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VIEWPOINT

Synthetic biology enabling a shift from domination to partnership with natural space

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Abstract

Synthetic biology is a field of science that examines biological systems through the lens of engineering with the explicit objective of rationally designing live objects for either fundamental or biotechnological purposes. Yet, the same conceptual frame also embodies its exact counterpart: the biologization of engineering, i.e., looking at rationally designed systems through the lens – and with the tools – of biology and evolution. Such a creative tension between technology-driven design and biological processes has one of the most conspicuous battlegrounds in modern architecture. Such an edge occurs in a time dominated by the evidence of climate change, ramping environmental deterioration, and the ensuing instability and mass migrations. The most recent influences of biology in architecture have moved from the adoption of biologically inspired shapes and forms in many types of buildings to the incorporation of new biomaterials (often functionalized with qualities of interest) as assembly blocks, to the amalgamation of live materials with other construction items. Yet, the possibility opened by synthetic biology to redesign biological properties *à la carte*, including large-scale developmental programs, also unlocks the opportunity to rethink our interplay with space, not as one more step in the way of domination, but as a win-win conversation with the natural environment. While various contemporary architectural tendencies clearly move in that direction, we propose a radical approach–exemplified in the so-called *Biosynthetic Towers Project*–in which complex buildings are designed and erected entirely through biological programming rather than assembled through standard construction technology. To make this scenario a reality, we need not only tackle a dedicated research agenda in the synthetic biology side, but also develop a new attentive mindset toward the environment, not as a space to be conquered for our exclusive own sake, but as one scenario of sustainable co-existence with the rest of the natural world.

Keywords: Synthetic biology; Bionic architecture; Evolution; Adaptability; Sustainability; Partnership

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1. Introduction

The history of architecture is one of human attempts to dominate tridimensional (3D) space for the sake of habitability (March & Stiny, 1985). Successive technological innovations have often contributed to this end. New materials and new mathematical tools have driven the progress of the field from the trial-and-error approaches of the pre-scientific times to the contemporary power of modern building materials and impressive computer-assisted design (CAD; Szalapaj, 2013), building information modeling (BIM; Abdelhameed, 2018) and artificial intelligence (AI; Debauche *et al.*, 2020) platforms. These tools enable robust prediction of basically any feature of a building much before it is materialized. But what we could call the purposely conquest of the 3D space is not exclusive to human-made architecture. The same process is reminiscent of another course ultimately driven by the same logic: the necessity of biological systems to arise and develop in a physical scenario with clear in or out boundaries, specialized functional assignments, and a coherent geometry for optimizing performance and durability (Lewis, 2008). Note that—unlike human-made buildings—such biological principles apply through different scales, from subcellular organization to very large structures (trees, termite nests, and beehives). Yet, while human-made architecture is most often the result of a rational planning, what we may call *biological architectures* are the outcome of billions of years of evolution. But can each other learn from their respective solutions to not altogether unrelated challenges? Given similar trials, it cannot come as a surprise that outcomes converge whether they are rationally planned or evolutionarily selected as the result of the random exploration of a solution space—as characteristically done by biological systems (de Lorenzo, 2018).

The interplay between technological design and live systems is the subject of what is now called *synthetic biology*, an interpretive frame of biological objects from an engineering perspective (Andrianantoandro *et al.*, 2006; de Lorenzo & Danchin, 2008). The key angle of synthetic biology is the assumption that the mechanical, physical, and chemical rationales that make live systems work as they do follow the same relational logic that engineers (electric, mechanical, computational) adopt for building complex objects (de Lorenzo, 2018). The advantage being that every biological property, including the development of physical structures in a 3D space, is ultimately determined by DNA. The main consequence of this state of affairs is that extant biological objects are already programmed through the sequences encoded in such DNA, which acts as the software of any live system (Danchin, 2008). The corollary of this narrative is that the growing affordability of DNA synthesis enables us to program live entities at our will (Gilbert & Ellis, 2018). We would need to qualify each of these assertions, but in general, the idea that one can program multi-scale biological systems with an engineering logic opens amazing opportunities to develop new products, assets, and–at long last–concepts with a potential to move architecture toward a different paradigm (Dade-Robertson, 2016).

