From Genome to Form: A Biomimetic Installation in Motion

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Abstract: The intersection of biology and architecture has become increasingly relevant in the context of sustainability, technological integration, and the search for adaptive and intelligent systems within the built environment. Biomimetics offers a powerful framework for translating the functions and processes of natural organisms into design solutions that can enhance architectural performance (Benyus, 1997). However, while formal analogies with nature have been well explored, there remains a gap in applying biological regulatory systems—such as genetic networks—as direct models for spatial and behavioural design.

This article addresses that gap by examining *Musical Morphogenesis*, a biomimetic and interactive installation developed between 2014 and 2017. The project is centred on the gene regulatory network of Arabidopsis thaliana, a well-studied model organism in plant biology (Meyerowitz, 1997). The research investigates how computational simulations of gene activation patterns can inform the development of kinetic architectural systems capable of self-organization, responsiveness, and expressive interaction.
The primary aim of this research is to explore how architectural elements can embody the logic of genetic development, transforming molecular pathways into motion, light, and sound. The study is driven by the question: How can gene regulatory networks be translated into performative, interactive spatial systems that reflect biological complexity?

To answer this, the project integrates a Boolean logic-based gene model into a physical structure composed of CNC-fabricated components, pneumatic actuators, LED lighting, and an interactive touchscreen interface. The methodology involves interdisciplinary collaboration across architecture, computational biology, engineering, and music composition, resulting in a system where user interactions can influence developmental pathways and trigger morphological changes in real time.

The key contribution of this work lies in its demonstration that biological computation can serve not only as inspiration but as a functional blueprint for architectural design. By making genetic dynamics tangible and interactive, *Musical Morphogenesis* presents a novel approach to biomimetic design that bridges scientific modelling and spatial expression within the broader framework of biodigital architecture.

1. Introduction and Context: Biomimicry in the Age of Biodigital Architecture

Biomimetics—the practice of deriving design strategies by emulating natural systems and processes (Benyus, 1997)—has become a cornerstone of contemporary biodigital architecture. As architects, engineers, and designers increasingly turn to biology, the focus has shifted beyond mere formal replication toward deeper integrations of functional systems and generative logics (Gruber, 2011). This paradigm evolution reflects a move from mimicking static biological forms to engaging with dynamic, behaviour-driven, and ecologically interdependent processes (Oliveira, 2020). Contributions to this trajectory include Peter Pearce's Structure in Nature is a Strategy for Design, which introduces the "minimum inventory/maximum diversity" principle—a combinatorial system in which simple modular components yield a wide range of complex forms (Pearce, 1978). This framework anticipates genetic regulatory networks; wherein minor input variations can result in vastly different outcomes.

The Eden Project (2001), designed by Grimshaw Architects, exemplifies this approach through its geodesic dome structures inspired by soap bubbles and dragonfly wings. These domes house climate-controlled biomes and are engineered for lightweight efficiency and modular adaptability. The project stands as a compelling example of how biomimetic principles can inform not only structural logic but also material economy and environmental performance. In a more radical shift toward responsiveness and interactivity, Philip Beesley's Hylozoic Soil (2007) integrates microcontrollers, capacitive sensors, and shape-memory alloys to create an immersive, reactive environment that blurs the line between the living and the artificial (Beesley et al., 2010). This installation signals a broader movement toward kinetic, environmental, and sentient architectures. Projects like Bloom (2012) by Doris Sung—featuring thermobimetal materials that respond to heat without electronics (Sung, 2012)—and HygroSkin (2013) by Achim Menges and ICD Stuttgart—using humidity-sensitive material for passive adaptation (Menges & Reichert, 2012)—continue this trajectory. While not explicitly rooted in genetic logic, these works demonstrate the potency of biologically grounded systems in shaping architectural behaviour and responsiveness.

