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ORIGINAL PAPER

Principles of biological design as a model for biodesign and biofabrication in architecture

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Abstract
Biomaterials represent a potential means for the construction industry to reduce its negative ecological impact. These materials require substantially different approaches from conventional construction materials to maximise their potential. In this paper we have outlined four principles of biological design that we argue are central for the successful implementation of a new construction paradigm through biodesign. These principles are: *Diversity*, *complexity and specificity* (of form), *durability through resilience*, and *feedback and adaptation*. *Diversity* of material is necessary to maintain the sustainability of biomaterials when scaled up to construction industry volumes. *Complexity and specificity* of form enable high performativity of the built environments when using low-impact materials. *Durability through resilience* allows designers to work with materials that would otherwise be considered too weak. Finally, *feedback and adaptation* are core principles of biological design that allow plants and animals to constantly evolve in response to changing conditions, across multiple time scales, and to manage design in complex systems. In conclusion we have argued that many of these principles are found in vernacular architectural traditions, but that emerging design and fabrication technologies can enable broader implementation that can combine the benefits of modern and vernacular buildings practice.

Keywords Biological design · Biodesign · Architecture · Biofabrication · Biomimetics · Construction 3d printing

Introduction

The shift from conventional to bio-based construction materials can represent a radical alternative to the current unsustainability of the construction industry. These offer renewable modes of production, full recyclability, and compatibility with the surrounding ecosystems. However, beyond serving as building blocks in established modes of construction, biology can show us an alternative model for organizing matter and information in space that can bring a truly sustainable revolution. If biomaterials are adopted in conventional structures, they may not live up to requirements adapted to concrete and steel, but when incorporated in a process modelled on biological principles, they can be transformative.

The propositions presented in this paper are based on experiences and projections from the *Protomycokion* demonstrator. They address how design and construction will need to adapt to best take advantage of the possibilities offered by a biodesign paradigm and manage its drawbacks.

Protomycokion (Fig. 1) is an architectural prototype of a 2-m-high column fabricated with fungal lignocellulosic materials using bioFDM (biologically Fused Deposition Modelling) 3D printing. The fungus is alive and active during the fabrication process. The mycelium grows through the printed substrate: binding it together and modifying its properties in beneficial ways. As the live fungus plays an important role in the making of the final object, its needs and requirements during the fabrication process had to be considered. This incorporation of living organisms represents a major potential of biodesign, but also poses a challenge as many established methods and procedures in construction engineering and design are conflicting with the organism. In this case, and we would argue in many biodesign scenarios, form and process become closely intertwined. This interdependence requires a new approach of design that is capable of navigating and negotiating such nonlinearity. In this article we do not intend to extensively describe the fabrication of the *Protomycokion* as this has been reported in previous

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Fig. 1 Protomycokion, a 3d printed column made from biohybrid materials

papers [1, 2] which go into greater detail with regards to the design, fabrication, and performance of the prototype. This prototype also does not represent a finalized solution for architectural implementation of biodesigned materials, through it is a significant step towards understanding the possibilities and demands of the processes. Instead, we will explore how designers and makers can respond to these circumstances that we suggest are of wider significance in the biodesign paradigm.

We suggest that biological morphogenetic processes are an important precedent, and that these can provide clues on how to address the complexity and interdependence that arise not only in this particular context, but in any design ambition which moves beyond the current paradigm of standardisation and internal independence (i.e., where non-linear dependencies within a building system are avoided as a strategy to avoid design and construction complexity). Within this context we distinguish between two terms that are similar but distinctly different: *Biodesign* refers to design (in our case architectural) that uses biological materials and/or approaches for human applications, such as buildings. *Biological design* on the other hand refers to the morphogenetic processes that connect genotypes to phenotypes, the processes, and agents that express code in DNA as spatial and functional organisms and structures. Scott Turner, in the book *The tinkerer's accomplice: how design emerges from life itself*, defines the term "design" within the biological field as "a peculiar coherence between a living structure and a function it performs" [3].

Indeed, this observation lies behind the recent (and the not so recent) interest in biomimicry—which attempts to find ways to apply this coherence of biological structures in engineering. We would propose that while it is useful to search out and replicate these forms or structures and their associated functions, it is far more promising to investigate and learn from the very processes that link form to function. These processes implemented in architectural design can be described through four overarching principles: *Diversity*, *complexity and specificity (of form)*, *durability through resilience*, and *feedback and adaptation*.