2. Biology challenging the straight line

For many centuries, Western culture viewed humans as fundamentally distinct from and superior to the rest of the natural world. Given this belief, it was natural for the primary motivation behind architectural pursuits to be the desire to control and exploit any available resources for our own benefit. Biological items, especially trees and other plant products were just seen as mere construction materials, whether by themselves or in combination with stones and other building assets. Their merge with the scientific, mathematical geometry started by Euclid (Sbacchi, 2001) originated some of the most representative examples of classical Western architecture (e.g., the Parthenon; Figure 1). It is remarkable that such architectural icons are altogether governed by pure straight lines and flat surfaces, which allow for designing a precise, predictable connectivity between the parts, definition of the boundaries, and an accurate description of the final construct. Moreover, building materials were based on *hard* construction components and intended to be durable for a long time in the same shape they were first put together. All these features are in sharp contrast with the biological occupation of the environmental space. Straight lines and purely geometrical shapes are very unusual in live systems at the macroscopic level (Figure 1). With some exceptions, biological objects are generally made of soft, flexible, and even plastic matter. Furthermore, they tend

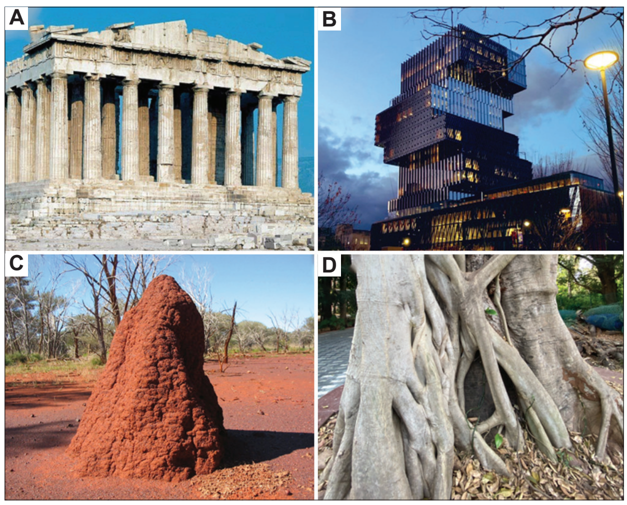

Figure 1. Geometry-driven architecture versus biological occupation of the 3D space. (A) The Parthenon is the most iconic example of historical buildings dominated by straight lines. (B) Center of Computer and data Science, Boston University, designed by KPMB Architects, an apotheosis of rectangular forms (credit: Ahmed Khalil). (C) A termite nest (credit: Australian Museum). (D) The roots of a banyan tree (Chennai, India)

to develop unexpected interactions with others and can age and evolve with time. It would therefore look as if the rational adoption of straight lines and compatible building materials were one of the most conspicuous manifestations of the human fondness to dominate nature, as they allow to suppress uncertainties associated with live counterparts. Other non-straight elements, which were later adopted (round and gothic arches, and domes), did not change the emphasis on Euclidean geometry (Sbacchi, 2001) as the core basis of any architectural project. Most often, non-linear forms were used almost exclusively for decoration.

Yet, one of the take-home lessons of contemporary systems and synthetic biology is the ability of evolutionary mechanisms (Morange, 2013) to solve complex optimization problems, which are not amenable to calculation from first principles (Krohs & Bedau, 2013). For example, assembling a new metabolic pathway for the synthesis or degradation of a target chemical compound typically starts with arranging a DNA sequence that encodes all the necessary enzymes, predicted either manually or with CAD resources (Hafner *et al.*, 2020). But this is just the beginning: the components of the route must be expressed in a specific stoichiometry through additional regulatory assets (*e.g.*, promoter sequences and ribosomal binding sites) to secure effective nesting of the construct in the pre-existing genetic and physiological network of the host, avoid toxic intermediates, and foster long-term performance (Stephanopoulos, 2012). Alas, such catalytic phenotypes are challenging to design, as the parameters involved in their optimization are either too high a number or they are simply unknown. One way is the application of what has been called *Gaudí's principle* (Porcar *et al.*, 2015) based on his hanging chain models (Figure 2). Under this frame, the starting point is a system which contains all necessary components to deliver a given function but lacks the proper connectivity and/or is endowed with unsuitable parameters and transfer functions. By letting the system fluctuate under an overarching selection criteria (for instance faster/better growth), the same biological object is made to evolve for finding solutions (Naseri & Koffas, 2020). Such an evolutionary and/or combinatorial approach typifies prime outputs to the initial challenge, regardless of the number of objectives that need to be simultaneously met. The process can in fact be entertained as a sort of physical computation, in which a complex metabolic problem is embodied in a material object, and the result is delivered as another physical entity endowed with the solution. If we were to do this rigorously, the large number of fine adjustments of the starting metabolic and regulatory devices could not be addressed through rational calculations. The best growers thus represent discrete attractors in a solution space which embody optimal genetic and physiological arrangements under given conditions. Therefore, in reality, biological systems can evolve and adapt to the environment capable of solving problems that are not yet amenable to straight engineering. As long as biological evolution cracks challenges that cannot be tackled otherwise, can we entertain also that biology empowers us to push architecture beyond the self-imposed limitations of what we could call *straight-line philosophy*?