Musical Morphogenesis enters this conversation with a distinct proposition: it does not merely take inspiration from biological forms or materials but instead simulates the organizational and developmental logics of a living organism. Specifically, it engages with gene regulatory networks, using computational biology as the foundation for its spatial, kinetic, and auditory responses (Oliveira et al., 2017). In doing so, it marks a transition from bio-inspired to bio-computational design, where architecture is not just informed by biology but structured by its internal generative processes. This shift from formal mimicry to algorithmic simulation is echoed in works such as the Silk Pavilion (Oxman et al., 2013) by the MIT Media Lab and the Elytra Filament Pavilion (ICD/ITKE, 2016). These projects integrate robotic fabrication and biological behaviour to create structures that evolve through fabrication processes. Yet, they stop short of simulating the complex, rule-based logic of biological development that defines Musical Morphogenesis. Earlier precedents like Jean Nouvel's Institute du Monde Arabe (1987) also introduced kinetic responsiveness, notably through its mechanical mashrabiya-inspired façade. Although pioneering in its time, it remains rooted in deterministic mechanical behaviour, lacking the internal feedback and self-organization emblematic of biological systems.

What distinguishes Musical Morphogenesis is its architectural embodiment of genetic computation. The structure evolves in response to user-defined gene activations, not merely reacting to environmental inputs but manifesting a self-organizing logic. It occupies a hybrid space between architecture and biology—part spatial construct, part computational experiment—thus contributing a new model for biodigital design. Rather than simply responding, it develops and transforms, positioning itself within an emergent field of architecture that seeks to evolve, adapt, and perform through biological principles encoded in digital systems.

2. Biological Foundation: The *Arabidopsis Thaliana* Gene Regulatory Model

Arabidopsis thaliana (Figure 1), a small flowering plant native to Eurasia, is widely regarded as the “fruit fly” of plant biology (Meyerowitz, 1997). Its short life cycle, compact genome, and ease of genetic manipulation have made it the preeminent model organism for plant molecular biology and developmental genetics. It is particularly well-suited for studying gene regulatory networks (GRNs), which are complex systems of gene interactions that guide the organism's growth and organ formation (Davidson; Alon).

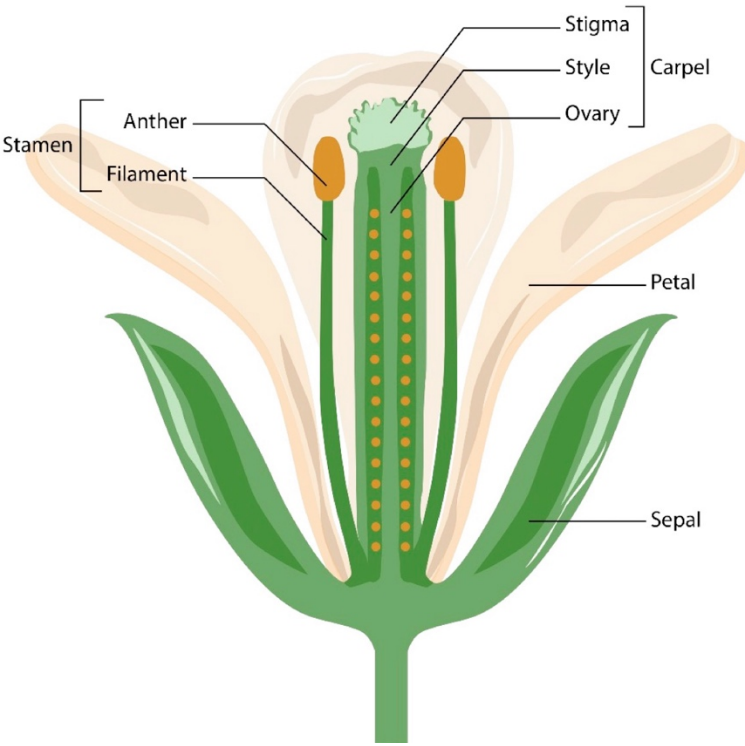

Figure 1. *Arabidopsis Thaliana*.

In *Musical Morphogenesis*, the developmental pathways of *Arabidopsis thaliana* were chosen for both their scientific richness and their architectural potential. The project simulates a GRN composed of fifteen genes responsible for the differentiation of the plant’s four key floral organs: sepals, petals, stamens, and carpels. Each gene is represented in the system as having one of two states—ON (active) or OFF (inactive)—as governed by a Boolean logic (Alon, 2006) model that captures key rules of genetic regulation.

