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AN APPROACH FOR DESIGNING ARCHITECTONIC STRUCTURES WITH BIO-INSPIRED PATTERNS

ABSTRACT

The paper focuses on applying bio-inspired generative design (GD) strategies in architecture. The aim is to produce innovative designs by developing architectural methods and tools that adapt patterns underlying biological behaviours. The emphasis in explorations was on biological phenomena that can play the role of underlying design patterns. The complex behaviour of natural systems represented by bio-inspired computational algorithms was then used to produce designs, i.e., information-related biological functions are transformed into technical functions to solve design problems. In this scenario, computer-generated design artefacts were produced by an algorithmically determinate system of rules. The suggested approach was tested through design experiments. Integrating biological and technical information was realized using a visual programming environment in a computer-aided design (CAD) system, facilitating design exploration and visualization. The logical set of rules was implemented to automate the design process. The obtained designs demonstrate the sustainability of the suggested approach.

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BIO-INSPIRED COMPUTING
BIOLOGICAL SYSTEM MODELLING

1. INTRODUCTION

It has been repeatedly shown that sourcing biology as knowledge and inspiration in architecture, frequently in conjunction with other sources, is effective.[1,2,3,4,5] Applying bio-inspired generative techniques in architectural design is the central subject of this study. The usage of systems for autonomous formation in the design process is implied by the generative design (GD) methodology. In these processes, designs emerge from modifying various applied generative system parameters.

Diverse natural or artificial systems could be used in a GD as mediums for creation. However, the application of automated computational systems is the most frequent. Furthermore, current computational systems increasingly feature a great deal of openness, dynamism, and unpredictable behaviour, forcing them to shift design from traditional, centralized approaches to nature-inspired, self-organizing techniques. Respectively, utilizing the complex behaviour of biological entities for generative systems heavily relies on computer technologies. Although different strategies have been explored, [6-21] there are still many opportunities to study, analyse, classify, and develop them in terms of design patterns and how they could be potentially systematically applied to solve design problems.

Correspondingly, this paper is directed at modelling bio-inspired mechanisms and exploring whether some biological behaviours can play the role of basic design patterns and generate designs. The aim was the creation of design procedures and tools from the adaptation of natural phenomena underlying each pattern. In the described approach, the development and application of a generative strategy based on biologically inspired patterns are part of the creative process. In addition, the application of these generative strategies in the conceptual stage of the design process is reviewed along with its potential and limitations.

Starting from the brief analysis of concepts, available methods, and tools, we propose and test an approach that combines biological and technical information in a compatible way through design experiments. The task was to select and outline design situations in which this approach is relevant and define design methods and tools.

Respectively, information-related biological functions are translated in terms of technical functions to solve problems of designing architectonic structures. In this set, computer-generated design artefacts are produced by an algorithmically determinate system of rules.
GD activity requires precisely defining the problems to solve and accurately comprehending the relationships, flows, and performances to provide design solutions with the desired qualities of biological systems. On the other hand, the GD methodology avoids preconceived solutions and psychological inertia due to the finite experience. The bottom-up approach drives designers through problem abstraction and after through the abstraction of solution.

In this research, the relationship between different fields is explored and visualized in a CAD system with the aid of visual programming. This approach was selected because architectural designers are familiar with CAD environments. Modern CAD systems enable constraint-based modelling in which every element may be connected using parameters, relationships, and references. The logical set of rules can be implemented to automate the entire or part of the design process, providing the possibility to create an integrated functional structure.

Using nature as a model and mentor and appropriating biological patterns can lead not only to rational design solutions but also to the design process's optimization. Finally, this paper may be interesting to those involved in architectural design and those generally interested in design methodologies, particularly computational GD strategies, because the approach can be generalized and applied to various design domains.

2. UNDERLYING CONCEPTS

Patterns in both animate and inanimate natural worlds are visible regularities, outcomes of complex self-organization governed by physical laws and biological processes. Sciences, including mathematics, physics, chemistry, and biology (especially evo-devo), can describe pattern formation at different levels and scales. Visible natural patterns find explanations in chaos theory, fractals, logarithmic spirals, topology, and other mathematical constructs. Exact mathematical perfection can only approximate natural entities; however, many patterns from nature can be modelled mathematically and simulated with computer graphics.

Attempts to explain the order in nature date back to ancient Greek philosophers, including Plato, Pythagoras, and Empedocles, who anticipated modern concepts.[22,23] Studies of symmetries and spirals remain relevant in modern times. Since Leonardo Fibonacci formulated the Fibonacci sequence in 1202.[24] spiral arrangements were the subject of studies by diverse authors, including Leonardo da Vinci, Johannes Kepler, Charles Bonnet, Karl Friedrich Schimper and Alexander Braun, Auguste and Louis Bravais, Adolf Zeising, and A.H. Church, D'Arcy Thompson.[25] Studies of soap films started in the 19th century with the pioneering work of Joseph Plateau, who formulated minimal surfaces.[26] The problem of foams, i.e., packing equal volume cells, was solved by Lord Kelvin. His 1887 solution was only improved after the 1993 Weaire-Phelan structure, which was applied to the envelope of the Beijing National Aquatics Centre constructed for the 2008 Summer Olympics. [27,28] Alan Turing studied mechanisms of morphogenesis.[29] He proposed a reaction-diffusion model and formulated the Turing pattern describing spots and stripes in nature. Aristid Lindenmayer developed the L-system, a formal grammar for modelling plant growth based on the mathematics of fractals.[30] Benoit Mandelbrot's Fractal Constructs[31] is the final contribution to the discipline of mathematics of patterns, which was gradually developed through the works of Gottfried Leibniz, Georg Cantor, Helge von Koch, Waclaw Sierpinski, and others.

Visible patterns in nature include symmetries, trees, fractals, spirals, chaos, flow, meanders, weaves, dunes, bubbles, foam, tessellations, cracks, spots, stripes, and patches. While symmetries are pervasive in nature, fractals only approximate the phenomenon of self-similarity (such as branching) since infinite iteration is not possible in the natural world. Spirals are common in plants and some animals, notably molluscs. Patterns, including chaos, flow, meanders, weaves, and dunes in nature, are the results of dynamic nonlinear processes. At the same time, bubbles and foams are optimal structures that, like all natural systems, tend to stabilize in a state of minimal energy. Respectively, these systems are applied in architecture for the design of lightweight structures like tensile membranes, researched and designed by Frei Otto[32] or or Buckminster Fuller's geodesic domes.[33] Tessellations are a common motive in art and design; however, it is less easy to find exactly repeating tiling in living things. Crack patterns are linear openings formed in materials to relieve stress, while spots, stripes, and patches in the biological world have evolutionary reasons related to natural selection and survival (*Figure 1*).

