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Potentials of Parametric Design in Architecture: Insights from Collaborations with Morphogenic Biology and Natural Biomimicry

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Abstract

This paper is based on the premise that by drawing inspiration from various natural forms and applying parametric programs to modify their specifications and settings, innovative and unprecedented designs for architecture can be generated. This approach differs from mere cloning or imitation of biological processes, as it leverages the fundamental principles of Nature to create novel forms.

Indeed, Nature is renowned for its exceptional architectural capabilities, as exemplified by history of art, architecture and design, which have consistently drawn inspiration from the natural forms. For instance, the Art Nouveau movement featured floral motifs, while the "Tulip" chair of Saarinen exemplifies the fusion of art and design with Nature.

The formal character of this inspiration is closely tied to the aesthetic dimension of the resulting products. Indeed, throughout history, technology has harmoniously interacted with art, observing and attempting to replicate natural shapes and qualities through analytical drawings and precise procedures. This synergy has led to the development of new disciplines, which have been combined for specific purposes, often resulting in the creation of novel forms.

This paper examines parametric design and its relevance to architecture. It shows how to translate the functional principles from the natural world into the design field, thereby integrating the principles of Nature into the design process. It thus offers insights into the potentials of parametric design by means of convergence in collaborations with morphogenic biology and natural biomimicry.

Keywords: Parametric design, Morphogenic biology, Biomimicry, Architecture.

Introduction

According to Wahl (2006) and Benyus (1997), the origins of design, initially focused on the aesthetic appeals of objects and subsequently influenced industrial manufacturing, although they emerged from the craft-based traditions. Today, design has transcended its craft roots, prioritizing experience over technology and developing powerful ways for people to interact with their environments. Indeed, it has evolved into a problem-solving process that enhances the quality of life and work for people, while also incorporating environmental health considerations. However, there are questions as to whether these developments are compatible with the traditional craftsmanship of the original design understanding. It is often asked if this marks a crossroad, where some choose to leverage the old craft traditions to improve the emotional quality of the product world, while others opt for a different path, integrating design thinking into all enterprises, albeit differently from how history and mainstream practice currently implements it.

It is noteworthy that the species in Nature have managed to survive for approximately 3.8 billion years through a dynamic process of adaptation, generating diverse materials, mechanisms, systems, strategies, and morphological transformations. According to Stevens (1995), various designs and morphologies of Nature have evolved to achieve forms increasingly adapted to their environments, utilizing configurations that minimize energy consumption, suggesting that the most efficient forms are those with greater possibilities of existence. Indeed, according to Vincent (2009), designers, architects and creative professionals have used Nature as a reference to resolve human problems through imitation of Nature or more precisely following what is now known as biomimicry. Nevertheless, there exist a significant issue with regard to these practices.

The Issue

It is well known that design as a craft creates useful and aesthetically pleasing objects. Indeed, industrial designs support the production of commercial products. Therefore, in schools and universities worldwide, a significant amount of time is devoted to mastering the skills of drawing, construction, materials, manufacturing, and finishing. Simultaneously, in most educational institutions, other subjects such as social and humanities topics, current global events, or literary knowledge are largely neglected. Similarly, natural, scientific, technological, constructive, and mathematical components are also often overlooked.

These omissions are peculiar. Design serves as the interface between technology and humanity, yet both aspects are insufficiently explored. There is no profound understanding of human behavior or social connections, nor are there natural, scientific, mathematical, or constructive approaches, despite these being the foundation of all technologies. The studies often produce craftsmen who are trained by other craftsmen. The message is design, design, and more design even though without looking at what design is, and how design could be, to be well conceptualized.

As a result, the outcome is exceptional craftsmanship, which produces the numerous designed objects we use at homes, in the community, and at work. This is all well and good, but these handcrafted skills are no longer sufficient for the increasing sophistication of 21st-century technologies in the houses, businesses, education, and entertainment. As long as designers confine their work to craftsmanship, they can create certain added values but never assume a leadership role. Designers work alongside engineers and business professionals, who are responsible for this process. They assist in the decision-making process but are not decision-makers themselves. Design as a craft is a commendable profession, but one that is limited in both scope and possibilities.

At the same time, driven by profound advancements in computer science and computer technologies in the fields of sensorics, communication, and displays, the world of technology is subject to rapid change, which increasingly influences society and the environment. Natural resources are being depleted, many regions of the Earth suffer from severe, health-hazardous environmental pollution, and social unrest affects us all. Climate change is taking a global impact on our living conditions. In fact, craft-oriented education cannot adequately address these issues.

Interestingly however, cooperation between parametric design, technology, and natural biomimicry has led to significant advancements in parametric production and design methods. This synergy involves the application of simulation of natural strategies and processes, analytical and artificial computer techniques, and algorithmic logic such as the evolution or genetics inherent variation, heritage penetration, and so on. This has resulted in the development of innovative solutions and enhanced design capabilities.

For instance, the hierarchical array of emergency design in rocket engines exemplifies the application of parametric design principles. Moreover, the use of materials with the same material logic as Nature allows for the concentration of external forces on capital materials and areas requiring greater structural resistance, resulting in homogeneous materials with varying properties. Advanced biological fabrics are an example of this approach.

Furthermore, the development of manufacturing processes involves the use of additional fibers and multi-material strategies, such as VPF and SWARM strategies, to mimic the organic growth and replace the collection and release of materials. This approach enables the creation of complex structures and materials that would be difficult or impossible to achieve through traditional manufacturing methods.

Lastly, the synergy between parametric design, technology, and natural biomimicry enables the generation and sustenance of design and performance ideas, whether on the formal or performative level. This is achieved by imitating the behavior and form of unlimited creatures in Nature, resulting in an infinite number of ideas and solutions.

In this context, this paper examines the relevance of parametric design in architectural design to help architects to conceptualize new architectural forms and spaces. Its objectives are:

- To identify the conceptual and practical aspects of parametric design.
- To ascertain how parametric design has been employed by architects to conceptualize novel forms and spaces.
- To identify how to employ parametric design to conceptualize novel forms and spaces.

Theoretical Framework

Biomimicry

Biomimicry, as defined by Benyus (2012), is a new science that studies natural models to imitate biological designs or processes to solve human problems (Vincent,2006; Forbes,2006). At the same time, in recent decades, there has been an accelerated advancement of digital technologies involved in the design processes of designers, architects, and other creative professionals. For example, CAD software has evolved into generative, parametric, and associative software, and digital fabrication technologies (DFD) have expanded their possibilities and technical advantages. The development of nano-materials, also known as smart materials, has enabled the processing of large volumes of data (Big Data), and has led to the production of collaborative robotics. This set of technologies forms digital platforms with unprecedented creative possibilities, characterized by interdisciplinarity, multi-disciplinarity, and trans-disciplinarity practices, changing the paradigms in the design process, evaluation, and prototyping. In fact, Oxman (2006) points out that digital technologies are starting to affect the way we represent, communicate, and materialize design ideas, impacting the entire design, culture and related processes.

Interestingly, as Sassa and Oxman (2006) show, the great potential and significance of digital fabrication technologies for design are now being recognized. Students and professionals are integrating their use, shifting from technical aspects of the machine itself to creative possibilities in the design process.

In this scenario, opportunities and possibilities never before seen are opening up for transferring natural characteristics to the human-artificial environment. In this, biological surfaces and textures play a fundamental role in the survival of species and their adaptive process. According to Wagensberg (2013), these membranes constitute the surface frontier that separates the interior from the exterior of organisms. Moreover, biological surfaces and textures perform various functions in organisms: they delimit and give structure to the body of the individual, serve as barriers that isolate from external conditions of humidity, temperature changes, facilitate thermal regulation, protect from predator attacks and blows, and often serve as a medium for perceiving the exterior and communication (Bar-Cohen, 2006; Lorenz,1991; Neri,2008).

