Digital Architectural Design Inspired by and Created with Nature

Valentina Perricone
Università degli Studi
della Campania Luigi Vanvitelli
valentina.perricone@unicampania.it
ORCID 0000-0002-1410-2695

Silvano Arcamone
Agenzia del Demanio
silvanoarcamone@gmail.com

Francesco Monti
Monti Architectural Firm
studio.monti.a@gmail.com

Abstract
Since the industrial revolution, the human world has been dominated by eco-systemically unintegrated and non-sustainable manufacturing and mass production leading to natural disasters and extinctions. However, a new perspective is now emerging: an architectural design that does not impose itself on nature but is born, inspired, and integrated with it. Over millions of years of evolution, high-performance strategies and materials have been developed in nature, providing valuable sources of inspiration. This contribution aims to provide a new vision in which the "learning from nature" approach combined with bio-based/biohybrid materials and with a coherent use of computational design and fabrication can be configured as a future direction of human design that can imitate and integrate nature through multiple dimensions. A research project is proposed: *BioArch 3.8* in which bio-inspired/bio-based design and robotic fabrication are used to realize adaptive shelters for emergency contexts.

Keywords
Bioinspiration
Architecture
Bio-based materials
Living building materials
Digital fabrication

The Collapse of Anthropocentric Architecture and the Emergence of a New Bio-Based Design

The industrial revolution marked the beginning of anthropocentric machine-based manufacturing and mass production leading to natural disasters, loss of biodiversity, and habitat degradation. Human constructions, systems, and processes emerged as extraneous, eco-systemically unintegrated and non-sustainable entities created solely to satisfy human needs, comprising a major portion of economic production, energy consumption, and carbon emission. This led to an unprecedented crisis and the need to design a new human world with a profound respect for the environment, resources, and life. One of the best practices currently re-emerging is the "learning from Nature" approach (also known as biomimetics or biomimicry) that combines the biological understanding of natural structures, systems, and processes with their abstraction and translation into technological applications (Benyus, 1997; Vincent, 2006). This approach is based on the assumption that during 3.8 billion years of evolution nature has provided unique and effective sustainable strategies that optimise materials and energy. Hence, nature is not seen as a source to be indiscriminately exploited, but as a measure and mentor to design human constructions in a way that is sustainable and integrated with surrounding environments (Benyus, 1997). This approach follows in the wake of a long tradition of observing nature, oriented towards the translation of natural strategies into human constructions, of which Leonardo da Vinci's work is an outstanding example. However, technological advances obtained in the field of computational imaging, simulation and digital fabrication have opened a new era and new perspectives. Biological structures and their functional strategies — responding to adaptive principles of lightness, stability, strength, flexibility, and resistance — can be mimicked and integrated into constructions that are built using robotics and advanced digital technologies, which can effectively recreate complex natural forms and structures.

Simultaneously, bio-based and biohybrid materials are rising as green alternatives to their petroleum-based counterparts, which have devastating effects on terrestrial and ocean life as well as an inherently toxic life cycle from their production to final disposal. In particular, bio-based materials consist of substances naturally or synthetically derived from living matters (Curran, 2000), whereas biohybrid or living building materials are based on microorganisms and used in construction or industrial design that display biological functional properties (Qui et al., 2021). Biobased and biohybrid materials are therefore based on inert or active natural components generating little or no waste, using small amounts of energy and producing multifunctional and adaptable systems.

For centuries, architecture has been subordinated to the form, structure, and function of buildings employing rigid and toxic materials. However, the combination of a biomimetic approach with bio-based/hybrid materials and the coherent use of computational design and fabrication is configured as the future direction of human design that can imitate and integrate nature through multiple dimensions. The efficiency of this approach lies in the countless forms of hybridism between biology and digital architecture: biolog-

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ical organisms excel in producing constructions and materials with limited resources and energy, whereas digital architecture excels in the adaptable and programmable control regarding construction generation.