Current research on the application of some natural patterns for producing artificial intelligent systems for GD in architecture has been the subject of several publications.[34,35,36,37,38]

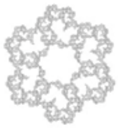
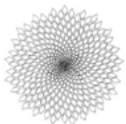
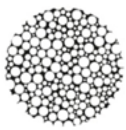
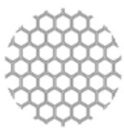
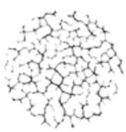
Type		Materialisation	Formation
Symmetry		_bilateral symmetry in animals _bilateral/radial/fivefold floral symmetry _sixfold symmetry in snowflakes _crystal symmetry	_developmental process _ecological causes _crystallisation process
Trees Fractals		_branching _self-similarity [e.g. clouds, river networks, geological fault lines, mountains, coastlines, animal coloration, snowflakes, crystals, blood vessel branching, Purkinje cells, actin cytoskeleton, ocean weaves]	_growth pattern modelled by L-system fractals _self-similarity approximated by fractals
Spirals		_plant spirals - arrangement of leaves on a stem, parts of composite flower head and seed head [e.g. sunflowers, pineapple, pinne cone] _animal spirals [e.g. molluscs]	_phyllotaxis spiral generated from Fibonacci ratio _special case of self-similarity _lowest-energy configurations that emerge through self-organisation _reaction-diffusion processes _natural selection causes
Chaos Flows Meanders		_vortex streets in form of zigzagging _patterns of whirling vortices _meanders in form of curved bands in rivers or other channels	_dynamic system modelling based on chaos theory, fractals, some cellular automata [e.g. Wolfram's Rule 30] _fluid flow processes
Weaves Dunes		_chaotic ripple pattern of any larger body of water or send [e.g. crescents, very long straight lines, stars, domes, parabolas, and longitudinal or seif shapes] _ patterns in vegetated landscape [e.g. forests on mountain slopes after wind disturbance]	_dynamic system modelling [e.g. modelling behaviour of mechanical weaves that propagate through a medium making it oscillate] _morphogenesis [e.g. weaves occurring in forests on mountain slopes after wind disturbance during regeneration]
Bubbles Foam		_soap films and spherical bubbles _foam of different materials in nature [e.g. living cells, radiolarians, sponge spicules, silicoflagellate exoskeletons and the calcite skeleton of sea urchin]	_minimal surfaces modelling [form-finding and optimisation - minimisation of energy] _dens packing structure modelling [note. foams composed of soap films obey Plateau's law]
Tessellations		_tessellated structures built by animals [e.g. nests of social wasps, honeycomb] _tessellations in animals' osteoderms [e.g. bony fish, reptiles, pangolin] _tessellations in plants [e.g. salk fruit, snake's head fritillary] _tessellated structures of minerals	_patterns formed by repeating lines all over flat surface, arrays
Cracks		_patterned ground in permafrost soils with an active upper layer _fissured pattern that develops on vertebrate brains [note. the pattern of cracks differ for elastic and inelastic materials]	_process of forming linear openings in materials to relieve stress [e.g. shrinking cracks caused by thermal concentrations, physical process of constrained expansion]
Spots Stripes Patches		_pigmentation patches in animals: spots [e.g. leopard, ladybug], stripes [e.g. angelfish, zebras], blotches [e.g giraffe] _vegetation patterns: stripes [e.g. tiger bush], patches [e.g. in flat terrains hexagonal gap pattern and spot patters] _patterns created by animals [e.g. Mima mounds of the of the Northwester US, fairly circle of Namibia] _growth colonies [e.g. bacteria colonies, slime mould]	_modelling reaction-diffusion systems / activator-inhibition mechanisms [e.g. shapes dependant on the growth condition, (in particular stresses), dynamics of chemical signalling (slime moulds), cellular embodiment (elongation and adhesion)] _evolutionary reasons [e.g. camouflage, signalling, mimicry, simbiosis] [note. pattern formation is genetically controlled, and often involves each cell in a filed sensing and responding to its position along morphogen gradient]

FIGURE 1: Visual patterns in nature

Bio-inspired mechanisms in design

Terms bionics/biomimicry/bio-mimetic/bio-inspiration/bio-appropriation are synonyms used to denote a multidisciplinary scientific field in the expansion that studies modes of transposition and implementation of patterns found in nature into science, engineering, art, and design. The aim is the production of optimal solutions that have specific desirable attributes of biological systems. *Figure 2* summarizes the comparison between biological and architectural systems.

Biological systems	Architectural systems
Efficiency because of the long and constant process of natural evolution	The improvement of efficiency solved through the process of optimization
Environmentally responsive and fit into their environment	Very little environmentally responsive
Environmentally influenced self-assembly	Externally imposed from
Hierarchical structure	Mostly monolithic, little or no hierarchy
Adaptive in function and morphology – growth and repair	Construction and fabrication

FIGURE 2: The comparison between biological and architectural systems

Just like nature, architecture is centred on organization and materialization, deals with morphology and structure, and is made up of individual functional elements that work together as a whole. However, the comparison (*Figure 1*) shows the superiority of natural systems and the high standards that nature has set before artificial systems. An example is the diversity of natural forms and organisms in metabolic balance with their surroundings, resulting from continuous evolution and development through natural selection. Therefore, deriving solutions for design problems from natural processes implies the position of nature as a mentor/model/system.

In line with the previous several interesting research projects and initiatives have been launched, such as *AskNature*, a project of the Biomimicry Institute, an organization dedicated to promoting the practice of looking to nature for inspiration to solve design problems in a regenerative way.[39] Another interesting initiative is *BioFabForum*, a community for knowledge exchange and experimentation around the manufacturing of/with biological materials.[40]

Building on the tradition of interdisciplinary research on natural structures established by Frei Otto at the University of Stuttgart,[41] the Institute for Computational Design (ICD) collaborates on various projects that use bio-inspired patterns and computational processes in architectural design.[42] For decades, the *MediaLab* at the Massachusetts Institute of Technology (MIT) has been conducting research on transformative systems, experiences, and technologies that help people reimagine and redesign their lives by fusing art, science, design, and engineering. Some of their projects combine design, biology, and the use of cutting-edge technologies.[43]

Also, the *Urban Morphogenesis Lab* at the Bartlett School of Architecture experiments with the application of the latest scientific findings within unconventional computing and biological and artificial intelligence to various complexity and scale of design from objects to architecture and the urban.[44] On the other hand, an example of an architectural firm specializing in biotechnology for the built environment is *ecoLogicalStudio*. The studio has built a distinctive portfolio of biophilic artworks, living architectures, and blue-green masterplans.[45]

According to Vincent,[46] there are three different levels of transposition of biological mechanisms into the architectural design process: copying, pattern recognition, and the TRIZ theory of inventive problem-solving-based approach. Copying biological entities is the lowest, most obvious, but insufficiently general approach. The properties of the most often copied biological objects include form, structure, and texture. Although this approach has a disadvantage that biological systems and their mechanisms can be taken out of context without sufficient understanding of the reasons for their effectiveness, there are numerous examples of copying formal patterns of natural structures such as leaves, shells, trees, and bones.