Nevertheless, there is a gap in knowledge related to methodology or procedure for transferring the morphological characteristics of natural surfaces and textures to human-designed products, systems, or spaces through the integration of parametric CAD software and DFD. In the light of this background, a research project titled "Repertorio de superficies y texturas bioinspiradas" has been proposed, which involves morphological experiments with DFD technologies. This project aims to develop an online repository of digital and parametrized textures in open-source format, to be used by designers, architects, and other creative professionals to improve and enhance various aspects of project developments such as functionality, usability, and sensoriality, as well as aesthetic and communicative attributes. Hence, there are new beginnings in this process, which must be well explored together with other design practices such as parametric design.

Parametric Design

As known, parametric design relies heavily on algorithms, which were first formalized by the Arab mathematician Al-Khwarizmi. He developed symbols and mathematical operations that addressed the everyday commercial challenges faced by the merchants at that time, by representing product values using numerical symbols instead of counting pebbles (Oxman, 2014;2021). In fact, these symbols such as 1.2.3.4... etc., which we currently employ, are considered the foundation of modern arithmetic.

Al-Khwarizmi's work also marked the beginning of using natural phenomena as inspiration for mathematical operations. This concept can be extended by drawing inspiration from the geometric shapes found in Nature, such as the Golden Ratio, which is often observed in natural forms. It is now well-known that this ratio, represented by the numerical proportion of 1:1.618, can be converted into mathematical operations. According to Oxman (2015), and Media Lab (2013), this inspiration for parametric design operates at three levels.

Form or Structure

- The geometric patterns and shapes found in Nature, such as the grammar of form, which can be used to inform the formulation of parametric designs. For instance, dynamic form grammar can be inspired by the movement of sea waves, as depicted in the Fig. 1-a.

- **Behavior:** Inspiration can be drawn from the movement of natural phenomena, such as the wind between buildings (Figure 1-b), the coordinated movement of ants, or the planetary motion within the solar system. This can be used to create a dynamic flow parameters.

- **Behavior on Generation:** This level involves the application of generative algorithms or parametric optimization techniques. These methods can be inspired by the behavior of natural systems, such as the movement of planets around the sun, and can be used to create novel and complex designs

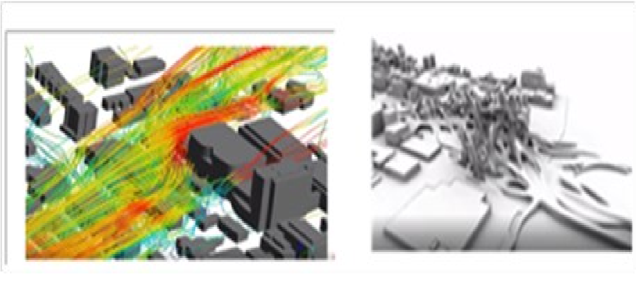

Fig. 1: Inspiring shapes from people’s movement and using parameters for Dynamic Flow
1-a: left & 1-b Right

Fig. 2: Inspiration from the movement of sea waves in creating architectural shapes
Source: Wikipedia

The Theoretical Framework

It is noted that traditional craft-based design did not require formal evidence, as the proof of the efforts was evident. Designs were guided by the refined intuition of the designer and could be appreciated by any critical observer. This approach worked well as long as design focused on relatively simple tasks such as wrist-watches, furniture, and household appliances. However, with the introduction of computers, communication networks, powerful sensors, and displays, even ordinary everyday objects became significantly more complex. People became confused and frustrated, and a new type of design was required to meet these demands. Intuition alone was no longer sufficient; design had to be oriented towards the technical knowledge of these technologies and consider the limitations and possibilities of ordinary people who had to master the use of the new devices. It has now become the designer's task to make devices understandable and usable precisely because the underlying operation is invisible to people.

In fact, the traditional design education has proved inadequate in this regard. Solutions have come from developments outside the field of design. The result, variously referred to as Interaction Design, User Experience Design, or Human-Computer-Interactions have evolved from approaches in the disciplines of Psychology, Human Factors, Ergonomics, and Computer Science. The Xerox Palo Alto Research Center and several universities worldwide have played an important role in this development.

The authors of this research paper themselves have entered the design field through psychology and computer science. Many of the concepts that serve as the foundation today have developed between the 1940s and 1970s. As computers have become accessible to a larger research community and shortly thereafter to the general public in the 1980s, this development has accelerated.

Service Design is another area that represents the changes in design practice. Services are not physical objects but rather interactions between people and systems. Service design is about psychology and business, not materials, forms, and shapes. Designing in this context requires different knowledge and formal methods for evaluation. In fact, so-called Service Design initially emerged from Marketing and Management, and not from Design, where it has been later incorporated.

Review of Literature

Many have examined these issues comprehensively. For example, Janine Benyus' book, Biomimicry: Innovation Inspired by Nature (1997), dedicates an entire page to the etymology of the term biomimicry and its foundational texts, which emphasize Nature as a model and guide (MIT Media Lab,2015; M-Hox, 2014). However, it is essential to consider the finer details of Benyus' definition, which can be simplified as "an approach and innovation that seeks sustainable solutions to human challenges by emulating Nature's patterns and strategies, tested over thousands of years" (Biomimicry Institute, 2019).

Simultaneously, Wahl (2006) provides a concise definition of biomimicry as a discipline that integrates Nature's processes and patterns into design, aiming to develop more sustainable solutions for infrastructure, products, or processes. This approach simulates Nature as a new science, consciously replicating its patterns and methods to solve human problems

(Benyus, 1997). Thus, as Bonsiepe (1992) and Hensel (2004) point out, biomimicry is based on a holistic, transdisciplinary, and interdisciplinary approach, aiming to create informed design.

The discipline of biomimicry, as described by Benyus, although formalized in modern times, has its roots in centuries of human practice and is now being validated through rigorous scientific methods. History of biomimicry is marked by numerous examples of its application, starting from Leonardo da Vinci's studies on flying machines in the 16th century (Fig. 3), which were inspired by the wings of birds and bats. This conceptually predates the term biomimicry, which was first described in the 1960s (Vincent, 2009; Vincent, Bogatyreva, and Bogatyrev, 2006; Harman, 2014; Hensel, 2004).

Similarly, the Crystal Palace, designed by Joseph Paxton for the 1851 Exhibition in London (Fig. 4), is an iconic example of iron architecture, featuring large glass areas and open interiors made possible by recent advancements in metal production. Indeed, the simulation in whale fins served as inspiration for Whale Power Corporation to create a more efficient wind turbine capable of running at low wind speeds. These show that there are ample examples of biomimicry producing exceptionally useful designed machines (Figs. 5 & 6).

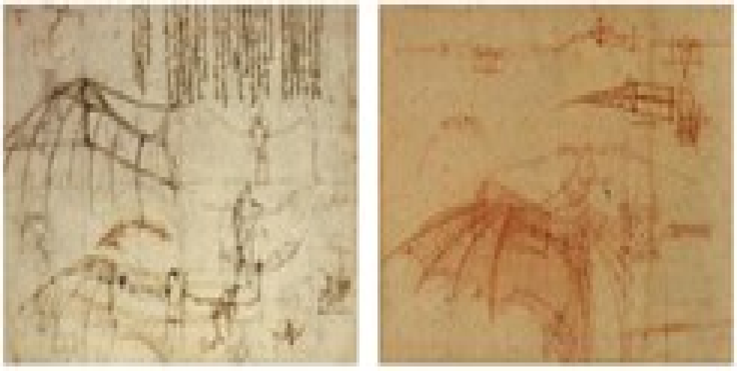

Fig. 3: Sketches with studies for flying machines. Leonardo da Vinci (Ornithopter, n.d.)