These gene states interact over time, generating a sequence of developmental states that evolve into a stable configuration—known in systems biology as an attractor (Davidson, 2006). Each attractor corresponds to a specific organ identity. When the visitor interacts with the installation by turning genes on or off through the touchscreen interface, they simulate mutations or regulatory changes, thereby altering the developmental trajectory. This alters which floral organ is ultimately expressed in the physical structure, such as a petal, stamen, or carpel. This model is not a literal genetic simulator, but an abstracted behavioural system inspired by real biological principles. It bridges the informational structure of developmental biology with the logic of generative design in architecture. In the context of the installation, this model drives not only form but also behaviour: the motion of petals, the illumination of the carpel, and the composition of sound (Figure 2). By using the Arabidopsis network as a generative design system, the installation translates invisible biological computation into a multisensory spatial experience. The result is a highly adaptable and expressive form of architecture that mimics not the appearance, but the inner logic of living systems.

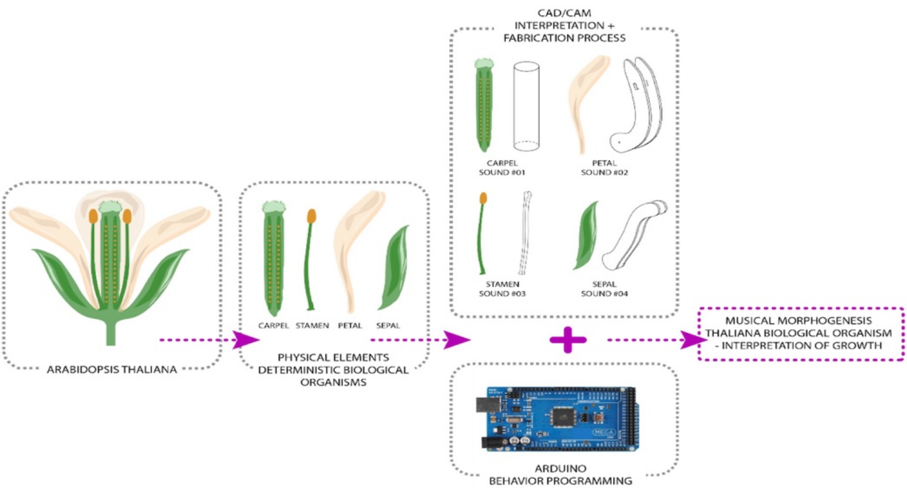

Figure 2. Strategic diagram of Musical Morphogenesis composition.

3. Translation Strategies: From Genetic Dynamics to Design Parameters

To transform the abstract logic of gene regulatory networks into an architectural experience (Dorin & McCormack, 2002), the musical morphogenesis design team developed a multi-layered strategy that combined biological modelling, material articulation, and sensory feedback. Each of the fifteen genes in the Arabidopsis thaliana network (Zeller and Luscombe, 2016) was mapped to specific behaviours in the installation - manifested through motion, lighting, and sound. The Boolean-based gene model was programmed into an interactive touchscreen interface. This interface allowed users to toggle gene states between ON and OFF, effectively simulating genetic mutations or environmental inputs. These changes would redirect the network's path toward a different developmental attractor, corresponding to one of the floral organs—petals, sepals, stamens, or carpel.

The architectural system responded in real-time. Pneumatic cylinders drove the kinetic movement of petals and sepals, opening or closing them in response to gene activation patterns. Stamen performed controlled pivoting motions, while the central carpel, rendered in translucent acrylic, pulsed with programmable light sequences governed by gene expression logic. The result was an immersive feedback system, where changes in gene logic became visibly and spatially embodied (Carpo, 2011).

Equally important was the auditory dimension: each gene was assigned a unique musical motif, composed to reflect its role in the developmental network. When activated, the gene's sound was triggered in harmony with its structural behaviour, creating a dynamic soundscape that evolved alongside the spatial changes. These motifs were layered, distorted, or resolved depending on the state of the system—effectively forming a "genetic symphony." This convergence of computational biology and interactive design resulted in a system that could evolve, perform, and express complex behaviour. The translation from biology to architecture was not symbolic but operational: *Musical Morphogenesis* enacted development, mutation, and emergence in a tangible, spatial language.