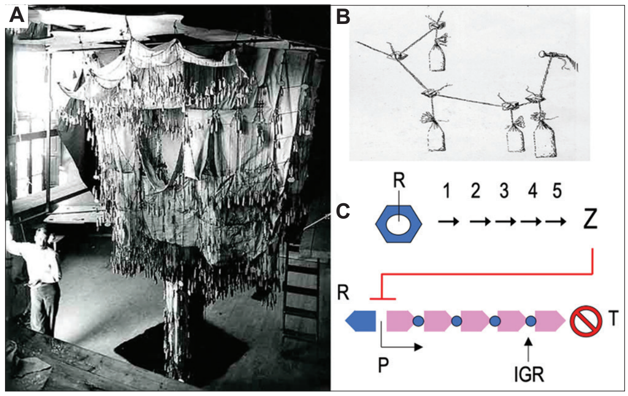

Figure 2. Gaudí's method for optimizing complex structures and its applicability to the genetic design of synthetic metabolic pathways. (A) String-weight engineering involves determining parameters for constructing a complex object where the interactions between nearby elements affect the entire system, and *vice versa*. Photo credit: Gaudí Museum, Barcelona. (B) Initially, a collection of components is physically connected to form an object. Weights are then attached to specific locations that will later become the peaks of the architectural piece. Through the force of gravity, the object undergoes deformation, resulting in an optimal distribution of angles and masses. Flipping the model upside down provides the stability parameters for the structure. (C) To achieve the best combination of enzymatic steps (1–5) for converting a substrate into a product (Z), various factors must be considered, such as appropriate gene expression levels controlled by the promoter P, the regulator, and the intergenic regions (IGR), as well as mRNA stability and termination (T). Introducing sequence diversification at these regulatory points and applying selective pressure to enhance Z production allows for exploration of the solution space until an optimum is attained (Adapted from de Lorenzo, 2018)

3. Technification of biology *vs* biologization of technology

One common and implicitly accepted tenet of contemporary technology is that by applying mathematical methods, advanced physics/chemistry, and more recently computational approaches, humans can prevail over the uncertainties and threats of the natural world. In other words, for too long a time, the environment has been perceived as an adversary to submit to and a source of resources to exploit. Attempts of technological domination of the natural realm (and their associated narratives) are reminiscent of recurrent historical events when a self-perceived strong country or society conquers a militarily weaker but culturally more influential civilization or society. The typical outcome over time is that despite early successes of the invaders, the more elaborated culture of those invaded takes over and eventually prevails. Along the line, we entertain that technological attempts to subdue nature to our own benefit will eventually change to incorporate many of the strategies and solutions that biological evolution has already provided or can provide to complex problems that are beyond our current capabilities (de Lorenzo, 2018).

One archetypal example of technical leveraging of biological phenomena is the adoption of evolutionary algorithms for the optimization of antennas for NASA's spacecraft (Lohn *et al.*, 2005). The rational design of such antennas is challenging as so many parameters are at stake. However, evolutionary design techniques can provide workable solutions by exploring the design space and delivering automatically applicable results. Note that in these cases, the design principles are not rational but rely on massive diversification-selection cycles that recreate Darwinian evolution. In a different but related frame, the first synthetic biology wave ambitioned to dominate extant biological systems by adopting engineering concepts and methodologies. Yet, 20 years later it seems clear that such a straight projection of one thing on the other has not delivered as expected (Meng & Ellis, 2020).

Biological systems inherently mutate and evolve (Cardinale & Arkin, 2012), not only when submitted to changing environmental conditions, but also often through mere genetic drift. Moreover, the performance of biological devices is characteristically context-dependent, which leads to the emergence of new interactions and properties. Finally, living systems grow and reproduce. These qualities dramatically depart from those of human-engineered objects (Hanson & Lorenzo, 2023). One way to move ahead is trying to suppress such undesirable features for making biology easier to engineer (Calvert, 2010). This involves, for example, orthogonalization of genetic devices, mitigation of evolutionary potential, digitalization of regulatory components and others. However, we speculate that efforts to defeat such inherent characteristics of living systems will not ultimately solve the problem. What to do then? In this case, the advice attributed to Saint Lupe of Troyes (383–479 AD) when facing Attila the Hun on his way to the conquest of Rome could be applied here: "… *if you cannot defeat your enemy, join him…*". Instead of treating to suppress upfront undesirable qualities that are inherent to living systems, the way to go might be to make an alliance of what the other side has to offer and learning how such side has developed solutions by other means (Porcar *et al.*, 2015) and even tackled problems that were not anticipated before.