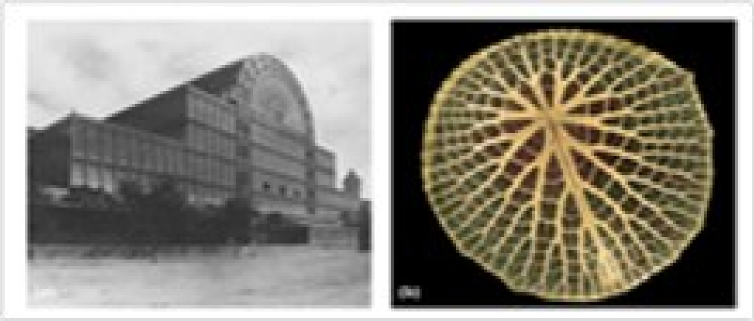

Fig. 4: (a) The Crystal Palace created by Joseph Paxton for the Great World Cup Exhibition in London in 1851 (Crystal Palace, s.d.).
(b) An X-ray image of a water lily (Victoria Amazonia) plate showing its robust structure. Source:Weston

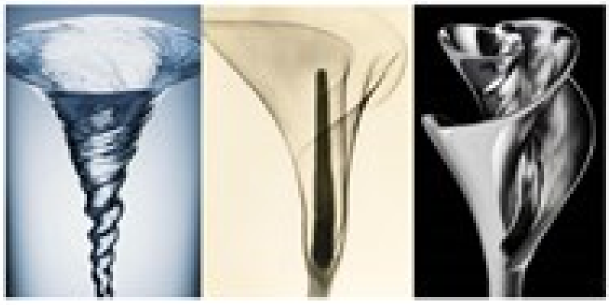

Fig. 5: a PAX. Fan art developed by Jay Harman and images illustrating the events in the natural environment that inspired its creation.

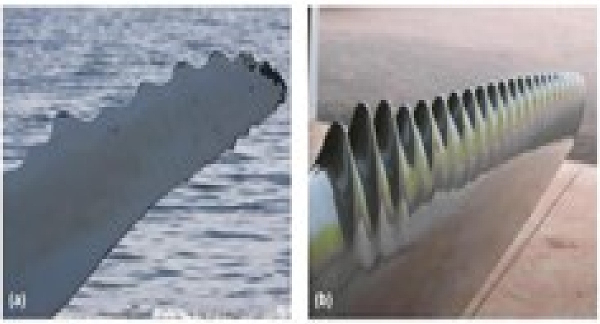

Fig. 6: Whale power wind turbine developed by Whale Power Corporation. (a) Details of the whale's side fin, (b) Details of one of the blades of the Whale Power wind turbine
Source: asknature.org

The term "biomimicry" was first used by the bio-physicist Otto Schmidt in 1969, in an article presented at the Boston Biophysics Conference (Vincent, Bogatyreva, & Bogatyrev, 2006). McKeag's study confirmed the emergence of other important innovations inspired by Nature, such as the application of a vinyl film with small grooves inspired by shark skin to a racing boat in 1987, which reduced friction by up to 8% (McKeag, 2013b; Hensel, Menges & Weinstock,2004).

Thus the concept of biomimicry has a rich history, with various sources of inspiration. For instance, the structural characteristics of water lilies, which distribute load throughout their surface, inspired Joseph Paxton's architectural designs (Forbes, 2006; Menges, & Weinstock, 2004). Similarly, the Wright Brothers' first flight in 1903 was influenced by their observation of bird behavior, leading them to design an aircraft with light and efficient wings (Benyus, 1997; Hensel, Menges & Weinstock, 2004).

In the 1950s, Swiss engineer George de Mestral developed Velcro, inspired by the morphological characteristics of burdock seeds (Forbes, 2006; Vincent, Bogatyreva, & Bogatyrev, 2006). Around the same time, Jack E. Steele introduced the term "electronic devices" in 1958, describing the discipline of producing solutions and applications based on biological knowledge (Vincent, 2009; Whale, 2006).

In architecture, the thermos-dynamic properties of termite nests inspired architect Mick Pearce to create the Eastgate Center in Zimbabwe in 1996 (Forbes, 2006; Harman, 2014; Turner & Soar, 2008). This event was preceded by several joint initiatives that contributed to supporting and benefiting from biomimicry. Given these examples, bio-inspired design emerges as a practice and concept that people regularly undertake across various disciplines. The twentieth century not only gave different terminology to the practice but also infused some of these methods and purposes, allowing these disciplines to truly spread science. However, this is not a cross-sectional aspect of all biomimetic approaches. Nevertheless, there exist many examples of intersection and convergence between parametric design and biomimetics with an emphasis on their methods and uses in materials and manufacturing processes, as shown below.

Table 01: Intersection and convergence between parametric design and biomimetics
Source: Author

Parametric design

Natural imitation

Implementing a methodology and interpreting the Algerian nature to create a mechanism capable of innovating dynamic solutions	Design methods simulate natural strategies and processes through artificial computer techniques and algorithmic logic such as evolution or genes and their inherent principles, variation, reasoning, heritage, etc., and what are the appropriate solutions EX a rocket engine T a hierarchical group of emergent design	**Design Methods** Simulating natural strategies and processes through artificial and synthetic computer techniques and algorithmic logic such as evolution or genes and their inherent principles variation, reasoning, triadism, etc. and what are the appropriate solutions.
Use of Materials The use of materials plays a passive role and adapts to the final form	Use of materials: The ordinary example of the farm where the results of forces are concentrated, the diversity of materials, the form of an example of a Roximan, Beast and Gem Chim Megenes, we swim biologically.	Design methods are the realm of natural strategies and processes used and magnified by Nature over thousands of years of evolution to create more written and implemented applications.
Manufacturing processes, secondary manufacturing of items and the logic of society	Additional fibers using multi-material strategies, VPF strategies and SWARRM strategies aim to achieve an organic growth logic that replaces the component assembly and material subtraction process bridge Jroselovegrove example: beast and Gemini Robert Stuart Smith (swarm)	Matter plays an active role in creating the form of the results from the action of static forces, for example, gravity on materials. In the use of materials, the properties of materials vary on an infinitesimal scale due to the requirements.

Technology

Nature

Research Methodology

This research employs an empirical and collective construct methodology to achieve the set objectives. It involves a comprehensive review of previous literature, followed by the selection of relevant contents and the identification of prominent authors and their common and divergent points of views. It also employed case studies: surveying, analyzing, and interpreting examples of methodologies, strategies, and projects at various stages of development, alongside the analysis of theoretical and practical cases in parallel. This approach offered clarification of techniques, both concrete and virtual, and the attainment of an effective understanding of theoretical concepts through a collaborative approach between parametric design and biomimetics. The analysis of the collected references enabled the identification of common aspects between the two topics, facilitating discussion and reflection on the implications.

The methodology also provides a structured and iterative process for the effective incorporation of bio-inspired textures into design projects. It points out that by following six steps, creative professionals can systematically identify relevant problems, select appropriate natural textures, experiment with digital tools, fabricate prototypes, evaluate their performance, and incorporate feedback to refine and improve the final design solutions.

This method involves six sequential steps:

1. Identification of problems and opportunities
2. Selection of textures
3. Digital morphological experimentation
4. Digital fabrication
5. Evaluation
6. Feedback and improvement

Findings 01: From Previous Literature

Distinguishing between Biomimetics, Electronic Instruments, Biofibers, and Biomodulation

It is revealed that Bio-inspired design encompasses various forms and purposes, including biomimicry, bio-morphology, bionics, biomimetics, and biofibers. These designations identify methods that originate from inspirations of Nature. However, despite similarities, the approaches differ. Whale (2006) argues that biomimetics and electronic tools are distinct methods with different operations. In some cases, such as the differentiation between electronic devices and biomimetics, approaches do not differ significantly. These designations identify methods that originate from inspiration in Nature.