Pattern recognition is the second level of translation (applied for design experiments in this study). At this level, a more general approach is used, which includes recognizing patterns and identifying principles and ways of solving biological problems. Many successful engineering solutions use simple and apparent principles from nature, such as structural hierarchy or the case of tensioned structures, where stress concentrations are eliminated thanks to their shape. The essence of this approach is in recognizing, solving, and eliminating problems. The scale of the problem can vary. At the nanometre-to-millimetre scale, observations equate to material synthesis; observations on the millimetre-to-meter scale are applied to objects, structures, and mechanisms; and at the level of a kilometre and more, populations and ecosystems are considered.

The third translation level is based on the TRIZ, a system developed for innovative engineering problem-solving. At this level, patterns are more abstract, and problems are defined within a narrow framework. The process consists of three steps: first, it is important to picture the ideal outcome without regard to the technological requirements needed to achieve it; second, express that outcome through the functional requirements necessary to produce it; and third, create a list of all the resources that are currently available.

Biological patterns are a frequent inspiration for the conception of generative systems in architectural design. Generative systems can be ordered (sets, symmetries, trees, tessellations, number sequences, the golden ratio, spirals), disordered (systems based on chaos, randomization, stochastics), and complex. Complex systems that represent a mixture of order and disorder function similarly to biological systems that are the inspiration and basis for their creation.

A complex system is any system that includes a large number of interacting components, agents, or processes. The overall activity of the complex system is non-linear. They are emergent and adaptable. Components, or building blocks of complex systems, can also be complex systems. Usually, complex systems are in the field of thermodynamic gradients and are characterized by energy dissipation. These systems are not in energy equilibrium but can be stable despite that.

The process of development in nature inevitably leads to complexities. Simple building units achieve hierarchical complexity in nature by economic means. For example, DNA coding of all natural forms is achieved using only four nucleotides, which use only twenty triplets to specify amino acids, producing proteins that construct hierarchically structured organisms. Also, the entire spectrum of specific properties of biomaterials is achieved using two polymers (proteins and polysaccharides) and several additives.

The previous supports the thesis that simple rules can generate the properties of emergence and seemingly non-deterministic behaviour. A set of small actions starts the process, and combined with other small actions, it works until a recognizable global pattern of behaviour appears. When a certain critical limit of complexity is reached, organisms gain the ability to self-organize and self-reproduce in countless ways, producing not only equally complex but also more complex entities from themselves.

Bio-inspired computing in design

Computer models are used in pattern formation studies to replicate various patterns. Some computer systems used to model complex systems are L-systems, Fermat Spiral (Vogels Sunflower), Phyllotaxis, Reaction-Diffusion Systems, Diffusion-Limited Aggregation (Drunken Man Algorithm), Evolutionary Computing, Neural Networks, Cellular Automata (CA), Artificial Life, and Swarm Behaviour. Applications of these simulations as generative systems in architectural design result in objects whose forms are not perceived as fixed entities but as reactive structures. These semi-organic objects behave, in a certain way, like living organisms.

The use of computer algorithms in design goes beyond the traditional CAD paradigms. By developing automated systems that anticipate conditions and respond to their requirements, computational algorithms more effectively utilize the potential of computers when generating design solutions on an interactive basis. Automated computational systems are most often used in GD processes. A computer-generated design is based on an algorithmically determined system of rules (program instructions). In this process, the human designer allows a generative computer system to participate in decision-making and the designation of the final designs, maintaining the position of the one who decides the rules.

GD discourse is inspired by instability and complexity, while methods applied in the design process are rooted in modelling the systems' dynamics. Darwin's theory of evolution also suggested a shift away from Newton's paradigm of stability and toward more recent research (e.g., by Ilya Prigogine) on instability, the phenomenon of small changes in initial states that result in significant amplification of the effects of change. On the other hand, the development process inevitably leads to complexities. According to Sodu, GD is a morphogenetic process that employs non-linear algorithms to build an endless number of unique, non-repeatable outcomes that, like in nature, are produced by idea code.[47] An example is generative schemes that use evolutionary algorithms (EA) to create variations.

Unlike the conventional approach in which the relationship between the subject (designer) and the object is most direct, the GD process involves creating a generative system (production means or exploratory construct) that mediates the creation of the object. In such a setting, the essence is mastering the relationship between the design object, rules (specifications), and conditions (constraints).

Usually, the GD process includes the development of a project diagram, a vehicle for creating variations development, and a means for selecting the desired results. Without the intention of linearizing, the process generally has two stages. The first stage includes a definition of the problem, the formulation of a set of rules, conditions, and restrictions relevant to searching for solutions and their transformation into an exploratory system/construct that, in the second stage, is used for design explorations and the production of solutions.

Some computational design tools that simulate the growth and development of architectonic structures and find optimal solutions include *Gener8* – an interactive tool for a surface generation that integrates growth and evolutionary search using EA and L-systems[48] ; *MoSS* (Morphogenetic Surface Structure) – a modelling tool based on the L-system[49] ; *AgencyGP* – a tool for designing non-hierarchical organizations[50] ; programme by Broughton et al. that uses L-systems[51].

Creation of tools for design exploration has been realized using scripting (e.g., *AutoLisp, Rhinoscript, Scriptographer*), classical program editors (e.g., *Processing, Fluxus, openFrameworks, Visual Basic, Phyton, C#*), or graphical program editors (e.g., *Max/Msp, Pure Data, Isidora, Grasshopper, Dynamo*). However, the widely used visual editor for the *Rhinoceros* 3D CAD system, *Grasshopper*, currently stands out due to the widespread usage of parametric tools, graphical programming, and the community formed around it.

Grasshopper offers components for generating tessellations, including 2D and 3D Voronoi diagrams, meshes, and meta-balls. Besides David Rutten's *Galapagos* evolutionary solver[52], a standard component in *Grasshopper*, various plugins that implement bio algorithms are developed, some of which are listed in *Table 1*. Also, the *Anemon* plugin by Mateusz Zwierzyski[53] enables the creation of loops in *Grasshopper* and could be used differently. For example, it could be applied to create irregular growth patterns based on L-systems using recursive functions. Finally, Daniel Piker's *Kangaroo physics*[54] plugin could simulate diverse physical processes.