The time is ripe to move from *technification of biology* (as ambitioned by synthetic biology) towards *biologization of technology* (as we advocate will eventually happen). This trend is growingly making it in the synthetic biology literature (Castle *et al.*, 2021) and prospects of merging top-down genetic engineering with evolutionary tinkering are getting at hand. But how do all these affect modern architecture?

4. Biology conquering architecture

As mentioned above, after millennia of improvised utilization of naturally occurring construction materials for building short-lived human habitats on the mere basis of trial-and-error, the birth of Western architecture can be traced to the time when Euclidean geometry was incorporated to edifice design (Di Cristina, 2002). An additional and characteristically human attribute was also the integration of aesthetic features, so that (according to Vitruvius 80–15 BC), the functionality should be combined with durability and beauty (Kruft, 1994). Vitruvius also argued that architectural perfection is reached when buildings embody the laws and shapes of the natural cosmic order, as exposed by mathematics, physics, and geometry. No wonder that for much of history, buildings have been based on such principles. Native forms of natural materials are eligible as resources for construction, for example, stones, tree trunks, and so on, were reshaped to follow geometrical and physical standards necessary for fitting a preset assembly plan. Virtually nearly every building erected in the past 20 centuries has followed such norms, all submitted to straight lines and other purely geometrical shapes. Even the plastic exuberance of the baroque period limited utilization of non-linear forms to adornment of otherwise purely geometrical structures–to be soon replaced by an ensuing bare neoclassical style. At the core of the breach between such types of architecture and the occupation of the 3D space by biological structures lies the connectivity among the components. Purely geometrical forms entered in *hard* materials enable the capture and design of habitable space with a minimal number of elements and the least total of connections amid them. The downside of the same is frailty to environmental changes–as clearly shown by the sensitivity (and frequent collapse) of many classical buildings when facing natural calamities (Al-Momani & Harrald, 2003). In contrast, biological 3D structures are shaped by malleable and highly connected parts, which certainly complicate their rational design but often endow extraordinary robustness to the final object. Things started to change, however, by the late 19th century, the time of major scientific discoveries on the nature of matter and the onset of evolutionary theory. Both mitigated the gap between the human realm and the rest of the natural world if they revealed that we are made of the same stuff of the surrounding world and intimately akin to plants and animals. Impressionist painting is one of the artistic expressions of such a change if it attempted to capture and represent the energy embodied in the material world by means of effects of light and rough brushstrokes of paint reflecting the inner dynamism of objects and living things (Metcalf, 2004).

Frontline architecture of the time was not alien to these developments, as epitomized by the above-mentioned Antonio Gaudí (1852–1926). He went beyond the prevailing modernist tendencies of his generation to create a distinct style in which shapes of naturally-occurring living forms were incorporated into his buildings, not just as decorations, but as core architectural elements (Huerta, 2006). His approach resulted in a type of designs dominated not by straight lines and circles but by hyperbolic paraboloids, hyperboloids, helicoids, and conoids (Figure 3). Such type of nature-inspired organic architecture was largely based on the adoption of string-and-weight models (Figure 2) which enabled an easy solution to complex multi-objective optimization challenges (Makert & Alves, 2016) through an approach reminiscent of adaptive biological evolution (Porcar *et al.*, 2015). Such tendency–which tries to leave behind the conventional straight line-based architecture has a more recent example in the work of Friedensreich Hundertwasser (1928–2000) and his utilization of non-regulated irregularities in his curvy buildings to deliver structural diversity that is reminiscent of the natural, living world (Hundertwasser, 1997). Gaudí and Hundertwasser can be regarded as pioneers of diverse architectural concepts that draw inspiration from structures found in living organisms. They even go so far as to emulate some of the mechanisms that biological systems employ in response to environmental changes (see Figure 3). These styles have adopted various denominations such as *bionic* (Yuan *et al.*, 2017), *biomimetic* (Aldersey-Williams, 2004; Chayaamor-Heil, 2023), *bioinspired* (Ripley & Bhushan, 2016), *biophilic* (Soderlund & Newman, 2015) and others. Yet, note that the interplay of architecture-biology at this point is that of echoing living structures in buildings which are made in any case of standard, hard construction materials. But is such structural inspiration enough?