In the fields of architecture, urbanism, and interior design, another term has recently joined the biophilic design vocabulary: "biophilia." Exploring the relationship between human beings and Nature, this approach aims to replicate experiences of this relationship in design to strengthen this connection (Burnett, 2017). According to Burnett (2017), biophilic design is an Evidence-Based design method for promoting improvements in health and well-being. The biomorphic form 114, as the term itself suggests, is defined merely for a purely aesthetic purpose and without any benefit on a functional level. The term refers strongly to the artistic milieu with expression in fields such as architecture, painting, and sculpture, but also to design (bioform, n.d.). Bio-inspired designs thus emerge as an umbrella term generally used to define different approaches that start from a source of inspiration from Nature, but differ in their application and purpose.

It is important to keep in mind that relatively speaking, the focus of biophilia is to enhance human well-being. Bio-morphology is relegated to the field of aesthetics. Although both bionics and biomimetics seek to create applied solutions by imitating the mechanisms of Nature, the former has a strong connection with engineering and technology, and the latter, in addition to seeking to imitate Nature also in terms of its processes and strategies, is essentially a science. Bioelectronics arises due to the strong connotation of ecology based on another equally intimate aspect: reflection of the impact of biomimicry on design practice.

Biomimicry, whose history has lasted for several decades in design—if not in general—is a topic of conversation hanging on the border between design and science. However, this position may be non-specific, which some see as a negative aspect, which makes this field in particular a fertile ground for opportunities for innovation and differentiation and capable of making a positive impact in the field of design. It involves the integration and promotion of concepts and knowledge from various fields. Collaboration between multiple disciplines—sometimes excluding the designer from what is usually his and his zone of mastery and comfort—and this approach offers the designer an alternative vision, and encourages to find solutions aimed at solving many of the problems that our society currently faces and this approach is trying to achieve.

In this sense, the biomimetic approach requires, above all, from the designer, the ability to interact and communicate with professionals from different fields as well as a high degree of acceptance, which is essential to integrate these concepts. This way of working would represent a departure from the origin of design (Lorenz, 1991), which characterizes design as a system and interface whose function is often to create bridges between different fields of knowledge. In the context of biomimicry, this thesis is reinforced by Wahl (2006), who attributes to the designer, the role of integrator in the process of integrating knowledge from different fields.

Indeed, this vision was also shared by Oxman (2015). As such, and taken in its own right, biomimicry does not represent a novelty to design practice, but only an approach to areas of knowledge with which design does not normally collaborate. If this approach alone does not lead to a disruption of the designer according to Lornze, Whale and Oxman as an intermediary between areas of knowledge, it raises the question as to what is the real impact of biomimicry and what does it bring when practiced in design. Whether Lornze Whale's words indicate that this new system is not disruptive in terms of the way design works, is the most important influence to consciously take a biomimicry approach to design.

According to Bonsiepe (1992) especially with regard to the sustainability of solutions created by the designers, it is a principle that, although part of the behavior and ethics of this profession, in the twenty-first century, still seems more like an aspiration rather than an actual practice.

With the millennium awakening came new products with new demands for which design was not adequate. A public hungry for the latest technological innovations or trends, in a constant search for new ways to differentiate itself from the masses, fuels the industry. This in turn responds by launching new products at intervals of time for each and increasingly and inevitably leads to a narrowing of the timeline between production and clearance (Bonsiepe, 1992). This is a reflexive dialogue of a production model based on mass production, with programmed obsolescence and abundance, which is now being called into question for being unsustainable.

Simultaneously, the abuses of Man on Nature have reached their peak in the present time, where sustainability has emerged as an inevitable topic. In recent years, there have been works of different kinds trying to push humanity towards a collective transformation that will be more social, cultural, and economic than ecological. The design sector, as stated by Bonsiepe (1992,), is often an accomplice in a product model and economic activity that has proven to have serious consequences. It must be the accompaniment of this change and the creation of sustainable solutions, more than it is desirable, obligatory. In this context, the integration of Biomimicry in design practice is suitable to help create more sustainable solutions that are created by simulation to solve problems.

According to Benyus (1997), these have been tested over years. According to Oxman (2010) however, it clearly emerges as a model that the designer can observe and draw valuable lessons from, allowing them to come up with more sustainable and effective solutions. Nevertheless, this would not be a strange way of representation for a designer when looking for solutions (Oxman, 2008), as it is a common practice that people have used for thousands of years, and Nature has inspired many of humanity's achievements. However, if our immediate focus is that industrial products with innovative properties may emerge from this approach, it may be a secondary aspect on which more relevant factors are imposed, including new materials and production processes that may be at the origin of these products and which have resulted from the biomimicry approach.

Materials science and manufacturing processes are two sectors that use biomimicry and have a pioneering role. The convergence of these sectors results in the creation of materials with properties and behaviors equivalent to those of natural ones, as well as in the development of manufacturing processes that mimic natural processes. The first steps in this direction are now being taken by several research projects such as those led by Neri Oxman or Achim Menges. They work in different areas, but their work indicates an overlap or convergence between biomimicry and parametric design.

Neri Oxman (2010), who leads the Mediated Matter research project at the MIT Media Lab, studies the development of processes that allow selective variation of material properties using additive manufacturing technology to replace current methods based on assembling components via processes closer to those found in Nature. In turn, Menges (2016) explores what he believes are the inherent computational properties of materials, with Michael Weinstock and Michael Hensel at the Emergence and Design Group, using morphogenetic processes to generate form through computational techniques and tools (Hensel, Menges, Weinstock, 2004).

These examples help understand innovations in these two fields, specifically, under the influence of biomimicry, which will have a direct impact on design and its practice. It is particularly in areas such as product or industrial design where the practice often involves manipulation of materials as well as exploration of production processes.

Design always has a turning point where new possibilities arise, and biomimetics can emerge as a specific area that holds the potential to transform design directly in terms of finding more sustainable solutions and providing evidence that aims to inspire and solve problems that the designer intends to solve. Sustainability of shapes, models, and ideas inspired by simulation with Nature, and influencing areas have an impact on the practice of design, as is the case in material science or manufacturing processes. As can be inferred from the words of Néry Oxman (2015), realizing the full potential of biomimicry, as well as many areas currently under development, will depend on the synergies that arise with other equally important areas of knowledge. Among them, design, which according to Oxman (2015), appears as a link for communication, establishing bridges and mediating relationships between different disciplines.

However, the relationship between parametric design and biomimicry linking the two approaches is as distinct as parametric design and biomimetic. Indeed, it is a complex task. As known, this relationship is not clear from the beginning, and we can immediately conclude that we are facing two design methods that exist in columns of opposites on the same spectrum. On the one hand, we have a strong and well-established approach to computer science, and on the other hand, we find another major one that is biology. However, we encounter the same opposition between synthetic and organic spectrums, between the natural and the artificial, and between machine and Nature that Oxman (2015) refers to in the introduction to "Design at the Intersection of Technology and Biology" (Fig. 7).

Conversely, it does not mean that the division is here. Both approaches are not complete and, in some cases, do not even correlate. This does not mean that they do not share common aspects-the same Nature that inspires biomimetic design is governed by precise mathematical criteria and laws, and (hence models) are also parametric (Fig. 7 & 8). As such, the following indicate a relationship between the two fields.