Integrating parametric and simulation tools into the design process has encouraged new rhetoric, allowing objective external information to determine the values that generate design solutions. Leach[84] believes that using performance as input in an architectural design opens the door to a new paradigm and that this approach to design *challenges the top-down hegemony of the form-making process by replacing it with a bottom-up logic of form-finding*.

Plugin	Author	Description
Rabbit[55]	Morphocode	Simulates diverse biological and physical processes, including L-systems and CA
Phyllomachine[56]	Daniel González	Simulates development processes based on the principle of phyllotaxis
Leaf[57]	Sadiwali	L-system engine
Fractal[58]	ARPM Design and Research	Allows creation of 3 different types of mathematically generated fractals derived from Fermat Spiral and Diffusion Limited Aggregation
Parkeet[59]	Parakeet3d	Generates geometrical and natural patterns/tessellations
Armadillo[60]	Dig.Tools	Generates arrays and tessellations
Starfish[61]	Michael Weizmann	Generates various patterns, mostly 2D tessellations
Bullant[62]	GeometryGym	Generates minimal surfaces, symmetry automation, tessellation (polygon packing), geodesic domes
Voronax_GH[63]	Programming Architecture	Generates Voronax, a structure obtained by relaxation of the Voronoi diagram over a free-form surface
Millipede[64]	Panagiotis Michalatos	Contains components that generate iso-surfaces and minimal surfaces
Minimal Surface Creator[65]	Cerver	Generates minimal surfaces from boundary curves or performs minimal relaxation on a mesh
Dragon-Turtle[66]	Cryptid	Has a turtle drawer, that allows for L-systems to be drawn with a series of predefined character relationships
Kthulhucat[67]	Willtao	CA engine
Goat[68]	Simon	Evolutionary solver
Octopus[69]	Robert Vierlinger	Performs Multi-Objective Evolutionary Optimization introducing Pareto-Principle for Multiple Goals, Backpropagation Neural Nets, and CPPN-HyeprNEAT
Biomorpher[70]	John Harding	Implements interactive EAs, enabling designers to engage with the process of evolutionary development
Oppsum[71]	Opossum Support	Optimization solver with surrogate models
Quelea[72]	Ixfschr	Simulates physical processes – the behaviour of complex systems composed of agents
Boid Library[73]	Jan Pernecky	Swarm behaviour library
Nursery[74]	Gwyllo	Simulates CA and Boid systems and can be used for agent-based modelling
Nuclei[75]	Madalin Gheorghe	Simulates particle behaviour ant their environment
Silvereye[76]	Silvereye	Particle Swarm Optimization (PSO) algorithm, a member of the Swarm Intelligence family of methods
Physarealm[77]	Maajor	Enables agent-based modelling based on Physarum Polycephalum algorithms (similar to ant colony algorithm)
Antoni[78]	Sepehr Beyhaghi	Simulation and optimization of ant colony system
Crispercas9[79]	Sepehr Beyhaghi	Combination of Genetic Algorithm-Ant colony-Particle swarm
Crow[80]	Pennjamin	Artificial Neural Networks
Dodo[81]	Lorenzo Greco	Collection of components for machine learning, optimization, and geometry manipulation, inter alia it includes neural networks and swarm optimization
LinchBox and *LunchBox ML*[82]	Nathan Miller	Generates diverse tessellations and includes machine learning components for regression, clustering, and neural networks
Wasp++[83]	Blake Hageman	Generates aggregations enabling deterministic control of aggregation patterns and hierarchical systems (based on L-Systems) and recursions

TABLE 1: Plugins that simulate biological patterns *Grasshopper*

Emphasizing the benefits of introducing top-down objectivity into the design process, Menges[85] writes that *finding form externalizes the relationship between the process of formation, the driving information, and the resulting form*.

On the other hand, Kilian[86] notices that the expression of design intent is moved from literally giving form to the specification of contextual parameters, initial conditions, and the optimization system itself. It is this definition of the relationships between the input data, the exploratory system, and the evaluation of the final product that quite precisely describes the design process in which the form-finding approach is applied. However, the claims related to the effects of introducing bottom-up objectivity into the design process are exaggerated at the moment and, in some way, camouflage the numerous and complex decisions and the choices that must be made in the design process.

The algorithmic implementation of generative systems has opened a debate about whether the application of this approach can be considered a design process. Krish[87] finds that GD is the conversion of computational energy into creative, exploratory energy that helps human designers explore various design possibilities under the influence of modifiable constraints. GD is an unconventional design approach, given that the digital media used for production have a critical generative capacity and that the forms produced in this way result from dynamic processes that are unique in their response to the set conditions.

The function of generative systems, in a certain way, exceeds the role of tools, especially in the sense that they actively participate in the creation of designs and, in some way, shape the designer's thinking process. In certain aspects, the system assumes the role of a designer, but the initial step of forming a construct (generative system) relies on the designer's abilities – intuition, perception, analogy, and imagination, which traditionally represent the driving force of architectural ideas. Finally, GD should not be understood as an autonomous direction within architecture since it does not address the content but primarily refers to the techniques used in the creative process.

3. DESIGN EXPERIMENTS

The application of bio-inspired GD strategies can be summarized with three key concepts: diagramming, collectivity, and evolution. Furthermore, it is possible to establish a relation between these concepts and concepts of representation, composition, and variation (*Figure 3*), which could be further translated into design aspects.[88] Nevertheless, it should be noted that information is the basis for creating objects and that GD always involves the evolution of the underlying data.

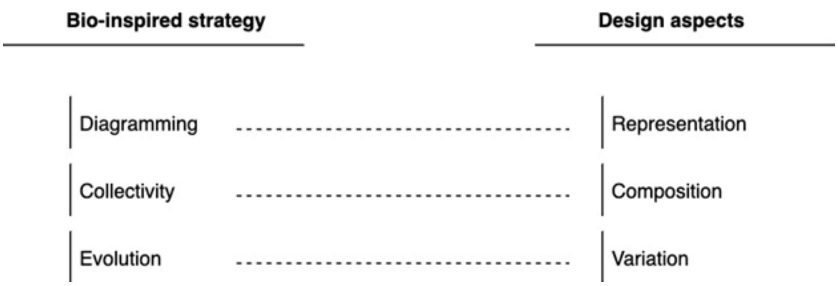


FIGURE 3: Mapping bio-inspired strategies into design aspects

The previous hypothesis was tested through six design experiments using the following bio-inspired patterns: L-Systems, Zoomorphism, Voronoi diagram, Swarming Behaviour, Phyllotaxis, and Cellular Automata (CA).

Method

In this study, research by design methodology was applied. The phases in the process, which are typical for GD discourse, include specification of design intentions, requirements, and constraints, generative system development, design exploration, and design selection. In addition, the pre-GD stage in this research also includes biological phenomenon analysis. The applied design process is based on GD for architecture workflow by Villaggi and Nagy[89] and illustrated in *Figure 4*. However, it must be emphasized that the design process is not linear, and these phases are not implemented sequentially.