Digital Biology and Architecture: Designing a Human World Inspired by and Created With Nature

"Bio is the new digital" as declared by Nicholas Negroponte and Joi Ito, respectively founder and director of the MIT Media Lab, referring to the incredible potential of biology to inspire and synthetically produce hybrid systems. Some examples include cell biosensors, "robotic" bacteria, clothes created with bacteria, and luminescent plants. Thus, biology appears to be futuristic and innovative, becoming increasingly advanced and decisive for human construction and technology. By studying living organisms, biology provides new knowledge that can be converted into the design of constructions characterized by new functionalities and performance qualities. In collective thinking, the idea of how this science can influence human design is gaining ground: Paola Antonelli, the curator of the Design and Architecture section of the Museum of Modern Art in New York, affirms that the greatest revolutions in the design sector will surely come from the joint work with biology. Nowadays, the link between biology and architectural design is more successful and increasingly consolidated. The road to innovation is further enhanced by the countless possible hybridizations that architectural design can establish with different biological sciences, such as biophysics, biochemistry, palaeontology, ethology, evolutionary biology, botany, zoology, molecular biology, morphology, and biomechanics. The relationships between biology and architectural design are numerous but they can be conceived as distinct yet complementary approaches. As stated by Neri Oxman (2015): biology operates from the bottom-up, expressing form and function through self-organisation, cell differentiation, growth, remodelling and regeneration; conversely, design practice operates from the top-down, establishing constraints that inform or guide the generation of form and construction. The effective connection is provided by a coherent use of computational design and fabrication that can connect the study of biological strategies with its translation into architectural design.

Inspired by Nature: Bioinspiration for a Functional Digital Architecture

Biology can digitally inform architectural design in the realization of multifunctional constructions based on the strategies evolved by organisms during their evolution, such as structural optimization, temperature and humidity control, shape changing, growing processes, noise reduction, self-repairing, and light control. Thanks to new high-resolution acquisition systems, biological structures can now enter the computational world in the form of 2D/3D drawings and can be investigated with advanced digital analysis and simulation techniques. In this regard, 3D models of natural structures from macro- to nanoscale can be acquired using different tools such as photogrammetry, 3D scanning, and more detailed computed tomography (du Plessis & Broeckhoven, 2019). On the other hand, there are also several digital simulation techniques, supported and informed by experimental data, which allow the study of complex biological structures from a mechanical, thermic, acoustic, optical, or energetic perspective (Perricone et al., 2020). This extensive use of digital techniques is generating new and advanced progress both in biological research, increasing knowledge of nature and organismal design, and in architectural design, leading to new constructions inspired by the functional constructional strategies identified in organisms (Speck et al., 2017). Natural structures can therefore be better and more efficiently analysed but also more easily transferred to product design for the realization of bio-inspired design artifacts. Biological models enter the digital process and connect to design, becoming archetypes or guides for product genesis. This creates a logical continuum in the transition from real (organism) to digital (3D biological archetype) and from digital (3D product model) to real (physical product) entities. The techniques of high-resolution acquisition and biological analysis together with computational design techniques and digital manufacturing are directly involved, allowing a rigorous and functional reproduction of nature's strategies. In this case, the statement "Bio is the new digital" assumes a further meaning: digitalized nature becomes the starting point for the realization of new architectural works, from which computational design can develop bio-inspired generative algorithms (Langella et al., 2020). An interesting example of this process is the *ELiSE Lightweight technology*, which automatically integrates technology transfer from organism to products and constructions in a unique automatic process, namely: screening and selection of the natural archetype, model abstraction, Finite Element Analysis (FEA), structural optimization, and final elaboration of the product (Hamm, 2015). Interesting examples in architecture are the numerous studies carried out by the synergy between the Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart, which every year investigate and experiment with new design processes to transfer biological constructional strategies into a series of demonstrative pavilions using advanced digital manufacturing techniques (ICD/ITKE Research Pavilions[1]). Researchers and students of the ICD /ITKE developed these bio-inspired pavilions exploring the potential of computational generative design methods and the use of computer-controlled production processes with particular attention to robotic manufacturing. The team works with expert biologists to identify new construction strategies which, mimicking biological processes, can be translated into lightweight and resistant architectures with a highly innovative appearance. Some examples include: coccinellid wing folding mechanism (2018-19); silk deposition of leaf miner moth larvae (2016-17); sand dollar skeleton constructional details (2015-2016/2020); water spider nest constructional principle (2014-15) Fig. 1; and lobster exoskeleton cuticle differentiation (2012).