Fig. 7: Michael Pawlyn - Side table produced in PLA by 3D printing, 2014
Source: Lindsay, 2020

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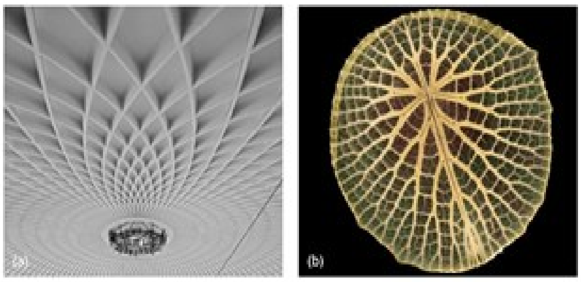

Fig. 8: (a) Coverage of Palazzetto dello Sport created by Nervi and (b) X-ray of a water lily (Victoria amazonica) leaf and its structural strength.
Source: Weston, 2012

Biomimicry and Parametric Design in the History of Design

Design problems are typically ill-structured. This implies the need for a search or exploration at the beginning of the design process. Once the problem is interpreted, ideas for a solution are considered, until one or more guiding ideas are selected as guiding principles for further development. This search consists mainly of ideation: generating ideas and reflecting on them until potential and partial solutions have become a final, complete, and well-integrated solution. In most design disciplines, the end result of the design process consists of a set of predominantly pictorial representations of the designed entity, together with specifications for its realization, which vary in accordance with the design phase and its 'granularity'. This means that properties such as form, dimensioning, details, material properties, and attached information are added and refined as needed at various stages of development.

This is an incremental process in which images serve two main purposes: First, they serve as inspiration in the search for ideas. Second, they provide the designers with feedback on the current state of development, enabling evaluation and revision. Representations can be internal or external images. External images are those we can see; internal or mental images are those we have in our heads and can only be seen with our 'mind's eye'. An internal image can be described, but it cannot be externally reproduced with exact fidelity. Any attempt to 'download' the mental image, for example, by drawing it on paper, can only be an approximation of the internal image. Both external and internal images are representations that designers use in the early, initial phase of designing.

Indeed, there are two types of external representations: those that designers 'import' from elsewhere and use in the design search, and those that they produce themselves during ideation, often in the form of sketches. Sketching for example, interacts with mental imagery, and therefore reproduces the internal representation. The role of external images is to bring into the design process representations from elsewhere. Self-generated representations, especially manual sketches contribute to the design process in a way that no other form of representation is able to emulate from a cognitive point of view.

Interestingly, the history of design itself represents a link between design, parametrics, and biomimetics, with numerous examples where both approaches co-exist. Antoni Gaudí, previously referred to as one of the pioneers of parametric design, was also a passionate explorer of Nature, translating many motifs from Nature into his work. For instance, the columns of the Sagrada Familia, which branch out into the structure, also provide structural properties (Vincent, 2014). Similarly, the roof of the Batló House resembles fish scales. However, it is the use of gravity as a condition, through the principle of inverted sequence (Davis, 2013a; Chilton, 2010), that serves as a concrete example of the coexistence of both approaches in Gaudí's work, where there is a natural principle of logic parametric at once, like Nature, where form is the result of forces acting on matter (Oxman, 2010).

However, Gaudí is not a unique example. The work of Frei Otto, which shares similarities with Gaudí's, is also known for using physical models to study their works and incorporating natural principles as inspiration. A concrete example is the soap bubble film study executed by the German architect (Fornes, 2016; Hensel, Menges, & Weinstock, 2004b; and Weinstock, 2004b), which served as the basis for many projects. In this context, it is the laws of physics that determine the work of Frei and Otto. Therefore, inspiration from Nature while working parameters at the same time is a condition for their work.

Relevant examples are also Heins Isler or Italian Pier Luigi Nervi, whose work reflects the combined use of both approaches. Nervi, for instance, designed the Palazzetto dello Sport for the 1960 Summer Olympics in Rome using the water lily as inspiration, resulting in a roof that is aesthetically pleasing, thinner, and lighter without compromising its resistance. This strategy allowed the creation of a wide scope, essential for the type of equipment involved (Button, 2016). In this context, it is important to highlight the relationship between form and structural principles, which characterizes Nervi's work (Leslie, 2013). This relationship also finds a parallel in Nature (Oxman, 2010).

Nevertheless, inspiration from Nature is not the only aspect found in Nervi's work. The characteristic geometry of Nervi's work allows us to anticipate the existence of parametric logic, a doubt that Leslie (2013) does not hesitate to take for granted. To maintain this conviction in the truth of Nervi is to resort to controlled geometry. On the basis of this argument, Leslie also places Pier Luigi Nervi among the pioneers of a parametric approach, and although like Gaudí or Otto, Nervi never applied the term parametric in the context of his work. Leslie's discovery, however, appears to be, in addition to being very relevant, supported in an indirect file when we observe the same strategy applied by others and authors now with recognized parametric methods.

Examples also include Phillips (2010), who resorted to the use of ruled surfaces to design the structure in reinforced concrete that integrates the library of the Archi-Union architecture studio, or the staircase he designed for the Jade Museum in Shanghai. Although these works were conducted by third parties, the works of Gaudí, Otto, Hessler, or Nervi appear as frequently cited examples in the context of parametric design as well as in the context of biomimicry. Indeed, to these could easily be added the likes of Buckminster Fuller, Neri Oxman, or Ross Lovegrove; these too being repeatedly mentioned within the scope of both approaches, or even the architect Michael Paulin, which reinforces not only the idea of their common use but also the fact that this practice was not limited to the past.

However, by passing the simple reference on to individuals whose work could be on both sides, relevant issues arise that require an answer, especially if the simple co-integration of concepts and techniques from both processes—and here the consistency is greater or less on the part of the authors—or the fact that some names are cited with seriousness in these two fields, appear as strong arguments that allow confirming the existence of a relationship between design Parametric and Biomimetic. Since these arguments are initially weak, there are more solid indications supporting the existence of this relationship. Among these, a substantive focus is on finding common efficient solutions for both approaches, or integration and exploration in the context of parametric design of concepts for biology that attempt to replicate themselves using computational strategies.

Competence and Eligibility as Global Measures

Although different, both biomimicry and parametric design are irrefutably efficient. They seek to imitate Nature and develop applications by replicating the patterns of Nature and strategies; indeed, incorporating efficiency inherent in this entity. In contrast, modular design seeks to create models in which activities can be translated at different levels: structural, formal, productive, etc. and the artifacts it produces, taking advantage of the latest developments in technology. In the context of parametric design, strategies are used to achieve this goal. Evolutionary processes integrate evolutionary and genetic algorithms that mimic the processes of evolution, recombination, and selection found in Nature (Weinstock, 2004). The resulting solutions are selected according to an equally fundamental criterion for this entity: efficiency. Using the same computational mechanisms that have been reconciled with developments made in the fields of material science and additive manufacturing, it also seeks to replicate the strategic use of materials implemented by Nature. Parameters may be replacing a production process based on the assembly of other components on the basis of organic growth (Lovegrove, 2016; Oxman,2015) forcing us to rethink the inefficient hierarchical logic, which is characterized by subsequent rationalization of form, which has hitherto been characterized by the production of artifacts (Oxman, 2010). This is a logic in which form is thought of first and structure and materials are accommodated accordingly.

Role of Biomimetics in Creating Materials with Distinctive Properties Employing 4D Printing Techniques

Using 4D printing techniques, as well as using 3D printing and Stratasys' Connex3 technology, allow the technology to diversify the properties of the materials that embody the object. In this case, it involves combining rigid and flexible materials, which is considered essential for the movement (MIT Media Lab,2014) and for producing huge objects consisting of materials with different properties. As demonstrated by the joint project by Neri Oxman and Iris van Herpen (Figs. 8, 9 & 10) who achieved, through the strategic use of materials (Oxman, 2010), certain techniques such as 4D printing technology. However, these technologies have limitations, including the time it takes for the production process (Barros, 2015; Tibbetts, et al., 2014). In the case of 4D printing, although it appears promising, it is still at an early stage and is only being tested in some research projects such as the one led by Skylar Tibbetts (2014).

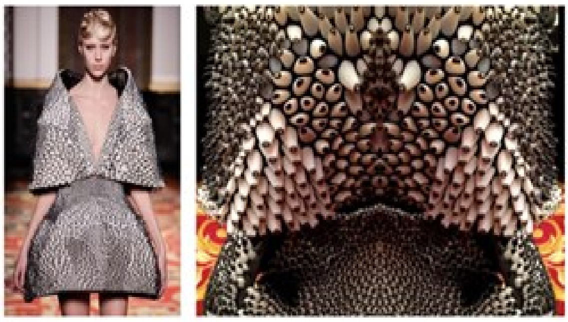

Fig. 9: Anthozoa, Neri Oxman, and Iris Van Herpen, 2013
Source: MIT Media Lab, 2013.