Figure 3. Non-geometrical architecture. Many of the works of Antonio Gaudí (A and B) and Friedensreich Hundertwasser (C and D) avoid straight lines and perfect geometrical forms as much as possible for the sake of bridging the technical and conceptual gaps between naturally occurring shapes and human-made buildings. Note in (c) even adoption of wavy floors for making inhabitants aware that they are stepping on Earth. Photo credits: Casa Pedrera (Barcelona) and Kunsthaus (Vienna)

5. Biologicals as active building components

The next step in the way to biologization of architecture involves the progressive incorporation of materials coming from the living world to building design. The traditional use of wood as the key component of many structures is now complemented by utilization of other biological goods endowed with useful properties. One low-hanging fruit in this respect is the use of fungal mycelia as insulation material (Attias *et al.*, 2020). These microorganisms incorporate vegetal particles into their hyphal network, producing composite materials useful to this end. The biomass of filamentous fungi often acts as nucleation sites for biomineralization of calcium carbonate, further expanding the usability of mycelium composites as structural materials. Furthermore, mushroom-forming fungi generate hyphae rich in cellulose and lignin together, conferring high rigidity to the overall interconnected structure and mechanically strong enough as structural components at the architectural scale. Mycelium-based blocks are already available as an alternative to plastic-based insulation materials and building assets, for instance, bricks. Note however that such items of fungal origin are typically inactivated with heat or other methods before use and, therefore, the qualities of interest are limited to their physical properties. Given that such properties are ultimately determined by DNA, perspectives are that fungi can be improved and leveraged beyond their material qualities for endowing biological functionalities to the architectural designs they join–alone or in combination with other microorganisms (Jo *et al.*, 2023). In particular, for generation of, for example, living architectural skins (National Academies of Sciences, Engineering, and Medicine, 2017; Armstrong, 2023; Persiani & Battisti, 2019) for bioremediation (Shavandi & Jalalvandi, 2019) of polluted urban sites (soil, air) and carbon capture (Singh *et al.*, 2022).

The notion of buildings with functionalized living skins is, in fact, one of the frontline research topics at the interface between architecture and synthetic biology (Armstrong & Spiller, 2010; Armstrong, 2015). Both outer and inner walls have been customarily used only for the separation of spaces in buildings, but their surfaces are basically limited to support, in case of decorative and/or low functional elements, such as paintings, portraits, mirrors, and so on. But, as proposed by the LIAR Project (https://livingarchitecture-h2020.eu/), such surfaces can, in fact, be converted into flat bioreactors to produce valuable substances *in situ* (in a sort of micro-agriculture) and remediate environmental toxicants. Early examples of this possibility include incorporation into buildings of exterior vertical gardens (https://newatlas.com/architecture/8-shenton-way-som/) and/or surfaces covered with moss for interior air purification (https://greencitysolutions.de).

A separate but related development is that of self-healing concrete (Vijay *et al.*, 2017). Despite its advantages, concrete tends to form cracks at various stages of its life cycle. Fortunately, some bacteria produce a range of minerals (in particular, carbonates) which can act as concrete fillers. This has originated formulations of bio-cements bearing specific microorganisms that once in place, can deposit solid minerals that plug potential micro-fissures in construction concrete. Again, given the ultimate dependence on DNA of these properties, such naturally occurring activities–whether fungal/bacterial remediation or functionalization of concrete—can be enhanced and adapted to specific needs through synthetic biology methods (https://neoplants.com/).

While the incorporation of living components into buildings is one significant stage in the interplay of architectural practice with biology, the underlying technological paradigm is still one in which the living world becomes submitted to human needs, and it just fills the gaps that are not yet amenable to sound engineering. But can we turn things around and develop a kind of architecture in which biology is not just an inspiration or one more asset along with others, but the principal driver of the building endeavor? This approach requires an attentive and caretaking attitude towards the natural world open to learning from it rather than sticking to our habitual, optimist belief that human technology can solve any problem, including conspicuous messes like climate change (Huesemann & Huesemann, 2011). How does this translate into the architectural realm? As Wil V. Srubar[1] put it "… *Nature has figured out how to do a lot of things in a clever and efficient way: we just need* to *pay more attention …*".

[1] https://sawdust.online/news/bacteria-in-this-building-material-keeps-it-alive/

6. A radical proposal: The Biosynthetic Towers Project and beyond

By looking at the way biological systems (in particular, woody plants) occupy the 3D space (Figure 1) and the possibilities of rewriting developmental programs opened by synthetic biology (Baltes & Voytas, 2015), we can entertain a future urban scenario where technology and nature team up for conforming an ecosystem able to provide an adequate habitat while being able to regenerate and evolve in a balanced and smart way. As an example of such picture, the *Biosynthetic Towers* (BTs) *Project* envisions a new system based on that conception as an alternative way of understanding urban planning, architecture, and construction, in which the biological component prevails over the earlier physical constraints and building technologies.

So far, there have been important contributions of synthetic biology in agriculture, energy, engineering, construction materials (de Lorenzo *et al.*, 2018), and even art (Ginsberg *et al.*, 2017), but it still has not reached a larger scale that could be used for developing a smart city planning. The BT Project puts forward a vision of how the future of our cities could be like if synthetic biology is radically applied to architecture and urban planning. The core of the BT project is the bioengineering of programmable trees (or tree-like biological structures) to develop into a building or a series of buildings that are living organisms that grow, change, evolve, regenerate, update, and transform over time. What could this look like?