Diversity

In the current industrial context relying on efficiency through standardisation, multi-purpose and homogenous materials are the default option. These materials rely on centralised production and extraction, and often come with significant environmental costs [4]. Incorporating living organisms together with digital design and fabrication enables us to adapt to the rich diversity of the biological world. The transformative processes of multitudes of (e.g.) fungal strains have the potential to create variable architectures, adapting to resource availability, local conditions, and divergent performance requirements. Through this approach, standardisation of materials and components could be replaced with codified relationships, where a vast library of fungal and material variations is used to meet an equally high number of unique situations and contexts. Initial results regarding the relationship between several fungal strains and the resulting mechanical properties, hydrophobicity, and the effect of temperature and humidity on the respective biocomposites can already be found [5, 6].

If biomaterials are to become a sustainable alternative to conventional building materials and replace large volumes of these, it follows that the resources used need to be of a diverse and heterogeneous origin in order to avoid the loss of biodiversity [7, 8] and decreased carbon sequestration [9] associated with monocultures and production forests. Göswein et al. [10] have studied the land availability for large scale production of bio-based construction materials in Europe. They conclude that current land resources are sufficient to provide for the construction industry needs and highlight that unconventional materials such as straw appear better than wood from resource and carbon storage perspectives. As part of their study, they conclude that cork is a potentially significant construction material only if it is considered in local contexts: availability exceeds demand in southern dry European markets, but at a cross-Europe scale it is not a viable alternative.

The ability to use a diverse mix of materials depending on local contexts, both in terms of plant habitats and existing waste-streams, is critical for a sustainable shift towards biomaterials.

In nature fungal strains utilise a vast variety of strategies and processes to survive and propagate. At the centre of these strategies are their ability to connect and transform material at the molecular level. By harnessing these transformations within a biodesign and biofabrication paradigm as demonstrated in *Protomycokion*, the raw materials for construction do not need to be standardised or centralised. Available resources, whether they are locally and purposefully grown or sourced from urban, agricultural or forestry waste, can be repurposed through controlled biotransformations.

In addition to materials of direct biological origin, locally sourced mineral materials including earth, clay and stone often have complementary properties such as high compressive strength and thermal capacity. They are often compatible with biological materials, and can be used in ecologically sustainable ways, particularly if centralised processing and transport is avoided.

Diversification is relevant not only in sourcing but also in material behaviours, as low-impact materials often exhibit nonlinear behaviours. For example, clay, whose material properties such as volume, vapor permeability and strength vary strongly with humidity. Lignocellulosic materials change shape when humid and exhibit isotropic or dynamic stiffness and strength. Such "live" properties are commonly found in vernacular material use but avoided in industrialised production as they lead to runaway complexity that is difficult to manage using top-down engineering approaches. However, like microbial transformations, these complexities can be managed through novel computational strategies, and open up possibilities for responsive and dynamic architectures.

Complexity and specificity

Like the form of the fungus gardens found in termite mounds (Fig. 2a) the geometry of Protomycokion (Fig. 2b) was heavily influenced by the processes through which the printed components were made. The constraints were defined on the one hand by the fungus' requirement to maximise surface area and connectivity between the internal air spaces (to ensure rapid and extensive colonisation of the pulp) and on the other the fabrication process. In order to thrive and grow, the fungus requires oxygen, and it only penetrates the substrate to a few millimeters' depth. This leads to the

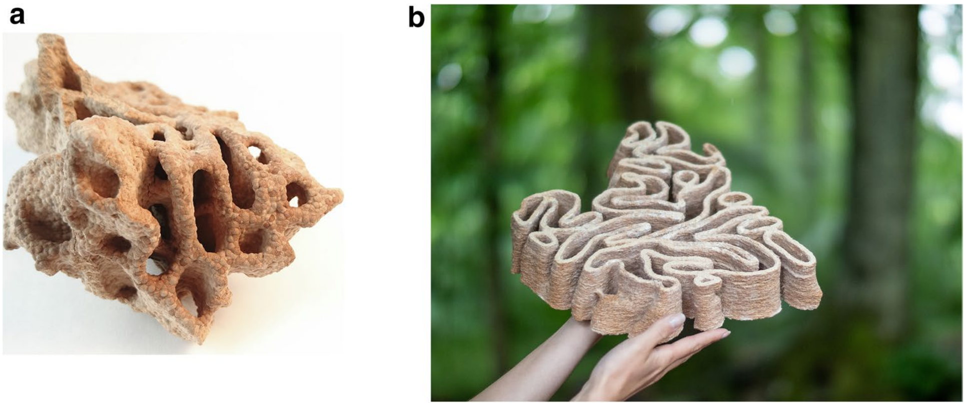

Fig. 2 **a** Fungus comb built by macrotermites from partly digested wood and fungal spores. The intricate geometry allows the fungus access to oxygen and allows the termites access to the majority of the material to care and feed. The build process that leads to the geometry is primarily driven by the termite body size and their movement patterns when constructing it. **b** The folding of the Protomycokion components are the result of very different processes/algorithms, yet result in similar appearance, as the constraints on the process (air contact and the size of the nozzle) are similar