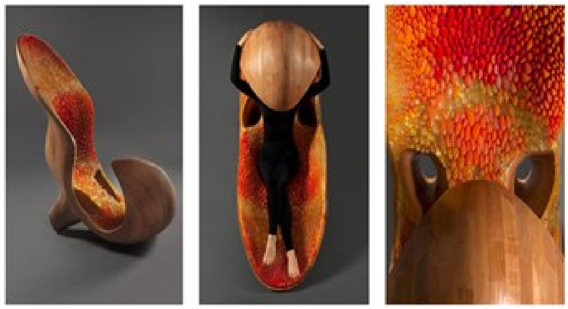

Fig. 10: “Gemini” Neri Oxman, 2014
Source: Neri Oxman/MIT Media Lab, 2014; Oxman, 2015

Fig. 11: The splint was created using a generative process and 3D printing.
Mhox Design, 2014.
Source: Mhox Design, 2014

Fig. 12: “Calgat (Can a Lily Grow aTelephone)” by Ross Lovegrove, 2010: An image in symbolic reference to the production of industrial artifacts through growth processes modelled
Source: Ross Lovegrove, s.d.

The case in point is the dress printed with a 3D printer using Stratasys' Connex3 technology. The technology enables diversity in the properties of the materials that embody the object (in this case combining rigid and flexible materials), which is fundamental to movement**.** The method used allows for individual production; the user's anatomy was obtained using a 3D scanner.

In fact, due to 3D printing technology with multiple materials, an irregular pattern is developed on the surface that absorbs sound. According to Neri Oxman, although only one material was used, the surface was printed with 44 different properties that varied in hardness, opacity and color corresponding to pressure points on the human body. Oxman states that, similar to Nature, the surface created differences in its functionality not through association with different materials or components, but because it varies continuously and precisely the property of the material.

Materials and Raw Materials

It is to be noted that in contrast to human production, Nature employs a hierarchical logic of matter and structure that precedes form (Oxman, 2010). In Nature, form is the result of forces acting on matter (Oxman, 2010). This is evident in "designed" structures, where areas requiring greater strength are efficiently distributed and areas without need are dispersed. In the context of parametric design, this logic is currently being replicated in projects such as those presented by Achim Menges, where materials take a decisive role and are more prominent than form (Menges, 2016). Materials possess computational properties regarding shape generation, and matter ceases to be a passive receptor of patterns, instead adhering to a specific role in the formation process within a logic where physical properties of parametric materials can be considered as parameters (Weinand, 2010).

According to Oxman (2015), the progress made in materials engineering has occupied a central position in recent years due to collaboration. The integration with additive manufacturing technology and its application in a non-traditional way has made it possible to pre-program artifacts produced through this method for specific behaviors or responses to specific stimuli (Tibbits et al., 2014). In fact, this has changed the structural properties of artifacts (Oxman, 2010). At the same time, multi-material technology or "heterogeneous materials" referred to by Tibbits et al. (2014) and Neri Oxman (2010) has emerged, offering a wide horizon of hypothetical possibilities that have been applied and are currently being studied in research projects exploring concepts such as 4D printing or self-assembling structures.

These topics form the core of the research conducted by Skylar Tibbits, which involves studying different possibilities for creating objects capable of building themselves using techniques such as multi-material 3D printing or gradients to combine materials with distinct properties or strategically control the distribution of materials (Tibbits et al., 2014). The results obtained through these strategies can be seen in the products such as BioLogic, an advanced textile developed by the MIT Tangible Media Group whose composition includes a specific type of bacteria that gives distinct properties to the material (MIT MediaLab, Tangible Media Group, 2015). BioLogic behaves like a living organism, eliminating the need for direct user intervention, and has a parametric behavior resulting from the computational capabilities of the material itself to create the form in a responsive manner (Menges, 2016).

BioLogic, as well as the research developed by Tibbits, are conclusive evidence that a turning point in materials engineering as well as the embryonic stage of developing materials is emerging from heterogeneous groups (Oxman, 2010). In fact, products may emerge in which the structure is closer to the logic of Nature, composed of materials whose properties vary at the microscopic level based on local requirements (Oxman, 2010) and produced by methods alternative to the logic of assembly (Oxman, 2015; Lovegrove, 2016). Then, the efficiency and sustainability of Nature's characteristics are also incorporated. In turn, the possibility of programming certain behaviors directly into the materials that make up objects can enable the making of products that require fewer electronic components and lower power consumption, opening doors to new features that the designer can exploit. It is predicted that this technological integration will soon be able to design materials similar to those found in Nature.

Parametric Designs that Encourage Innovation, Inspired by Nature

The apparent simplicity of Nature does not reveal its complexity. Perhaps only recently and with the advent of modern science has Man explained this development. Still however, new discoveries continue and are being made at an increasingly rapid pace. The development of new technologies–for example, the electron microscope that made it possible to take images on small scales–has made it possible to uncover the mechanisms inherent in some natural phenomena that are hitherto poorly understood. In effect, innovation has made a new resource more accessible the possibilities created by the knowledge obtained through the new resources.

Fig. 13: “Living Kitchen - The Future of Matter”.
Source: Michaël Harboun, 2010

In this project, Michaël Harboun (2010) speculates on the application possibilities of programmable matter, a concept investigated by a group of scientists at Carnegie Mellon University in Pittsburgh, United States under the name "claytronics". It is defined as a programmable matter made up of tiny robots: smart devices that use electrostatics to hold together, communicate and change their position in space. The introduction of information into these robots allows them to form new geometries when reacting to external stimuli.

In the context of biomimicry, the smallest scales and areas often harbor the greatest potential for innovation. Examples such as the microstructure of shark skin, the wings of the morpho butterfly, and the feet of geckos have led to numerous innovative applications, demonstrating the validity of this statement. Interestingly, it is at the microscopic level, where efficiency has been pushed to its limits, that Nature exhibits its parametric character, as noted by Fuller (Baldwin, 2012). The dialogue between science (discovery) and engineering (application) has given rise to new opportunities for innovation, which arise from the convergent nature of disciplines, as highlighted by Lorenz (Faria, Aranha & Trads, 1991). Indeed, Neri Oxman (2015) has emphasized the futuristic influence of biomimicry, suggesting that the technology considered perfect today can evolve to change the way we produce things.

However, according to Lovegrove, the current production method, based on the assembly of components, can lead to the emergence of methods similar to those found in Nature, where products grow through biological processes. This concept challenges designers to think about their objects as assemblies of separate parts with different functions (Oxman, 2015). Lovegrove's vision parallels the need to abandon the logic of assemblage and adopt a model closer to the natural model, which depends on growth and physical, digital, physical, and biological components. However, emulating Nature's underlying production processes cannot be implemented through manual processes alone. Nature's extraordinary complexity necessitates the support of algorithms and processors. Leveraging recent technological advancements in computational applications, manufacturing processes, and materials (Neri Oxman, 2015), it is possible to break down natural mechanisms, transform them into data, interpret them using algorithms, and convert them into parametric models.

It is argued that this approach may enable people to effectively mimic Nature. For biomimicry, which focuses on mimicking Nature's processes and strategies (Biomimicry Institute, 2019), a parametric approach emerges. Conversely, for parametric design, Nature serves as a recurring model. Biomimicry and parametric design are therefore complementary and produce convergent approaches, as evident in the work and vision of Neri Oxman (2015) from a biomimetic perspective.