The goal of analysing a particular biological phenomenon is to identify design potentials that might be turned into design aspects. The result of this phase is an abstracted pattern that describes the functionality of the analysed biological system and will be further exploited in developing a generative system.

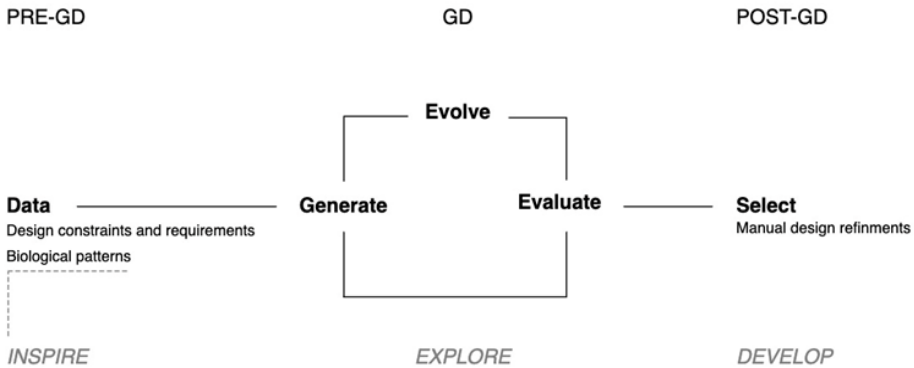


FIGURE 4:
Representation of the GD process based on the workflow proposed by Vilaggi and Nagy[90]

Within the phase of generative system creation, the task was to define the design procedure – an algorithm based on the bio-inspired pattern. The algorithm was then implemented using *Grasshopper*, a visual programming editor. Custom *Grasshopper* definitions, developed for every design situation, drove parametric design explorations within the *Rhinoceros* CAD environment. Parametric modelling facilitated the fast production of design alternatives.

Given that the applied GD approach is based on the interaction of the designer and the computer, a dynamic context for form exploration, interpretation, and decision-making was built using various objective and subjective information. In this setting, the bottom-up design gradually emerged during the iterative process by manipulating parameters, modifying and improving parametric settings, and human-designer interventions. Although computational tools drove the process of design alternatives production, the designer's creativity, intuition, knowledge, and experience controlled the entire process, from problem abstraction, through explorations, to the selection of the design alternative suitable and interesting for further development. On the other hand, using autonomous computational methods in the design process enabled the avoidance of preconceived solutions and psychological inertia due to the designers' finite experience and the emergence of unanticipated design outcomes. Furthermore, applied design methodology offered varying nature-like designs confirming that the forms derived from the process informed by bio-inspired patterns could be functional, structurally rational, and aesthetically pleasing.

4. RESULTS AND DISCUSSIONS

Figure 5 summarizes design experiments performed in order to test the design hypothesis.

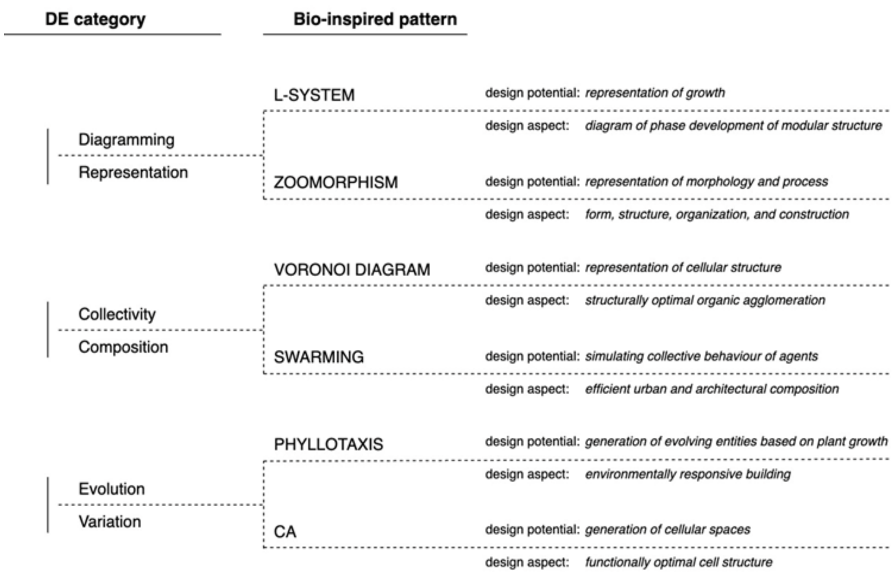


FIGURE 5: Design research overview

Design experiments: Diagramming/Representation

The first example tests the application of diagramming strategy in the design of modular architectonic structures with the prospect of growth and extension through the phase construction. The growth pattern of biological entities was seen as design potential for representing the phase development of an architectonic structure. Therefore, the growth pattern represented by L-systems was used in creating of the design exploration system.

L-systems is a parallel rewriting system developed by biologist Aristid Lindenmayer in 1968 as a result of his studies of the development of simple multicellular organisms, including yeast, filamentous fungi, and the growth pattern of various types of bacteria.[91] The system was later extended to describe higher plants and complex branching structures. L-system represents an example of formal grammar that consists of a set of production rules, an alphabet of symbols that may be used to create strings, a starting “axiom” string from which to build, and a method for turning the generated strings into geometric shapes.[92]

It was created to describe how simple organisms develop formally and to illustrate the neighbourhood relations between plant cells. The L-system applications include modelling plant development's growth processes, describing the plant cells' behaviour, modelling the morphology of various organisms, and generating self-similar fractals.[93] Some non-biological application of L-systems was examined by Goel and Rozenhal[94], while Hansmeyer[95] focuses on architectural application.

In the example, the L-system pattern was used to explore the design of modular architectonic structures' layouts. The capacity of the L-system to describe growth patterns was exploited to represent the principle underlying phase construction of the structure. The algorithm was implemented using Morphocode's plugin *Rabbit* for *Grasshopper*.[96] The developed *Grasshopper* definition included components that facilitate the generation of recursive 2D patterns, which are then interpreted three-dimensionally in terms of the space frame. This definition generates patterns from the input string, a rule definition, and the number of generations. Also, parametric input could be assigned to the angle in composition. Several input strings and rules were used to generate patterns before the decision of the most suitable based on aesthetical and functional qualities (*Figure 6*).