4. The Installation as a Biomimetic System and Technical Overview

Musical Morphogenesis was conceived not merely as a visual metaphor for a flower but as a fully integrated biomimetic system—an architectural construct that emulates the self-regulating and dynamic behaviour of living organisms (Oliveira et al., 2017). This immersive, interactive installation functioned as a synthetic organism whose components were informed by the logic of genetic networks, realized through cutting-edge fabrication, responsive mechanics, and computational control (Knippers & Speck, 2012; Badarnah & Kadri, 2015; Celani, 2012).

The physical structure (Figure 3) was developed using CNC-milled Valchromat MDF boards in various colors and thicknesses. Chosen for their expressive color range and machinability, Valchromat panels allowed for both visual clarity and efficient digital fabrication. The architectural body comprised eight black vertical structural pillars supporting five circular horizontal platforms, each representing a developmental stage of the Arabidopsis thaliana flower. These platforms housed the kinetic organs—twelve red petals, eight blue sepals, eight yellow stamens, and a central translucent acrylic carpel—each mapped to specific gene activations through a computational interface.

Figure 3. Musical Morphogenesis structure and color scheme.

Parametric modelling using Rhino and Grasshopper ensured geometric coherence, symmetry, and hierarchical control across components. Every element was designed for modularity, ease of assembly, and structural resilience, essential for repeated exhibition in varied venues (Burry, 2011).

Kinetics were central to the installation's expressive power (Figure 4). Petals and sepals executed opening and closing movements via compressed-air cylinders connected to solenoid valves. These motions were programmed to respond dynamically to gene expression patterns selected by users. Stamens performed delicate, tilting gestures through linear actuators, while the carpel emitted color changes controlled by addressable RGB LEDs embedded in its acrylic form. Unlike other organs, the carpel's behaviour was based on light intensity and hue variations, offering a contrast to the pneumatic gestures of the surrounding parts (Lienhard, 2014).

All kinetic elements were choreographed through a pneumatic system controlled by an Arduino Mega microcontroller stacked with a custom PCB. Each gene in the regulatory network corresponded to a musical motif and an actuation script, allowing the structure to reflect biological processes in real time. Importantly, no behaviour was pre-scripted; instead, the installation reacted fluidly to user interactions, allowing nearly infinite variations in gene expression paths and resulting flower morphologies.

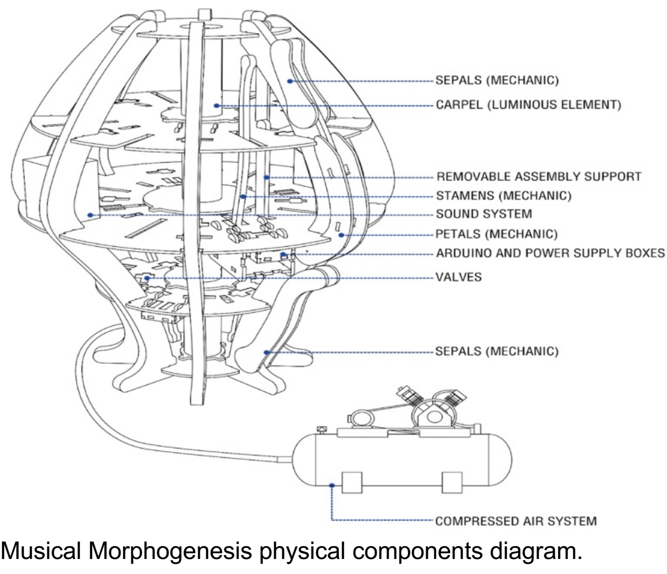

Figure 4. Musical Morphogenesis physical components diagram.

At the core of the installation was a touchscreen console that housed the interface (Figure 5). Built using a mini-PC and developed with Processing and Pure Data, the software visualized the gene network and allowed users to activate or deactivate genes. The state changes initiated real-time modifications in both the physical model and the sound environment. As users engaged with the system, a generative soundtrack played musical sub-themes linked to the 15 genes, reinforcing the concept of a living, evolving organism composed of interacting subsystems.