Evolutionary Design: A Genetics Approach to Design via Evolutionary Numerical Models

Development of technology that gradually separated Man from Nature also allowed for the development of basic technological means to reveal the mechanisms inherent in this entity. Nowadays, the paradoxes remain in the file and the same method is the origin of many methods that attempt to replicate these operations in natural resources, resource utilization and mathematical operations. Gradually, concepts such as evolution or genesis were introduced and explored. In various fields outside the field of natural sciences from which they come, computing sciences appear as one of those fields in which there has long been interest through these concepts and the processes inherent in them (O'Reilly, Hemberg, and Menges, 2004). Based on these concepts, algorithmic techniques have been developed and have begun to be used in the field of programming. These techniques include operators that use parameters similar to those in the natural domain, namely, Selection, Variation, and Inheritance, which are replicated in algorithms defined as evolutionary or genetic operators. According to Rivka Oxman (2006), this has been a frequently used tool in many areas of investigations.

According to Holland (1992) and Oxman (2006), genetic algorithms are parallel computational representations of the processes of variation, crossing over and selection based on efficiency criteria common to most evolutionary processes and adaptation. In this context, the concept of genetic code refers to a set of rules that define a particular class or family (Oxman, 2006). This type of algorithm allows the use of variations through the process of reproduction that occurs through hybridization and mutation (Oxman, 2006) of individual solutions. Together, they can be tested and evaluated based on the performance of simulation environments and in order to find the most appropriate solution that can be later recompiled and modified to produce improved offspring that incorporate desired ancestral characteristics (O'Reilly, Hemberg & Menges, 2004).

However, the use of evolutionary algorithms has not been limited to the field of computational science. It occurs also in the field of project disciplines such as design, architecture and evolutionary technologies, and according to Rivka Oxman (2006), it is part of a long period of research tradition. From this context, approaches such as evolutionary design or genetic design seek to explore processes of evolutionary Nature and its applications in the project. In this field, this type of algorithms has been the basis of computational techniques for evolutionary personality and are mainly used for optimization purposes (O'Reilly, Hemberg & Menges, 2004; Oxman, 2006). However, these are currently viewed for their adaptive qualities that allow the implementation of performative morphogenic processes (O'Reilly, Hemberg & Menges, 2004) that can be governed through an interactive exchange of information (Oxman, 2006).

Natural replication patterns, such as those indicating evolutionary mechanisms, and biological organisms begin to occupy a central role in the context of design (Oxman, 2006). This involves especially the models related to the concept of morphogenesis, a process that has been explored through computational mechanisms with the purpose of generating a model (Oxman, 2006). Interestingly, Rivka and Robert Oxman (2010) outline this approach as digital morphology. It undergoes a digitally reproduced model-finding process that allows solutions to be derived through generative and operational processes. It should be noted that in these approaches, there is a clear attempt to harness evolutionary and growth processes within a computational framework (O'Reilly, Hemberg & Menges, 2004).

The goal is to use these tools as a generative design tool not only for optimization purposes, but also in order to produce complex and adaptable shapes. However, from the evolution of these strategies, the focus is no longer limited to shape generation. Rather, it also seeks to achieve the emergence of complex or even intelligent behaviors in a systematic logic, which is what is expressed in the concept of contingency. Discovered by Hensel, Menges, and

Weinstock (2004), the term ‘Emergence’ used in this context refers to the irreducible properties of a system. That is, properties held by a system composed of its parts that are not held individually (Weinstock, 2004).

According to Weinstock, in the field of natural sciences, this term refers to the production of complex forms and behaviors by natural systems that have an irreducible complex form. However, this concept has spread to other areas, among which implicitly is the project practice where mechanisms inherent in the process of emergence are used to create and develop “designs” in a virtual environment through morphogenesis (Hensel, Menges & Weinstock, 2004).

Through extensive integration of technology and concepts from biology, a group of researchers seeks to uncover the mathematical laws upon which natural systems depend and can be used by artificially designed systems (Weinstock, 2004). The main goal is to recreate the process of producing organic growth as expressed by Lovegrove (2016), or Néry Oxman (2015). For design, the integration of evolutionary algorithms in its practice represents an added value that makes it possible to explore different solutions created through the generative process. Unlike what happened in the past where this type of assumption was exploited, the strategy is characterized by its formal nature (Carpo, 2016), and the integration of analytical data to drive the process of forming the form-or morphology-which is infused in these strategies is personal. In the future, new possibilities may emerge resulting from greater technological integration–including additive manufacturing, programmable additives, information technology and artificial intelligence–and there is stronger, interdisciplinary convergence.

This circumstance perhaps fulfills the necessary conditions for creating environments in continuous mutation resulting from the exchange of constant information and analyzes such as those proposed by Spyropoulos (2016), which is the idea of a future in which the creative process is shared. Equipment and technologies that had a passive role in this process now become active participants, able to influence the final result. As other factors are included in the equation, the level of unpredictability of the results increases, and the gap between the designer's initial idea and the final result increases. The designer will stop being the creator of the forms or interact with them, and begin to interact and intervene only in the interactive framework of the mechanism that generates the form (Oxman, 2006).

In the context of the strategies presented, even the idea of the final result is closely related to design, and it is questionable what it replaces in the context of continuous mutation, evolution, adaptation and the basic concepts of fields such as biology, which have now been used in the field of design (O'Reilly, Hemberg & Menges, 2004; Hensel, 2004). Evolutionary algorithms generate and manipulate sequences of characters that act as population genotypes and entire structures. These genotypes serve as data to input parametric structural models that become phenotypes. These individual structures are analyzed and evaluated sequentially until an optimized result is reached where the goal is to find a balance between multiple requirements. Successive generations rely mostly on genes for the best solutions from the previous iteration. Individuals are recreated and mutated to create a new set of multiple solutions. It produces a cycle that takes the previous output as soon as the new input is created (Bollinger, Grohmann, & Tessmann, 2010)

Here, ‘emergency’ refers to the production of forms and behaviors by natural systems. which has irreducible complexity (Weinstock, 2004). The term was adopted in the field of architecture specifically to invoke complexity. According to Weinstock (2004) the term contingency appears emulated in the literature of many disciplines, including evolutionary biology, artificial intelligence, complexity theory, cybernetics, and the theory of systems.

Findings 02: From the Case Studies

Case Study 01: GEMASOLAR Center - A Photovoltaic Energy Center Inspired by Sunflowers

The increasing demand for more sustainable energy sources in recent times has led to the emergence of gardens around the world and large-scale units dedicated to the production of solar energy.

Fig.14: heliostats in Florida
Source: asknature.org, 2017

Among the most, the use of photovoltaic cells, which convert solar energy into electricity energy, is perhaps the one we are most familiar with. However, there are other methods with the same purpose. The use of heliostats - large mirrors used to direct light solar radiation, focusing its incidence on a specific point - are used to take advantage of the sun's rays. It produces a beam of sunlight and through this, it is able to generate high temperatures, and is used to heat water producing steam used to operate turbines responsible for producing electricity (asknature.org, 2017). Structures of this classification exist. However, the problem has been known for a long time. Installed at distances relatively close to each other, the panels produce adjacent areas. The shadow covers each other, which leads to losses in efficiency (asknature.org, 2017).

The solution that was found to overcome this problem has come from a natural phenomenon previously described: the distribution of sunflower seeds, which are packaged and governed by precise mathematical logic, following a spiral pattern in which each seed rotates at a golden angle of about 137 degrees with respect to its neighbour, thus ensuring maximum efficiency in terms of sunlight exposure for each seed (asknature.org, 2017). This was a translation of this natural principle for application purposes At the origin of the Gemasolar PV plant in Andalusia, this approach in addition to reducing about 20% of the space needed for the installation, has led to gains in terms of its efficiency (asknature.org, 2017).