1 https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions

diid No. 76 — 2022
Doi: 10.30682/diid7622p

Fig. 1 *ICD/ITKE Research Pavilion 2014-15*. Demonstrative pneumatic fiber-reinforced pavilion inspired by the water spider underwater nest construction and made using robotic fabrication processes. *Authors*: Institute for Computational Design and Construction (Prof. A. Menges) Institute of Building Structures and Structural Design (Prof. Dr.-Ing. J. Knippers). Source/Credits: ICD/ITKE University of Stuttgart. https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/icd-itke-research-pavilion-2014-15/

Created With Nature: Environmentally Integrated Materiality for a Sustainable Digital Architecture

Architectural design can provide multifunctional sustainable constructions using bio-based and biohybrid materials. Biological materials and living organisms together with robotic elements can perform collectively to build sustainable, self-organizing, energy-efficient, and adaptive constructions. Indeed, through growth or deposition into specific shapes or patterns, biological components can perform building functions. These can include the structural system, or the building envelope functions such as shading, thermal insulation, moisture barrier, and ventilation. Biological elements can be guided and shaped during robotic construction so that the material deposition and organismal growth are controlled through the construction of mechanical scaffolds or the manipulation of specific directional growth stimuli.

In this regard, there are several existing examples of digital constructions that rely on biobased and/or biohybrid materials. The experiments conducted by MIT Media Lab provide avant-garde paths towards a design no longer defined by the mere assembly of discrete parts but by an architectural design based on bio-based materials and an integrated genesis and growth that in ecological terms make a difference. In the field of “Material ecology”, Neri Oxman and her team have built architectural scale structures based on synthetic biology processes and natural materials that work and interact with the environment (Oxman, 2010a). An example is *Aguahoja*, a 5-meter-high structure made by robotic manufacturing and composed of biopolymers of cellulose, chitosan, and pectin, mouldable in water and degradable in nature at the end of the life cycle (Ling, 2018) Fig. 2. Another outstanding model of hybridization between robotic and biological fabrication is the *Silk Pavilion*: a domed-shaped scaffold constituted by different robotically prefabricated modules with an intricate pattern of silk threads. The scaffold pavilion was completed by silkworms that filled all the gaps in the pattern with their silk, which was guided by variations in density and light predefined by robotically-applied threads. Regarding biohybrid materials, organisms that produce materials or grow filling spaces can be used to realize or strengthen building components, integrating them into

Fig. 2
Aguahoja I. Demonstrative pavilion developed using 3D printing biomaterials, mainly cellulose, chitosan, and pectin. Shape and material composition were guided by physical properties, environmental conditions, and fabrication constraints. *Authors*: J. Duro-Royo, L. Mogas-Soldevilla, D. Lizardo, J. VanZak, Y. Tai, A. Ling, C. Bader, N. Hogan, B. Darweesh, S. Sharma, J. C. Weaver, N. Zilberman, […] and Prof. Neri Oxman. Elaboration of: https://oxman.com/projects/aguahoja

construction processes or infrastructure outcomes. In literature, these include bacterially produced cellulose, growth of mycelium, and bacterially induced cementation (Henrich et al., 2019). In particular, fungal mycelium growth has been used in several cases in load-bearing building components, furthermore providing excellent thermal insulation and carbon sequestration performance in the building envelope Fig. 3. Self-repairing properties achieved via biological organisms have also been demonstrated several times in literature, such as the use of bacterial calcium carbonate deposition (*Lysinibacillus sphaericus*) for self-healing of cracks in concrete or the shaping of rubber plant roots (*Ficus elastica)* in the Living Root Bridges (Henrich et al., 2019).

Fig. 3
Mycelium bricks. Biomaterial developed by Biohm company and used in construction, it can sequester about 16 tonnes/monthly of carbon. *Authors/Credits*: Biohm company. Elaboration of: https://www.micropia.nl/en/discover/microbiology/mycelium/ and https://www.biohm.co.uk

Bioarch 3.8: A Research Project on Digital Bio-Inspired Design to Realize Adaptive Shelters for Emergency Contexts

Inspired by natural strategies, BioArch 3.8 emerges as a future architectural design process. This manifesto-research project consists in the realization of an interactive abacus of customizable digital biobased and bioinspired shelters for emergency contexts following an original and innovative approach of synergistic collaboration