First, as shown in Figure 4, no excavation would be required to lay the foundations of the intended building. There are not even construction works necessary because the system grows and evolves by itself. The initial planning is just based on a grid, where programmed seeds containing basic construction information have been planted on. Gradually, the seeds will start to transform into small cabins that could be used by people as living spaces or could be set for commercial or recreational purposes. This new embryonic organism contains additional growing information for the next evolution step of the BT. This way, the system expands following a slow and iterative process until it gets bigger and smartly merges with what is around it, naturally flowing with its context (Figure 5). Second, the whole system works with natural mechanical actions typical of living organisms, such as suction, condensation, inertia, uptake, or absorption, with little or no need of

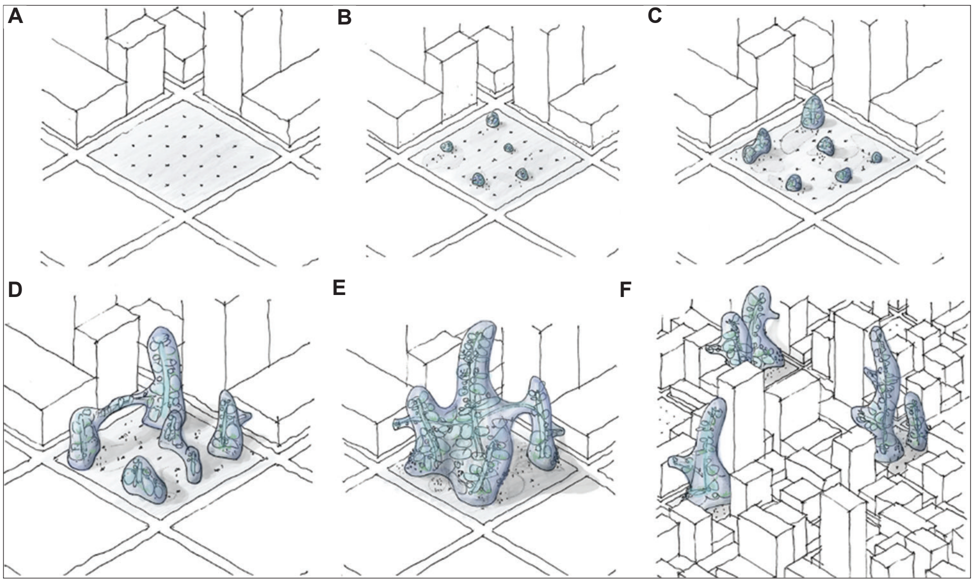

Figure 4. Stages in the development of a biosynthetic building. (A) The intelligent seed grid as the towers *foundations*. (B) Initial forms of small individual living spaces. (C) Formation of collective living spaces by adhesion. (D) The biosynthetic system develops as linked towers. (E) The Biosynthetic Tower matures. (F) The towers blend in with the existing town and promote urban transformation

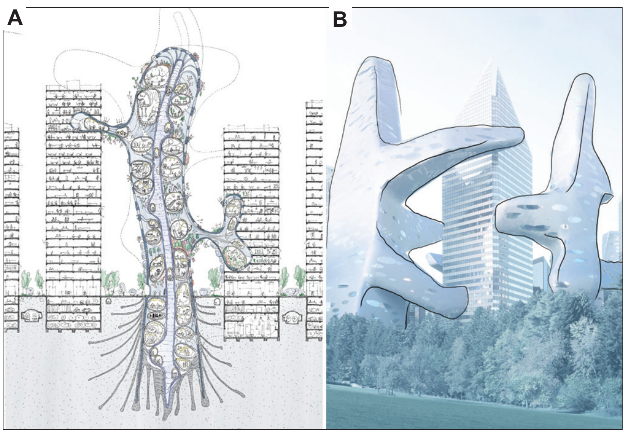

Figure 5. Inside and outside of the Biosynthetic Tower. (A) The overall structure of the building adopts the outline of a tree, where roots act as foundations and energy supply and where a central core branches out to support the different rooms and to serve as a guide in its extension and connection with other towers and buildings in its immediate surroundings. (B) Simulation of how the fully developed Biosynthetic Towers could become integrated in the pre-existing urban landscape

electricity input other than its inner natural power as a living organism. Energy supply is based on the chemical reactions of bacteria with natural agents (such as sunlight, water, air, and temperature) and the vegetal, animal, and human activity inside. The skin and stem of the tower configure one self-supporting structure. Besides, there are multiple elements such as flexible fabrics, microcavity membranes, filaments, fluids, and sticky matter that permit the BT to be sensitive towards exterior agents and to respond smartly to its user's requests. For example, if the inhabitant feels such as sitting or lying down, by just touching a pad on the wall, a chair or a bed can emerge from the inner skin of the living space. And third, the physical supports of the towers lack traditional systems of reinforced concrete or steel construction and rely altogether on woody materials. Some details of specific parts and functionalities of the building are outlined in Figure 6; note that all are based on known properties of the biological elements at stake.