requirement for high surface area and vertical connectivity to ensure constant oxygen supply over the days to weeks over which the fungus growth takes place. During this phase the construct must be kept moist, which in turn places requirements for the geometry to support the stability of the printed structure until final strength is obtained though drying, which kills or deactivated the fungus.

By encoding these as relational constraints, (Fig. 3) their continuity can be ensured in the global design context. It also allows for global constraints resulting from the architectural use of the structure (such as structural integrity, space-shaping, or aesthetics). As an example, the local orientation of the column walls can be constrained to follow the stress curves in predicted load scenarios.

In Protomycokion, the vertical connectivity of the interstitial spaces are constructed in such a way that the network of channels propagates through the entire vertical column, while frequent curvature, interconnections, and multidirectionality ensure stability. The algorithm used to achieve this is a reaction diffusion that generates a Turing pattern [11]. This pattern arranges the interstitial spaces as an outer and inner void. This ensures the use of the column as a humidity or temperature regulating structure, with the inner space being connected to an HVAC system or a phase-change heat buffering structure, as the thin walls and large surface area ensure a potential for mass or humidity transfer to the outer environment.

Scaling performance

In biological design, function is often achieved by manipulation of form rather than bulk material properties. Of course, at some level even the material properties of construction materials such fibre insulation or concrete are derived from the spatial arrangement of material at smaller scales. But their spatial arrangements are mostly constrained to a single scale and are homogeneously arrayed throughout the material. In biology there is no such boundary between form and material, and the spatial differentiation is continuously and fluidly applied across scales [12]. This characteristic contributes to the nonlinear interdependence of such systems, unlocking functional integration and high degrees of optimisation, but requiring different approaches to managing complexity in design, such as working with a transcalar methodology [2].

The complexity of form in biological organisms can be traced to the problems of scale and matter transport that arise when very small organisms combine to form larger, multicellular organisms. In single cells, diffusion is the main transport mechanism that allows cells to operate, bringing nutrients, energy and oxygen where needed. At larger scales however, diffusion is an exponentially slower process, and other bulk transport mechanisms are necessary. These can take multiple forms, such as convective flows, in blood vessels, or capillary flows, as found in the trunk of a tree. When the matter brought through such bulk flows enters a cell or passes through a boundary this is mediated by a membrane that allows for selective passage of molecules. Here again, the scales are such that diffusion is the principal mechanism. As diffusion flows cannot be scaled up by increasing the speed of a fluid, it is instead necessary to increase the surface area of the membrane. Consider the lungs of a mammal: the surface area of the membrane—the walls of the alveoli—must be enormous to accommodate the necessary mass transfer. To solve this problem, the lung is essentially a highly folded interface, where fractal organisation of space allows the membrane to fit in the limited volume of the lungs.