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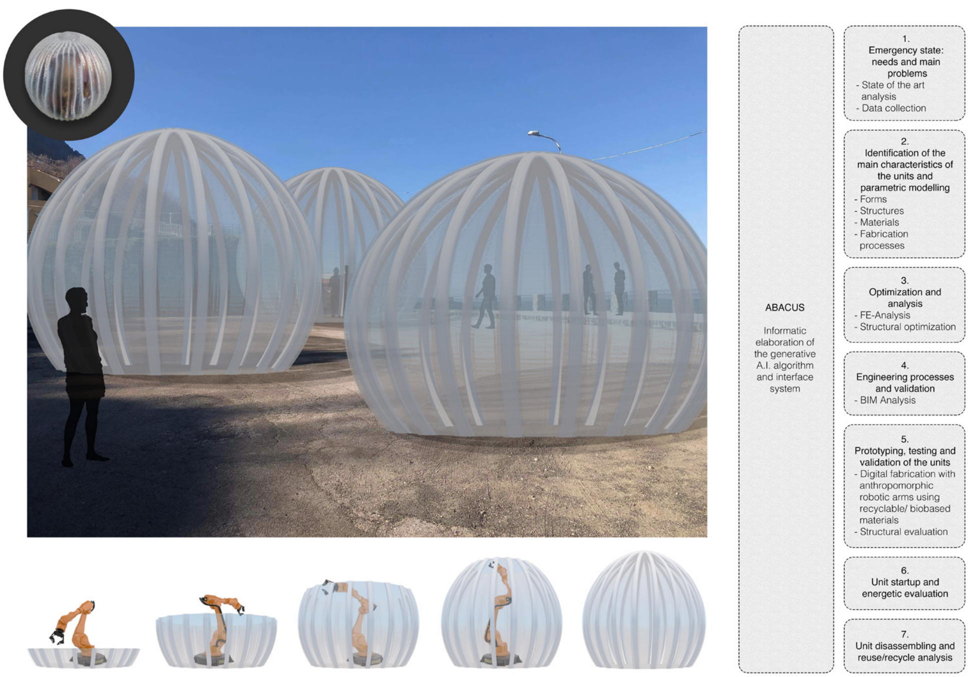
between biological, architectural, engineering, and design methodologies. Emergency contexts, such as earthquakes, floods, or pandemics, seriously strain urban systems and their infrastructures. Due to climate change and overpopulation, these phenomena are occurring at a faster rate than in the past and are expected to increase in the near future. Frequently, the impacted territories lack facilities or spaces to host logistics centers and to accommodate large numbers of evacuees. Within this framework, the architectural design requires the highest degree of adaptability and effectiveness to build structures characterized by high strength and structural efficiency, dynamic adaptation, and rapid construction processes. Hence, the combination of the biomimetic approach with bio-based materials and a coherent use of computational design and fabrication is configured as one of the best solutions in this context to rapidly realize adaptive and resistant shelters. Along this line, the BioArch 3.8 project predisposes an abacus of pre-designed adaptive parametric shelters for emergency contexts constructed using robotics and biobased materials. While robotics provide rapid fabrication, the use of bio-based materials allows the sustainable and programmable disposal and recycling of shelters when no longer in use. The shelter abacus is generated by a parametric algorithm inspired by organismal adaptive structures and mechanisms that tend to optimize the cost/benefit ratio and minimize the energy and materials used for their development and maintenance. In conjunction with digital fabrication tools, the use of parametric design offers the possibility to create shelters shaped by metric data (parameters) and individual needs (variable) implementing analytical and deductive methods of bioinspired design. In particular, the advantage is twofold: firstly, it makes it possible to optimize time and costs by using generative methods processed by artificial intelligence which are much faster than those of humans, at the same time including the structural analytic part; secondly, the shelters, materialized through artificial intelligence algorithms together with natural concepts, are customized to respond to specific needs. The customization of digital shelters aims primarily to fulfil post-catastrophe needs that are extremely variable depending on the type and duration of the event and the impact on the inhabitants. For example, when an emergency becomes persistent, the assigned structures must be durable to meet daily and social needs in an optimal way. The creation of *ad hoc* residential structures is crucial, as is the construction of collective spaces, e.g., schools, hospitals, and logistic centres. To address these needs, BioArch 3.8 provides shelters personalised for family units and types of use for a successful reception system. From a psychological perspective, it is important for people experiencing such trauma and discomfort to have well-made customized housing with comfortable architecture that can represent a safe and private place. The construction of the shelters is based on digital fabrication techniques, which are programmable systems capable of autonomously creating parametric and customized structures processed with modelling software. These include computer numerical control (CNC), additive manufacturing, and collaborative robotics. The advantage of using these technologies is both economic and time-related, since costs and personnel involved in the construction are drastically reduced as is the realization time, an important factor in the first post-event phase. Indeed, the entire structural design and development stage is delegated to the initial programming of the shelter 3D model abacus creation, immediately replicable with the use of digital fabrication. The shelter 3D models can be identified in the abacus by inserting specific variables, e.g., available space dimensions, type of use, number of residents per unit, presumed duration of the unit. This automation can be regulated *apropos* in order to safeguard the generation processes at every stage and does not require numerous operators, who could instead be assigned to other activities such as population assistance and crucial rescue actions. The described BioArch 3.8 project entails a seven-phase conception and validation process to generate the abacus and produce adaptive shelters in a short time Fig. 4. While innovative, the project is based on currently available and accessible technologies, such as parametric 3D modelling, FE-Analysis, structural optimization, BIM analysis, 3D printing, collaborative robotics, and artificial intelligence informatics systems. As a result, this process leads to shelters with adaptable forms and structures directly conceived for their functions, fulfilling specific crucial needs, and for the surrounding environment. As a future perspective, the shelters will be designed to be self-sustained by wind, water, sunlight, and biomass, becoming an integrating component of local natural systems.