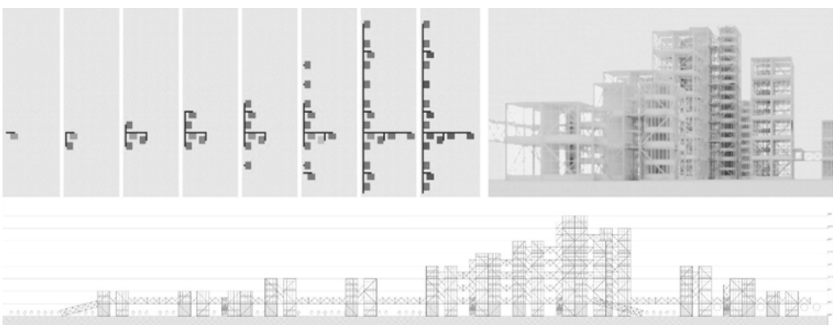


FIGURE 6: Design exploration using L-Systems
(Studio M01–Spatial Structures: Synergetic patterns, class student Karlo Mihalus Dianovski, University of Belgrade – Faculty of Architecture, 2019)

In the following example of the diagramming/representation strategy, zoomorphism was used for formal, structural, functional/organizational design aspects and the construction process. The application of zoomorphism in architecture was discussed in several publications.[97,98,99]

Inspiration for the design was driven by *Arthropoda*, a class of invertebrate animals that have an exoskeleton and a morphologically clear, heteronomous body segmentation. The exoskeleton of these animals serves not only as protection but also as a surface for the attachment of muscles. In addition, this waterproof membrane protects against desiccation and provides a sense of interaction with the environment. The architectural intention was to transform qualities of the exoskeleton, segmentation, and environmental responsiveness to design aspects of a research center building. These qualities were architecturally interpreted by forming a building envelope made of rigid spatial structure (exoskeleton) and environmentally responsive soft fiber-reinforced membrane. The organic aesthetic of the structure was additionally achieved by segmentation (*Figure 7*).

The design was generated by a definition that uses components of several *Grasshopper* plugins. Applied plugins include *Exoskeleton*,[100] a plugin that transforms a network of connected lines into wireframe mesh by creating rounded nodes using the principle of the convex hull of a set of X points in Euclidian space. For finding convex hull Gift wrapping/the Jarvis March algorithm was applied. Also, a component that implements the Catmull-Clark algorithm, *WbCatmullClark* of the mashing plugin *Weaverbird*,[101] was used to refine the edges and curves of the generated mesh. Finally, due to the functional/organizational requirements, the building was divided into three segments using the custom Grasshopper C# component.

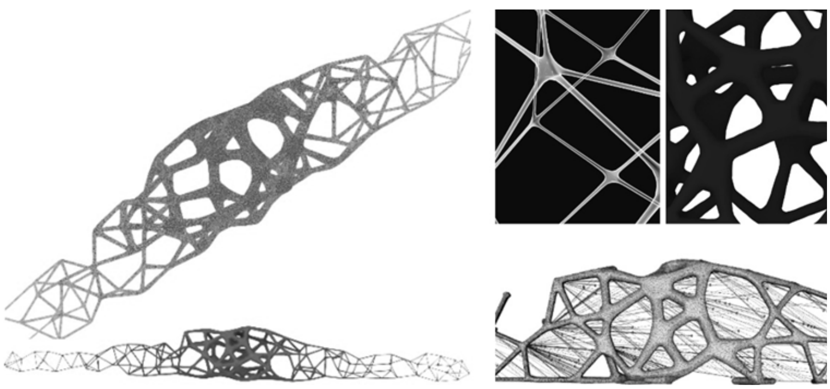


FIGURE 7: Design exploration using zoomorphism
(Studio M01–Spatial Structures: Synergetic patterns, class student Isidora Zimović, University of Belgrade – Faculty of Architecture, 2020)

For generating fiber patterns in the reinforced membrane Agent component of the *Quelea*[102] plugin for agent-based modelling was applied. This part of the code simulates a specific construction process – the waving of threads by a swarm of small robots that can move on both horizontal and vertical surfaces. Similarly to the spider's web weaving process, these robots would densely weave and intertwine the layers of fibers and harden them with special glues. Previous was realized by giving small robots, represented by "agents" in a simulation, a certain intensity of force and behavior patterns, which then form threads, i.e., carbon fibers on the membrane (*Figure 7*).

Design experiments: Collectivity/Composition

The application of collectivity/composition was tested by designing an organic architectonic agglomeration composed of cells representing vertical urban gardens. The design ambition was to create a spatial structure that would retain the optimality and organicity of biological structures such as cells and bone microstructure. The Voronoi diagram was applied to model the nature-like structure. This geometric tool facilitates understanding the physical constraints that drive the organization of biological tissues.

Voronoi tessellation is a partition of a geometric entity into regions close to each given set of objects. In the simplest case, these objects are just a finite number of points in the plane/body and are called seeds/sites/generators. Each seed has a corresponding region, called the Voronoi cell, consisting of all points of the plane/body closer to that seed than any other.[103] The Voronoi diagram has application in crystallography, a science of determining the arrangement of atoms in crystalline solids. The pattern is also differently applied in architectural design.[104,105,106]

The algorithm that enables the partition of the design domain (the cubic volume) into cells (polyhedrons) around a randomly generated set of points (Voronoi seeds) was implemented using a standard *Grasshopper* component for generating Voronoi tessellation in 3D. However, in order to satisfy the building's functional requirements, an additional part of the code for generating ortho Voronoi cells was written. Numerous aggregations produced by the code were first narrowed by using subjective aesthetic criteria, and then on selected designs, structural analysis was performed using Finite Element Analysis (FEA) plugin *Millipede*.[107] This enabled informing the decision-making process with the structural performance of aggregations. The outcome is a composition that resulted from gradual adjustments based on functional, aesthetical, and structural requirements (*Figure 8*).

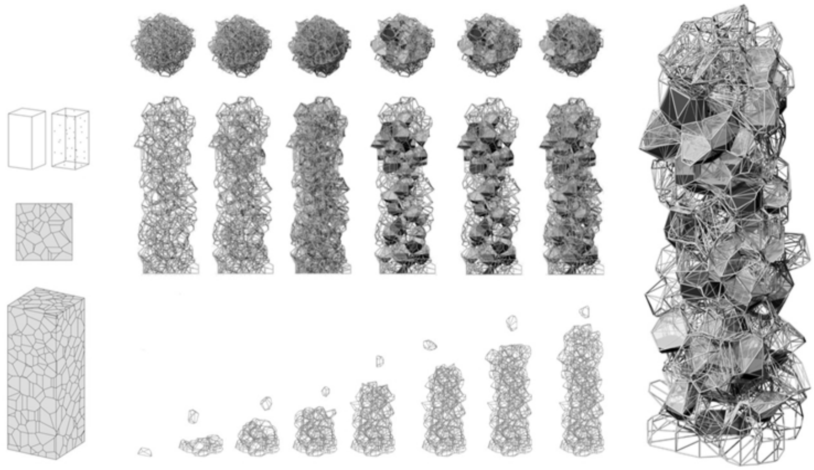
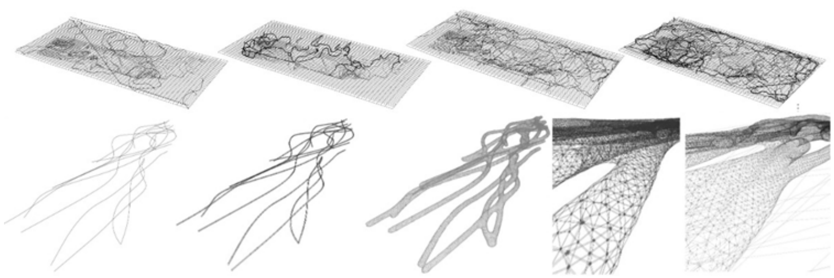