The infrastructure supporting this behaviour mirrored biological systems at both functional and symbolic levels. A visible network of air tubes, electrical wiring, and control circuits weaved through the structure, analogizing vascular and nervous systems. These conduits distributed pneumatic pressure and control signals necessary for organ movement and sensory expression, consolidating the metaphor of Musical Morphogenesis as a self-organizing body.

The integration of all systems structure, actuation, lighting, sound, and user interface was achieved through a unified digital workflow. Parametric and system mapping tools enabled precise coordination among components, ensuring that the architectural response was seamlessly grounded in the biological model. The result was a performative, biodigital installation that did not merely represent biological principles but functioned through them, demonstrating the potential of architecture to embody, communicate, and operate as a living system.

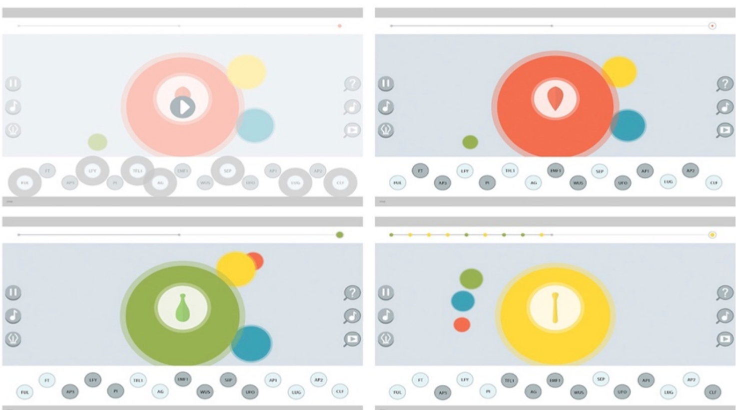

Figure 5. Musical Morphogenesis interface application screen shoots.

5. Visitor Interaction and Public Reception

Musical Morphogenesis was conceived not only as a kinetic architectural installation but also as a participatory and educational experience. During its tour across six venues in the Lisbon metropolitan area between 2016 and 2017, the installation attracted more than 2,500 visitors, ranging from school-aged children and educators to scientists, designers, and the public.

At the heart of the interaction was the touchscreen interface - a dynamic panel that visually displayed the fifteen-gene network underlying the Arabidopsis thaliana model. Visitors could toggle genes ON or OFF, effectively assuming the role of a cellular signal or mutation within a living system (Figure 6 and 7). These actions triggered a recalculation of the network's development path and a corresponding shift in the flower's morphological expression. The interface thus provided an intuitive and visually engaging entry point into complex systems biology.


Figures 6 and 7. Musical Morphogenesis public interaction – Belém Art Fest 2016 (left) + Calouste Gulbenkian Foundation 2016 (right).

Audience responses varied in depth and focus. Younger participants often approached the installation playfully, experimenting with gene configurations to watch the petals move and lights shift in color. Adults and academics, on the other hand, frequently engaged in deeper conversations about the implications of using genetic modelling in architecture, with some visitors identifying links to evolutionary theory, bioethics, or synthetic biology.

Beyond interactivity, the installation functioned as a platform for science communication. Its choreography of sound, motion, and light dramatized otherwise invisible genetic processes, translating abstract biological phenomena into sensory experiences (Kolb, 1984; Ratto & Ree, 2012). The immersive quality of the environment—its color palette, kinetic gestures, and evolving soundscape—invited reflection on the interconnectedness of form, function, and information in both natural and designed systems.

Importantly, Musical Morphogenesis created a learning environment that was neither didactic nor prescriptive. Visitors were encouraged to explore, intervene, and even cause unexpected outcomes. This openness to variation underscored a central theme of the project: that complexity can arise from simple rules, and that design systems—like living organisms—thrive through interaction, diversity, and feedback (Gershenfeld, 2005).

6. Reflections and Conclusion: Toward a Biodigital Morphogenetic Design Methodology

Musical Morphogenesis (Figure 8) presents a compelling case for rethinking the conceptual, technical, and methodological frameworks that underpin biomimetic and interactive architecture. Rather than relying on the mimicry of natural forms, this project draws from the computational and organizational logics of biology specifically, the gene regulatory networks that orchestrate development in living organisms. This shift from form to function, and from representation to simulation, situates *Musical Morphogenesis* firmly within the emerging field of biodigital design.