For instance, the interior of the organism tries to ensure that all the spaces inside it receive an adequate amount of natural light (Figure 6A). In turn, the outer skin of the system is formed by light and solar energy collectors that can transport photons to illuminate, by means of ampoules as lamps, those deeper places where it is more difficult for direct sunlight to reach. The BTs are in continuous and slow growth and transformation (Figure 6B), so the circulation routes that run through its interior must absorb these movements. The inhabitants circulate by means of a mechanism consisting of capsules that advance by peristalsis (or progressive contractions) through tubular organs (Figure 6B), which run through the extensions of the organism connecting the different habitable spaces. As if they were parks or green areas of a city, certain sections of the skin of the BTs function as fertile surfaces where vegetation can grow. These spontaneous gardens (Figure 6C) not only serve as places for the enjoyment and relaxation of their inhabitants but also function as cultivation fields or greenhouses that complement the food supply of the towers' inhabitants. The part of the lowest façade of the BTs that is closest to the street functions as a storage and loading (Figure 6D) and unloading base for vehicles compatible with the system. A mucous membrane allows such vehicles to adhere to and slide over the skin of the towers. Now, the driver of these vehicles decides to access the tower, a hole is opened both in his vehicle and in the façade, allowing him to penetrate inside the tower. Inside the living cells, the floor, walls, and ceiling will form a single autonomous and intelligent unit (Figure 6E). From a tactile inner skin, privacy, and comfort parameters typical of a home can be controlled. There is no furniture since it emerges from the inner skin of the cell at the request of its inhabitants (Figure 7). The same happens with other domestic elements such as loudspeakers to listen to music or screens to watch a movie. The BT's system of installations is also integrated into the organism itself. Rainwater and solar energy are recycled and stored (Figure 6F), thus serving as sources of supply for the future. The management of organic waste, wastewater, and air extraction is carried out by means of a network of tubular vessels that run attached to the structure and membranes of the organism.

In sum, the BT Project is a futuristic anticipation of how the merging of architecture, urban planning, and advanced synthetic biology could converge for the sake of sustainable building-making in harmony with the rest of the living world. The project's ambition is to make humans think of an

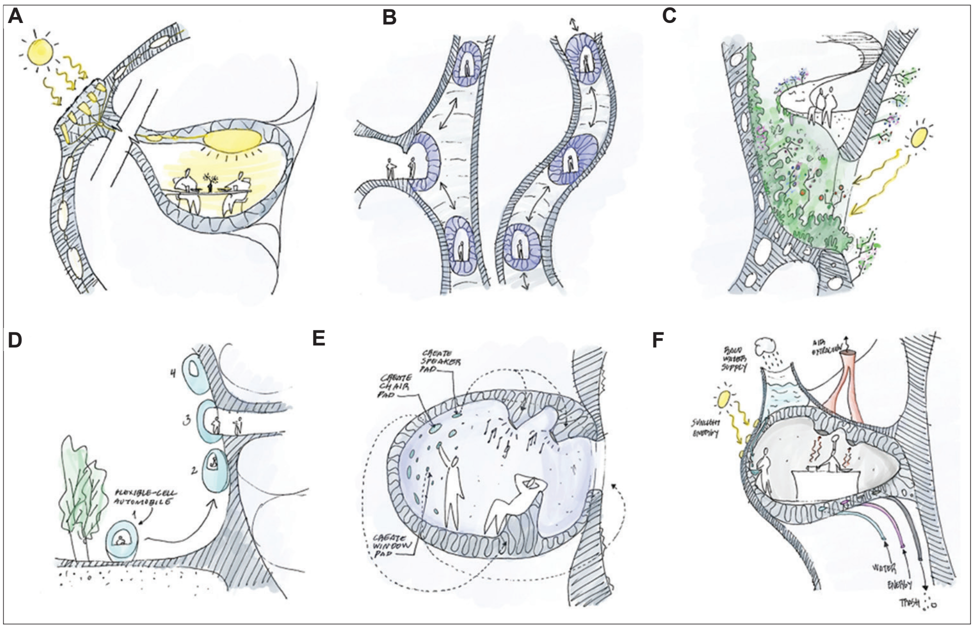

Figure 6. Key functionalities genetically programmed in the Biosynthetic Towers. (A) Sunlight capture and CO_2 fixation. (B) Transportation structure. (C) Spontaneous garden. (D) Storage membranes. (E) Smart skin. (F) Fluid and energy logistics (see text for explanation)

