment. Principles of biomimicry in design: adaptation, material and system, evolution, emergency, form, and behaviour in terms of CAD, CAM design and architectural and structural optimisation are important sustainable methodology factors for building life cycle [118–125].

5. Conclusion

This paper discussed how the underlying geometries found in Nature could be a powerful tool for architect-engineer. Implementing the new optimisation approach, based on topology optimisation (possible to achieve thanks to new digital tools), in conjunction with new fabrication methods and research for new materials, can benefit sustainable development in architecture and construction.

Despite fruitful research and implementation of both materials and structural systems inspired by patterns from Nature (which have contributed to the significant development of Computer Aided Architectural Design), there is still a need to develop this field of science. Interdisciplinary collaboration between materials engineers, designers and the search for modern fabrication is still a challenge that needs to be addressed on the excellent use of bioinspiration in any branches of human crafts. This is particularly visible in research limitations in architectural scale objects. The most significant barrier is the search for solutions at bionic hierarchical structures in terms of the materials used and how the supporting skeleton is built and developed at the macro-scale systems. Rapid Development of modern tools and research on facilitating digital fabrication are the focus of the search to translate the fundamental understanding of biological behaviour into practical engineering application. The future scope of the study conducted by the authors consists of interdisciplinary research based on different material fabrication and improvement of biomimetic algorithms application in architectural designing at the early stage of design.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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