At its core, the project exemplifies a bottom-up, rule-based methodology (Frazer, 1995; Weinstock, 2010)—a morphogenetic approach where architectural outcomes are not predefined but emerge from systems of interaction. The implementation of Boolean logic to simulate gene activity mirrors the decision-making processes of biological cells. As a result, the structure is not merely kinetic or responsive, but computationally alive—capable of evolving in response to human interaction and systemic logic.

This research set out to explore how gene regulatory networks—essential to biological development—could serve as generative and performative models for architectural design. Through the development and exhibition of *Musical Morphogenesis*, the study demonstrates how biological computation can be transposed into a multisensory architectural system that is at once interactive, kinetic, and developmentally expressive.

One of the project's key conceptual contributions lies in its challenge to conventional notions of authorship and control in architecture. By allowing users to activate or deactivate genes and steer the developmental trajectory of the installation, it invites unpredictability, co-creation, and emergent form. The architectural behaviour becomes contingent on feedback loops, akin to biological systems that adapt based on both internal states and environmental stimuli (Maturana & Varela, 1980). In this way, the project proposes a shift in architectural authorship—from centralized control to distributed influence and real-time negotiation.

The methodology—anchored in Boolean logic, parametric design, modular fabrication, and interactive control—offers a replicable framework for architects and designers seeking to engage with biological systems. Its integration of digital modelling and fabrication with genetic simulation and public interaction foregrounds a model of architecture as a performative, evolving system.

Musical Morphogenesis contributes three key outcomes to the field of biodigital design:

- **(a)** A proof-of-concept model that demonstrates how architectural systems can simulate genetic development through computational logic.
- **(b)** A participatory platform that renders complex biological systems legible and tangible to the public, enhancing science communication and interdisciplinary dialogue.
- **(c)** A foundation for future morphogenetic and biodigital methodologies rooted in computational biology and systemic thinking.

Beyond its technical innovation, the project advocates for an architecture that is not simply "smart" or "responsive" in the technological sense, but intelligent in the biological sense—capable of transformation, self-organization, and ecological engagement. It argues for a reframing of architecture as an evolving interface between humans, machines, and the logic of life itself. Ultimately, *Musical Morphogenesis* proposes a vision of buildings not as inert containers but as dynamic, generative ecologies—responsive, communicative, and adaptable. It opens a path toward architectures that express the intelligence, complexity, and interactivity of the natural world, offering new tools for addressing both ecological and social challenges through the lens of computational biology and biodigital design.

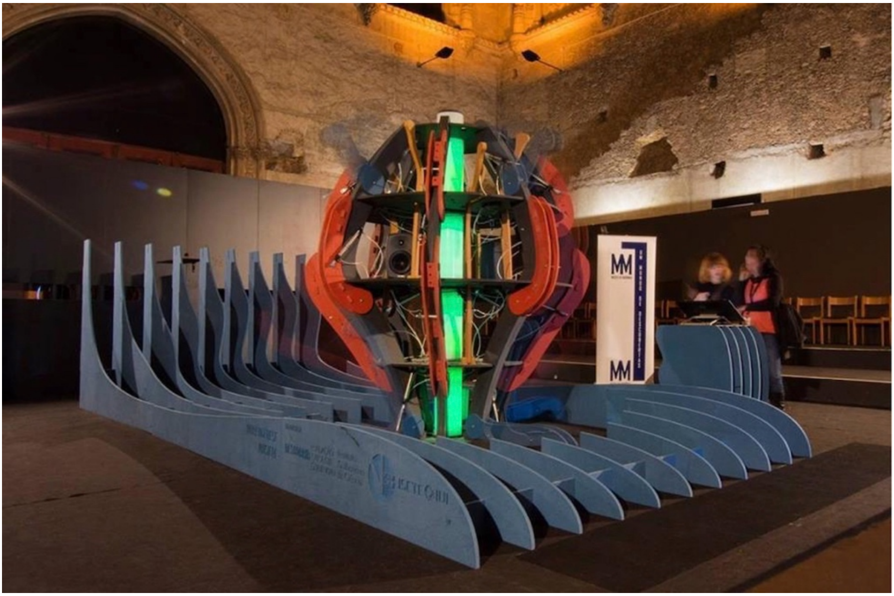

Figure 8. Musical morphogenesis public exhibition at Belém Art Fest 2016.