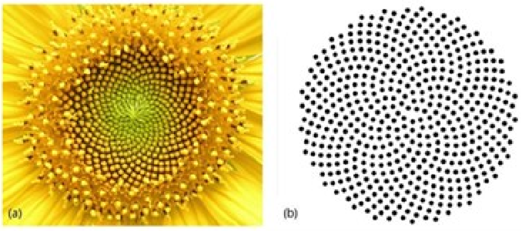

Fig. 15: (a) Details of the central part of a sunflower.
(b) Illustration of Vogel's formula representing a sunflower pattern.
Source: asknature.org, 2016

Fig. 16: Gemasolar, photovoltaic power
station, Andalusia, Spain
Source: asknature.org, 2017.

Case Study 02:
Geodesic Shapes of Buckminster Fuller

The iconic geodesic structures created by American architect Buckminster Fuller are perhaps better known than himself. These structures are closely associated with the work Fuller developed throughout his career, leading many to consider him their inventor. However, as revealed by Jay Baldwin, Fuller never claimed to have invented this type of structure himself. Rather, he stated that he was the first to discover it and recognize its advantages. It is said that he was convinced of this, and believed the geometry was natural in the sense that it already existed in Nature as a mathematical principle applied to achieve optimal results.

The lightness and strength of geodesic structures, due to their triangulated surfaces that evenly distribute weight, has made them the basis for many of Fuller's extensive works. However, as Baldwin points out, it is not immediately obvious where Nature makes use of geodesic shapes. Looking on smaller scales reveals examples of Nature employing these structures, something impossible for Fuller given the resources available at the time. It's also notable that Fuller never used the term "biomimicry" in reference to his work, despite the fact that his geodesic domes incorporated Nature's criteria like material economy and energy efficiency.

Baldwin argues that Fuller demonstrated a "consistent understanding and use" of biomimetic principles, and many more examples could be added to illustrate this approach. However, considering the ancient examples is enlightening enough, and adding other cases would not significantly contribute to a more comprehensive understanding of biomimicry's practical application, impact and possibilities. The most relevant examples are not necessarily the most successful, but rather those that apply the natural principles they claim to incorporate.

Fig. 17: “Montreal Biosphere”. Buckminster Fuller, 1967 - exhibition created same year (Montreal - Biosphere, 2017)

Case Study 03:
Palazzetto Dello Sport - Rome
Architect Annibale Vitellozzi and Pier LuigiNervi

The relevant examples are Heins Isler or Italian Pier Luigi Nervi; people whose work reflects the combined use of both approaches. Nervi, for which the Palazzetto dello Sport was created for the 1960 Summer Olympics in Rome using the water lily 160 as inspiration. Thus, he was able to design a roof that, in addition to being aesthetically pleasing, is thinner and lighter structurally without compromising its resistance. This strategy therefore allowed the creation of a wide scope, fundamental to the type of equipment involved (Button, 2016), 2016 (Pawlyn, 2016). Like Gaudí and Otto, Heins Isler used physical models – models that are suspended in the study process, for its famous shells (Shelton, 2010). Isler's work is thus equally designated as parametric or bio-inspired in character. However, because of its similarity to examples already referred to a more detailed description of Isler's work and the Palazzetto dello Sport was created in Rome by the architect Annibale Vitellozzi and Pier LuigiNervi. Nervi played an important role in the study and development of a roof made of preformed reinforced concrete elements (Leslie, 2013).

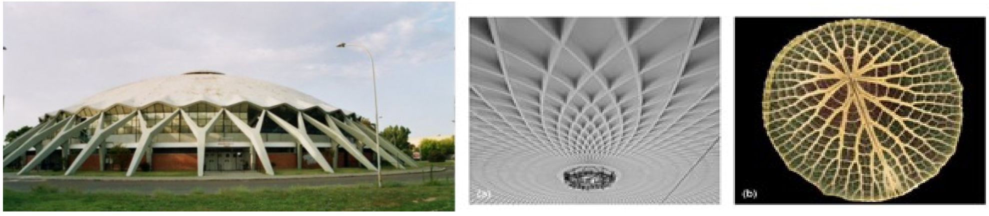

Fig. 18: (a) Coverage of Palazzetto dello Sport created by Nervi and (b) Image showing X-ray of a water lily (Victoria amazonica) leaf and its structural strength.
Source: Weston, 2012).

Case Study 04:
Gem Changi Airport in Singapore - Waterfall Changi Airport, Singapore. Moshe Safdie Rain Whirlpool –

Jewel Changi Airport in Singapore is a unique and fascinating destination that combines entertainment, shopping, and recreational activities under one roof. The airport's main attractions include the Rain Vortex, the world's tallest indoor waterfall, and the Shiseido Forest Valley, an indoor garden with suspended walkways and over 61,000 trees and shrubs. The Rain Vortex is a seven-story high waterfall that recirculates rainwater and is surrounded by a terraced forest setting. The Shiseido Forest Valley is one of Asia's largest indoor gardens, featuring a variety of tropical flora and fauna.

The Jewel Changi Airport is also a massive shopping center with nearly 300 stores, offering a wide range of products and services. Moreover, it includes a hotel, early baggage check-in facilities, and a Changi Experience Studio that provides an immersive experience showcasing the airport's history and operations.

Visitors can access Jewel Changi Airport from Terminal 1, 2, and 3 via elevated walkways, making it easily accessible to both transit passengers and tourists. The airport's design is based on an inverted toroidal semi-dome roof, which provides a column-free interior and allows for a diverse range of activities and plant life.

Overall, Jewel Changi Airport is a must-visit destination for anyone traveling through Singapore, offering a unique blend of entertainment, shopping, and recreational activities that make it stand out from other airports worldwide.

Fig. 19: Waterfall at Changi Airport, Singapore.
Moshe Safdie (Rain Vortex)

Conclusions

This research reveals the effects, benefits, and excellence resulting from cooperation between parametric design and natural biomimicry and demonstrates this effect, especially at the design level, and the development of materials and materials (responsive digital materials), as well as at the manufacturing level, and how this cooperation led to:

1. Developing design methods, mechanisms and strategies by generating and sustaining unlimited ideas

2. In addition to the impact of this cooperation on the development of materials and raw materials, especially developing them into responsive digital models - materials capable of making decisions without human intervention - this is what is called agency, as it leads to the behavior of the material in a behavior similar to what exists in nature and similar to the behavior of a living organism.

The transfer of morphological characteristics from plant species surfaces and textures to artificial elements through biomimicry has diverse application possibilities in design, architecture, engineering, and other fields. Bioinspired textures enable the resolution and enhancement of usability, sensoriality, functionality, aesthetic communication, and other aspects.

The integration of DFD and parametric software has significant technical advantages for the application of bioinspired textures. Parametric software allows for the generation of complex geometries, which can be modified and applied to various surfaces in a wide range of projects. DFD, on the other hand, enables the materialization of natural morphologies with versatility and effectiveness. It is essential to consider the limitations and restrictions of these technologies. Parametric software requires specialized users, particularly for advanced configurations, which also necessitate high-performance computers. DFD requires consideration of the high cost and limited access to high-definition digital fabrication technologies (stereolithography, UV ray printing), as well as extensive fabrication times. This opens the option to combine these technologies with traditional or analog techniques.

It is observed that the methodology for applying bioinspired textures, used in the initial phase in the academic setting, in industrial design projects, presents a logical and coherent sequence, constituting a guide for the correct and pertinent application of textures. This methodology for using textures, combined with the project methodology, supported by Bonsiepe's ontological scheme (1999) and involving multidisciplinary actors, has allowed for the addressing of relevant problems, accurate design proposals, and future possibilities for product insertion in the context presented. The projects completed in the industrial design program have reached the stage of materializing the first prototypes through FDM digital fabrication technology. It is necessary to conduct user validation in the context of observed activities to obtain feedback that enables improvement proposals.

It is expected that in future stages, the methodology will be further evaluated and refined, as well as the active sensorial perception of users evaluated, contrasting results obtained in academic settings with experiences in professional, business, and social contexts.

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