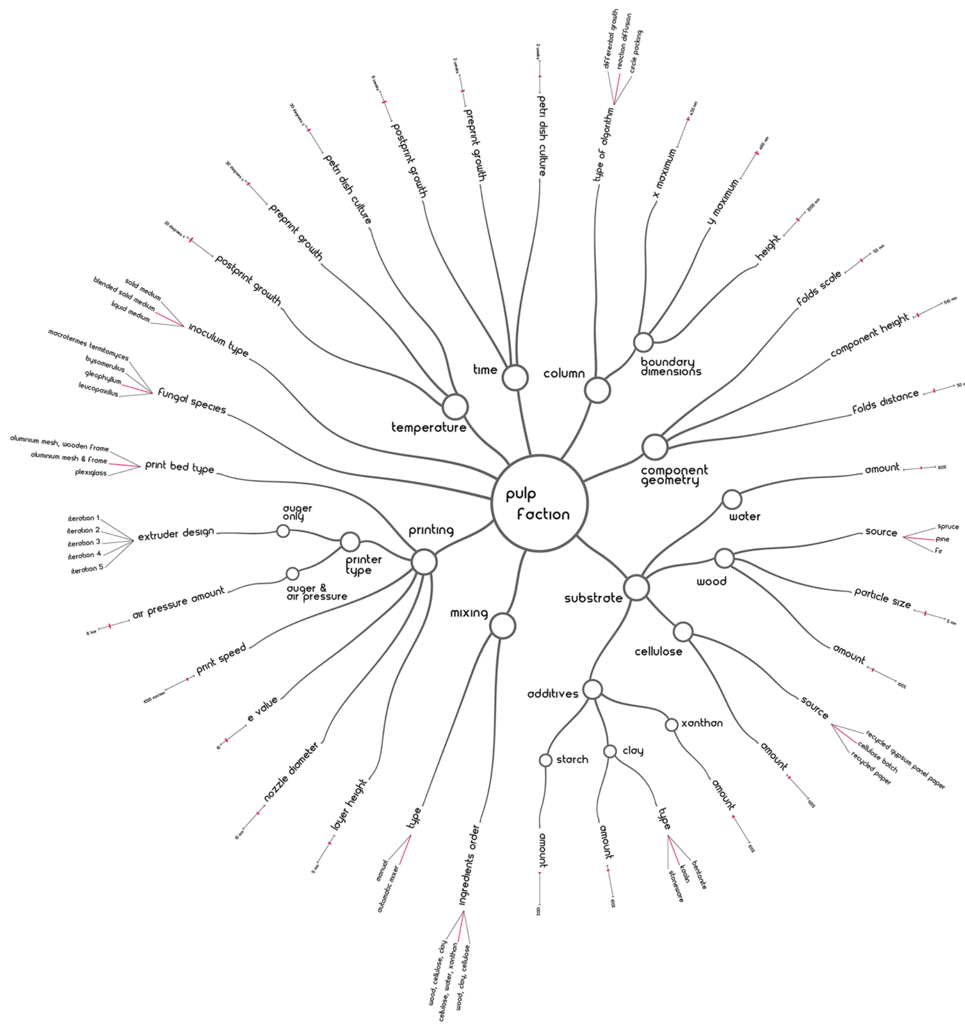

Fig. 3 Diagram over the relational design parameters in the making of Protomycokion [2]

This principle appears elsewhere in biology. The boundary is not (exclusively) a barrier meant to separate two spaces, but rather an exchange, an interface. The bigger an interface that can be fitted between two spaces, the more *work* can be done. Folding is thus an important spatial organisational principle for higher organisms [13].

Similarly, the envelope of a building, or any boundary between distinct spaces, represents a potential to harness the energy present in the differential gradient. Digital fabrication technologies allow for the fabrication of highly complex forms that can use similar principles to fold interfaces to maximise their effect. This represents an opportunity for architecture to harness the energy of a variable environment, to replace the dependence on external energy sources for heating, cooling and other manipulations of internal climates.

Local specificity

Variability and specificity are crucial aspects of complexity. Organisms exhibit incredibly high levels of adaptability to local conditions – a tree growing in windy conditions away from shelter will take on a form that responds to the forces acting on it and will be quite different from another tree of the same species growing in sheltered conditions. The development of a tree's form is constantly reevaluated and directed by the influence of the environment of the tree. Not only is the overall shape affected by the environment, but the allocation of additional material within the tree is directed by the local experience of stress, leading to a highly optimal distribution of material [14].

This aspect of biological design represents a fundamentally different process from engineering or architectural design. The genotype is not a blueprint; there is no particular form encoded in the DNA [15]. Instead, form (or *phenotype*) emerges as the result of the encoded process within a particular context. This design paradigm, *development* in biology, is the key to 'breaking through the complexity ceiling' to use the words of the computer scientist Peter Bentley [16].

Architectural design incorporates significant amounts of site and context specific adaptations. However, if we shift perspective to component and material scales, this specificity of architecture is typically phased out in favour of standardisation. As digital fabrication emerges as a viable construction paradigm, our ability to generate and make complex and specific forms increases [17]. Through the use of biological agents, this ability is harnessed at the molecular scale [2]. Computational design provides a crucial tool in how to create, understand and guide these complex forms, particularly when employed to encode processes and relationships rather than forms directly.

Durability through resilience

Modern architectural culture is partial to permanent and static materials and forms. This is contrary to biological bodies, where individual cells are perishable, but the overall form remains [18]. The biological design system is inherently circular and provides a convincing perspective for material use. In a time of ecological and climatic emergency it is not viable to erect buildings that gain their sustainable credentials through the assumption that initial resource consumption is spread over a long time. This is particularly true when society, cities and nature are changing at an ever-increasing pace due to technological developments, population growth, migration, and climate change.