FIGURE 8: Design exploration using a 3D orthogonal Voronoi diagram
(Studio M01–Spatial Structures: Synergetic patterns, class student Irina Žerađanin, University of Belgrade – Faculty of Architecture, 2019)

FIGURE 9: Design exploration using a swarming pattern
(Studio M01–Spatial Structures: Synergetic patterns, class student Isidora Kojović, University of Belgrade – Faculty of Architecture, 2019)



In another example, the application of collectivity–composition was tested using the swarming, collective behaviour of diverse entities, particularly animals, of similar sizes, which aggregate together to generate the urbanistic and architectural design. From a more abstract point of view, swarm behaviour is the collective motion of many self-propelled entities. From the perspective of the mathematical modeller, it is an emergent behaviour arising from simple rules that individuals follow and do not involve any central coordination. Active matter physicists also study swarm behaviour as a phenomenon that is not in thermodynamic equilibrium and, as such, requires the development of tools beyond those available from the statistical physics of systems in thermodynamic equilibrium.

Agent-based modelling is a rule-based computational modelling methodology that focuses on rules and interactions among the individual components or the agents of the system. This modelling method aims to generate a population of the system components and simulate their interactions in a virtual world. Agent-based models start with rules for behaviour and seek to reconstruct the observed patterns of behaviour through the computational instantiation of those behavioural rules. The application of agent-based modelling in architectural design was the subject of various studies.[108,109,110,111]

To conduct design research computational algorithm using *Quelea*,[112] a plugin that simulates the behaviour of complex systems was developed. The program simulates simple agents (geometrically represented by points) that are allowed to move according to a set of basic rules. Trajectories describing particle motions in the post-GD phase were translated into architectonic structures (*Figure 9*). Agent-based design approach facilitated to embed in the architecture of several characteristics of biological agent models, such as modularity, emergence, abstraction, and stochasticity. The rules of its agents define the modular behaviour of an agent-based model. Existing agent rules can be modified, or new agents can be added without modifying the entire model. Emergent properties are exhibited through individual agents that interact locally with rules of behaviour. Agent-based models result in a synergy that leads to a higher-level whole with much more complex behaviour than each agent. Abstraction is exhibited by excluding non-essential details and simplification, while stochasticity is manifested through the system's behaviour that appears to be random.

Design experiments: Evolution/Variation

The evolution/variation was explored by designing a vertical garden for food growth in greenfield urban areas. The design intention was to create a tower that would embody plant growth and enable optimal sunlight. The phyllotaxis phenomenon was appropriated in this example to create a GD explorer.

From the physical perspective, spirals are the lowest-energy configuration that emerges through the self-organization process in dynamic systems. From a chemical perspective, a reaction-diffusion process that includes both activation and inhibition can produce a spiral. From a biological perspective, arranging leaves as far apart as possible in any given space is favoured by natural selection as it maximises access to resources, especially sunlight, for photosynthesis. The application of phyllotaxis pattern in architecture was the subject of several studies.[113,114,115,116]

Phyllotaxis, appropriated from botany, is related to the spiral arrangement of leaves on a plant stem. Botanists define the phyllotactic range as part of the circle through which a new leaf rotates from an older one. In a repeating spiral, the rotational angle from the leaf to the leaf can be represented by a fraction of a full rotation around the steam. The divergence angle is set based on two assumptions. First, the plants have an infinite number of leaves; second, maximum sun exposure is the only factor determining the leaf's position. Although this is not entirely true, the standard angle in nature is 137.5 degrees, or 1/phi, approximately 0.618. The numerator and denominator usually consist of a Fibonacci number and its second successor.[117] Also, a growth spiral can be viewed as a special instance of self-similarity from the perspective of the contemporary fractal construct.

For simulating phyllotaxis, the plugin *PhylloMachine*[118] was used. *Grasshopper* definition produced mesh with phyllotaxis proportions that have a topology described by two Fibonacci numbers. A simple number sequence describes mesh topology (indices of vertices of faces, parastichies spirals, cycles, and topological neighbours) without geometric calculation. This parametric definition aided design exploration and production of a range of formal solutions by varying parameters of the mesh geometry, including height, radius, division, smoothness, angle, and depth. The result of design exploration is a variety of cellular meshes in architectural terms interpreted as the building's exoskeleton (*Figure 10*).

Besides aesthetics, building performance related to the insolation necessary for plant growth was used in the process of design selection. Insolation as objective criteria, informed decision-making process ensuring the functionality of the design. This approach facilitated the design to evolve towards a solution that has better environmental responsiveness. The environmental analysis was performed using the plugin *Ladybug*.[119] The outcome of this design experiment is a structure that was a result of variation and gradual adjustments based on performance and aesthetical demands proposal.

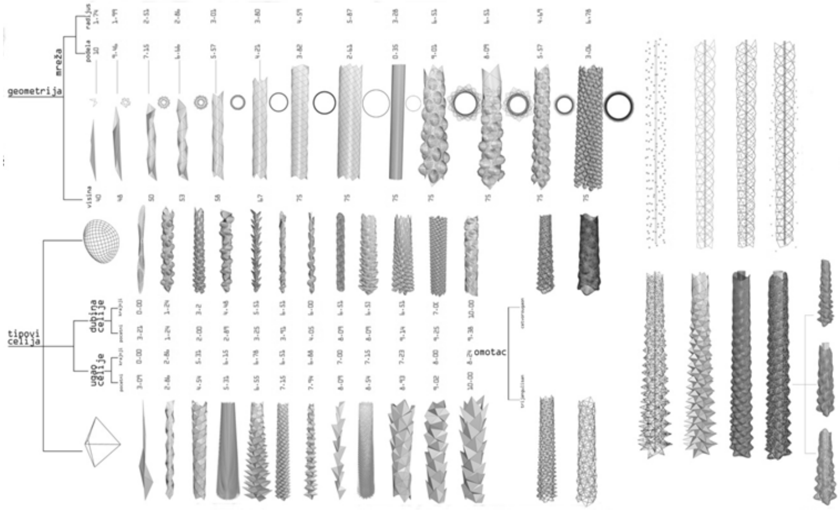


FIGURE 10: Design exploration using phyllotaxis pattern
(Studio M01–Spatial Structures: Synergetic patterns, class student Teodora Marić, University of Belgrade – Faculty of Architecture, 2019)