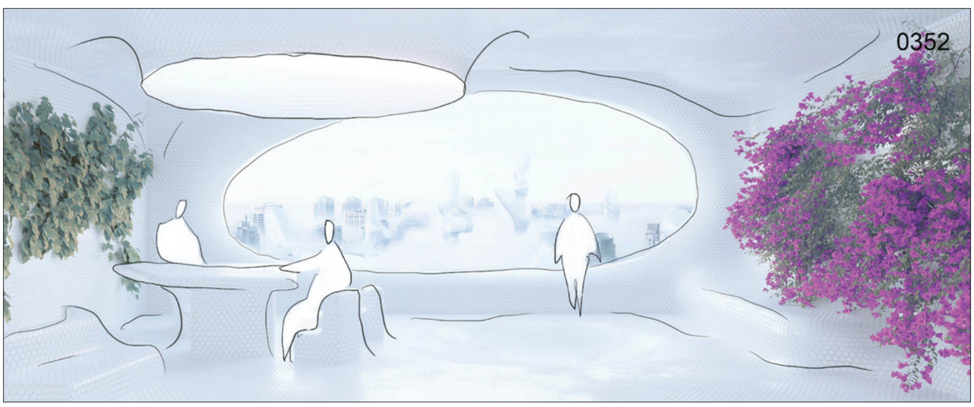

Figure 7. Towards all-organic human habitats. DNA-based programmability of multi-scale biological development empowers synthetic biology not only to engineer large living structures but also specific functionalities at the dimension optimized for human use. This involves, for example, emergence of shapes and objects usable as typical pieces of furniture

alternative way of understanding how we live in the cities, and how we move within them, especially during uncertain times like today. Obviously, the BT project is not the only one that has dealt with similar issues. The Supplementary File provides a list a non-exhaustive inventory of architectural initiatives and undertakings that align well with the philosophy of the BT project. They are about letting nature lead the solutions for healing the damage that unchecked technological development has inflicted on our common planetary habitat—and to which traditional construction methods have so significantly contributed (Habert *et al.*, 2020).

7. Conclusion

We live in a time characterized by what has been called a *polycrisis*[2] (environmental, societal, and migratory), along with unprecedented technical and scientific advances that enable us to revisit our interplay with the natural environment, both as an ethical mandate as well as a necessity for survival. The early 2000s witnessed the onset of synthetic biology, a veritable game changer in the way we leverage biological systems for human sake. In reality, synthetic biology opens an unprecedented two-way, win-win channel between engineering (which also encompasses technology-based architecture) and the living world. On the one hand, synthetic biology lays out a way to reprogram biology by accessing and rewriting DNA sequences following the logic of electric, mechanical, and computational engineering (Andrianantoandro *et al.*, 2006). On the other hand, the same channel makes available evolutionary mechanisms (a kind of *natural computation*) that living entities exploit for adapting and proliferating in a dynamic environment. By learning such a biological language, we can move from domination to partnership with the natural world for a sustainable, albeit quite different, future. Given that the construction sector has one of the major impacts on climate change and environmental deterioration, it is urgent to develop the conceptual and technical tools for making the above-discussed BTs projects (and others listed in Supplementary File) a reality.

While the proposal of all-organic, living buildings is indeed futuristic, the challenge is by no means fictional or a mere fantasy. One can make a list of gaps in our current knowledge of plant and animal developmental programs necessary to develop each of the biological components and focus on research efforts in filling them. While full morphologies of plants are still difficult to program, there has been considerable progress in recent years in reshaping root (Morris *et al.*, 2017) and branching (Nicolas *et al.*, 2022) architecture with rationally designed genetic circuits (Brophy *et al.*, 2022; Kocaoglan *et al.*, 2023). There is no reason why such studies cannot advance toward the determination of complex shapes in woody plants, including their aerial parts. The same applies to plant growth rates. As this quality is also genetically encoded, chances are that plants engineered with superior abilities of CO_2 fixation and biomass production (a super-active research field at this time; Tan *et al.*, 2022) can be also designed for the erection of organic buildings within a sensible period of time. The same for each of the functionalities are indicated in Figure 6. Obviously, we are not there yet in the scenario sketched in Figure 7. But the time is ripe for considering it seriously and giving it a chance, not just as a virtue but as a vital need.

[2] https://www.weforum.org/agenda/2023/03/polycrisis-adam-tooze-historian-explains/

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Conflict of interest

The authors declare they have no competing interests.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

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Not applicable.

Further disclosure

A preliminary version of the Biosynthetic Towers Project was submitted to the 2021 edition of the eVolo architectural contest (https://www.evolo.us/).

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