Fig. 4
***BioArch 3.8*. Research project entailing a seven-phase process to generate an interactive abacus of customizable digital biobased and bioinspired shelters for emergency contexts that are realized using digital design and fabrication techniques. *Authors*: Silvano Arcamone, Valentina Perricone, Francesco Monti. Image elaborated by Silvia Verde and Francesco Monti.**



diid No. 76 — 2022
Doi: 10.30682/diid7622p

Conclusions

In the history of humankind, nature has always been a source of inspiration. In the course of history, important figures in the world of architecture, biology, and design - such as Antonio Gaudi, Frei Otto, Pierluigi Nervi, Joseph Paxton, Santiago Calatrava, Renzo Piano, Peter Pearce, Julian Vincent, Petra Gruber, Neri Oxman — have chosen to use this bioinspired design approach, which has led to original creations inspiring the future generation of human constructions. Indeed, the “learning from nature” approach combined with technological innovations pursued in the field of 3D modeling, simulation and digital fabrication has determined the creation of a new architectural design inspired by and created with nature. The progress is the result of an effective emulation and integration of capacities found in nature into artificial design and materiality. This predicts the collapse of anthropocentric architecture and a change of paradigm in the architectural design process and its resulting outcomes. The process will no longer be based on a mere assembly of discrete parts, but on a generative process in which shapes, structures and materials directly result from their functions, local available sources and forces acting upon them (Oxman, 2010b). Materiality and deposition methods will be based on heterogeneity, anisotropy, adaptability, self-repairing and multifunctionality, in which the degradability will be a function of their time and utility and biodiversity will be measured and mentored. In this perspective, architecture will pave the way for a new and fundamental step forward in human history, leading to design constructions that will supersede the negative dichotomy between nature and artifice. In this complex framework, the emergency context is configured as one of the most challenging and critical areas of future architectural application due to the short construction time and the need for maximum optimization of space and customization. The BioArch 3.8 project aims to satisfy these needs by using the most advanced strategies based on sustainable and feasible bio-inspired and bio-based technologies.

In conclusion, humans are an integral part of the evolutionary process not only as occupants of space but as space generators. In this case, human creations look to nature as a form of inspiration and guidance, and to digitalization as a new tool, ensuring the creation of a human world edging ever closer to natural laws of construction, without imposing itself on nature but being inspired by it and integrated with it.

Valentina Perricone
Naturalist and marine biologist, Ph.D. in “Environment, Design and Innovation” at the Università degli Studi della Campania Luigi Vanvitelli. She collaborated with the Smithsonian Tropical Research Institute of Panama and the University of Florida, USA. Her research topics regard functional morphology and biomimetics.

Silvano Arcamone
Architect, project manager and expert in public works and urban regeneration, initially at local entities and successively at the Agenzia del Demanio, where he initially held the role of Head of Technical Services in Emilia-Romagna and, since 2020, he has held the role of Head of Public Works of General Management.

Francesco Monti
Dynamic architect, with multiple experiences in emergency architecture. Among his projects, the work on Indian urban centers in Mumbai emerges as one of the challenging architectural activities giving support to the local urban planning studies and completing the research focused on the creation of building systems for informal settlements.

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