In the last example, evolution/variation was also explored by designing vertical modular cell structures for food production. The phenomenon that inspired design was nature's morphogenetic process of pattern formation. Pattern formation in developmental biology is a process through which essentially similar cells in a developing tissue in an embryo take on complex forms and functions. In nature, pattern formation is genetically determined, and each cell in a field senses and reacts to its position along a morphogen gradient during pattern development. Short-distance cell-to-cell communication via cell signalling is then used to refine the initial pattern. To simulate this process, CA as a conceptual form generator was applied. This system was used to facilitate the exploration of volumetric spatial configuration features and to indicate levels of natural lightning using cell states.

Originally developed in the 1940s by Stanislaw Ulam and John von Neumann, CA is a tessellation automata. A CA consists of a regular finite-dimensional grid of cells, each of a finite number of states, such as on and off. A set of cells called neighbourhood is defined relative to the specified cell for each cell. An initial state (time t=0) is selected by assigning a state for each cell. Then, a new generation is created (advancing t by 1) according to some fixed rule (generally, a mathematical function) that determines the new state of each cell in terms of the current state of the cell and the state in its neighbourhood.

Typically, the rule for updating the state of cells is the same for each cell and does not change over time, and is applied to the whole grid simultaneously. However, exceptions are known, such as the stochastic cellular and asynchronous cellular automata. It was not until the 1970s and Conway's Game of Life, a two-dimensional CA, that interest in the subject expanded beyond academia. Then, in the 1980s, Stephen Wolfram engaged in a systematic study on one-dimensional elementary, CA. His research assisted Matthew Cook in showing that one of these rules is Turing-complete. The application of CA in architectural design was presented in several studies.[120,121,122,123]

In order to use CA for open-ended design exploration, a tool that generates 3D compositions was developed using Morphocode's plugin *Rabbit*.[124] An elemental unit/cell architecturally is interpreted as a functional unit – a room/garden. The generative tool enabled to exploration of variations of possible solutions resulting from the tempo-spatial development of initial cell configuration over time (*Figure 11*).

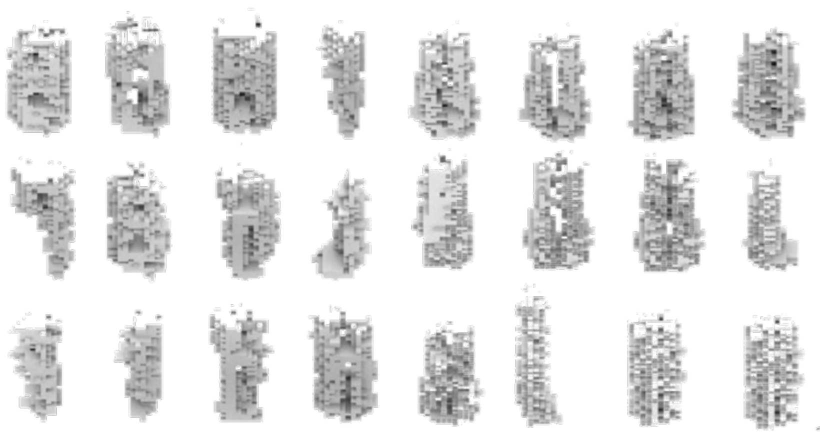


FIGURE 11: Design exploration using CA
(Studio M01–Spatial Structures: Synergetic patterns, class student Katarina Petrović, University of Belgrade – Faculty of Architecture, 2019)

During the generative system creation, in all presented examples, much work was dedicated to analysing and describing the underlying biological phenomenon. Applied CAD system enabled constraint-based modelling in which every element may be connected using parameters, relationships, and references. Parametrization facilitated fast and easy manipulation and changes.

Also, the choice of adequate design methods and tools that will not disturb the nature of the creative process was important—selecting program modules, creating costume codes, and extending tools to fit architectural requirements and provide a design exploration environment that is flexible and enables fast production of alternative solutions characteristic for the initial phase of the design process. Additionally, design generation and performance analysis within a parametric CAD environment have proven to be effective in facilitating fast and easy changes, control of the from-finding of complex geometry, the emergence of various designs, and evolution towards effective solutions in the iterative design process.

On the other hand, GD activities needed a precise definition of the problem to solve to accurately understand the relation, flow, and performances of obtained designs. The lack of predetermined shapes prevents designers from striving for predefined solutions and limitations they could introduce in the exploration process. Instead, interactive manipulation of parameters produced diverse shapes, enabling relatively fast exploration. Complex designs created by bio-inspired patterns are valued for their spatial features in architectural design and for the outcomes' frequent unpredictability or unexpectedness, allowing designers to expand their imagination boundaries. In this set, the design results from the adequate combination of parameters, and the task of the designer, positioned between soft control and management, is to define sets of parametric relations. Results are figurations that closely build different relations within its environment.

5. CONCLUSION

The study shows how bio-inspired patterns might be used as a design driver for the conceptual design of architectural structures. Computational technologies enable the implementation of diverse, complex systems based on biological phenomena that can direct the GD process toward producing exciting proposals. Furthermore, bio-inspired patterns should not only be seen as a method to intensify the form of architectural structures but also as a method to improve performance.

Design situations presented in this paper test distinctive principles of applying bio-inspired strategies – mapping/representation, collectiveness/composition, and evolution/variation. The design process in all cases involved exploration of the biological phenomenon, formulation of design inputs, employment of a design exploration system, and evaluation of the end products.

In all cases, design is created through designer–machine interaction, which drives digital parametric modelling. Design explorations and improvements are based on simulation feedback and the designer's explicit decisions and modifications grounded in experience, perception, or intuition.

Like in all generative processes, the final form was not predetermined, but the design evolved during the exploration phase under the control of an algorithm with a certain degree of autonomy. Diverse shapes could be created by interactive parameter manipulation, allowing for relatively fast exploration. In the applied generative framework, computational tools are restricted to specific tasks. At the same time, designers consider different design requirements and choose a design (out of the range of solutions) that best fits various aspects and is interesting for further development.

Further research could include explorations by applying other bio-inspired patterns and possibilities of further design automation. For example, optimization algorithms could be introduced to automate the search process. Finally, bio-inspired design is an interdisciplinary field, and the development of co-design and co-fabrication strategies based on the collaboration of diverse disciplines and the inclusion of diverse knowledge and expertise in the design and construction processes is another research direction.

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