7. Bibliography

- Alon, U. (2006). *An Introduction to Systems Biology: Design Principles of Biological Circuits*. Chapman & Hall.
- Badarnah, L., & Kadri, U. (2015). “A Methodology for the Generation of Biomimetic Design Concepts.” *Architectural Science Review*, 58(2), 120–133.
- Beesley, P., Hirosue, T., Ruxton, S. (2010). *Hylozoic Series*. Riverside Architectural Press.
- Benyus, J. (1997). *Biomimicry: Innovation Inspired by Nature*. HarperCollins.
- Burry, M. (2011). *Scripting Cultures: Architectural Design and Programming*. Wiley.
- Carpo, M. (2011). *The Alphabet and the Algorithm*. MIT Press.
- Celani, G. (2012). “Digital Fabrication Labs: Pedagogy and Impacts on Architectural Education.” *Nexus Network Journal*, 14(3), 469–482.

- Davidson, E. H. (2006). *The Regulatory Genome: Gene Regulatory Networks in Development and Evolution*. Academic Press.
- Dorin, A., & McCormack, J. (2002). “The Evolutionary Design of Generative Visual Art.” *Applications of Evolutionary Computing*.
- Frazer, J. (1995). *An Evolutionary Architecture*. Architectural Association.
- Gershenfeld, N. (2005). *Fab: The Coming Revolution on Your Desktop—from Personal Computers to Personal Fabrication*. Basic Books.
- Gruber, P. (2011). *Biomimetics in Architecture: Architecture of Life and Buildings*. Springer.
- ICD/ITKE. (2016). *Elytra Filament Pavilion*. University of Stuttgart.
- Knippers, J., & Speck, T. (2012). “Design and Construction Principles in Nature and Architecture.” *Bioinspiration & Biomimetics*, 7(1).
- Kolarevic, B. (2005). *Performative Architecture: Beyond Instrumentality*. Spon Press.
- Kolb, D. A. (1984). *Experiential Learning: Experience as the Source of Learning and Development*. Prentice Hall.
- Lienhard, J. (2014). *Bending-Active Structures: Form-Finding Strategies Using Elastic Deformation in Static Structures*. ITKE.
- Maturana, H. R., & Varela, F. J. (1980). *Autopoiesis and Cognition: The Realization of the Living*. D. Reidel.
- Menges, A., & Reichert, S. (2012). “Material Capacity: Embedded Responsiveness.” *Architectural Design*, 82(2), 52–59.
- Meyerowitz, E. M. (1997). “Genetic Control of Cell Division Patterns in Developing Plants.” *Cell*, 88(3), 299–308.
- Oliveira, M. J. de, Sousa, J. P., Costa, V. C., Oliveira, S. M., & Mena, A. (2017). Musical morphogenesis – a self-organizing system. In M. J. Oliveira & F. C. Osório (Eds.), *Kine[SIS]tem – From Nature to Architectural Matter* (pp. 235–245). Lisbon: CIAUD. ISBN 978-989-8862-25-9.
- Oliveira, M. J. (2020). *Towards a Bio-Shading System Concept Design Methodology* (Doctoral dissertation). Lisbon: ISCTE-Instituto Universitário de Lisboa.
- Oxman, N. (2010). *Material-based Design Computation*. MIT Press.
- Oxman, N., et al. (2013). “Silk Pavilion.” MIT Media Lab. Mediated Matter Group.
- Pearce, P. (1978). *Structure in Nature is a Strategy for Design*. MIT Press.
- Ratto, M., & Ree, R. (2012). “Materializing Information: 3D Printing and Social Change.” *Information Society*, 28(5), 337–343.
- Sung, D. (2012). “Skin Deep: Breathing Life into the Layer Between Man and Nature.” University of Southern California.
- Weinstock, M. (2010). “The Architecture of Emergence.” *AD Reader*.
- Zeller, G., & Luscombe, N. M. (2016). “Gene Networks: What’s in a Node?” *Nature Methods*, 13(4), 293–294.