In ecology studies the understanding of resilience has shifted away from *engineering resilience* defined as the time it takes to return to the initial state after a disturbance. This definition does not accurately describe ecology, but is more relevant for linear systems and contexts where the aim is to resist change and to conserve existing structures. Resilience in *complex adaptive systems* is instead defined as the ability to absorb disturbances and "and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks" [19]. Adaptive systems harness change as an opportunity for "renewal, regeneration and re-organization following disturbance " (ibid). Therefore, resilience offers the capacity to adapt to change and allow for continuous development, and this can be a relevant challenge to integrate in the building culture.

In the case of Protomycokion, the resilience of the fungus itself was utilised to resist contamination from undesirable bacteria and moulds. The inoculated material was kept in a sterile environment in the pre-extrusion phase, allowing the fungus to establish itself in the material. During and after printing, the sterility of the environment is difficult to maintain fully. But since the fungus was already established in the material at this time, it was able to resist colonization by opportunist species that would have otherwise quickly taken over the printed structures.

Ecologically sustainable architecture that follows more biological principles can be found in vernacular earth villages that still exist in several places in the world [20, 21]. Clay-based buildings such as these require ongoing upkeep to be maintained in their usable state. If these processes are followed, the buildings maintain their resilience and maintenance is kept at a minimum. If not, they slowly revert into a natural state, returning to the landscape or they become raw materials for new constructions. Since the materials are unprocessed either chemically or through heat, the built environment is fully reversible, and extensions or modifications can be made with little effort. Energy use and transport are minimal to non-existent, and because of the reversibility of the materials the ecological impact can be negligible.

If biomaterials exhibit lesser durability than industrially engineered materials, they are also more flexible, dynamic, and recyclable. A building built on principles of constant re-shaping and maintenance is also inherently adaptable. Technological development in the form of robotics, 3d printing, simulation, and biomaterials science have the potential to reduce the burden of ongoing maintenance which in the past has been one of the main driving forces away from vernacular materials towards industrial ones.

Mechanical resilience

With the advent of modern construction materials, the art of using geometry to ensure structural stability (as seen in the construction of historic arches and vaults) was largely replaced by the universal performance of the material itself. Weaker materials often come with lower ecological footprints and turning to a *strength through geometry* strategy can enable a more sustainable resource consumption in the construction industry [22]. As is seen in the case of Esfahak village, such strategies can result in dense, multi-storey settlements even without modern simulation tools (Fig. 4a-c).

Furthermore, ecological systems tend to rely heavily on redundancy and interaction [23]. Redundancy was defined by Wildavsky in Hassler & Kohler [24] as a "degree of overlapping function in a system permits the system to change by allowing vital functions to continue while formerly redundant elements take on new functions". As an example, consider the evolutionary success of spider webs is partly due to the material properties of silk, as well as the architecture of the webs. Particularly 3-dimensional webs like tangle webs show high robustness and resilience in all directions. Even at 100% strain the integrity and functionality of the web is

Fig. 4 **a-c** Village Esfahak in Iran. The 1–3 storey village is constructed almost entirely from the local clay-rich soil. Through a combination of excavation, adobe walls, and vaults, the buildings provide a rich architectural experience and pleasant interior climate

maintained; the redundancy of fibres in the complex tangle allows for sequential failure, avoiding catastrophic collapse [25].

Figure 5 shows the artwork "Nimis" by Swedish artist Lars Vilks. It represents an extreme form of architecture that relies on redundancy in both process and structure to ensure its integrity. It has been under constant construction from 1980 until the artist's death in 2021. It is made from driftwood and nails, and there is no overall blueprint or determined form, instead additions of new structural members are made based on local (in time and space) sensing and decision making.

Preventing obsolescence

Contemporary understanding of circular construction (a crucial approach for long term sustainability in the construction industry) is predominantly driven by design for disassembly. This notion relies heavily on principles of separation of function and standardisation of components [26] to achieve reusability and recyclability and requires high levels of system integration and centralised infrastructures [27] that are not always achievable or desirable.

These strategies also carry a risk that adaptation may be difficult to realise. By the time there is a need to modify or extend the building, technology may have developed to the point where the initial logic no longer applies, is made unusable through the expiry of proprietary systems or physical moulds or has simply been forgotten.

Vernacular and biological building principles function on a different logic and suggest another approach towards circular construction. By shifting from standardised and modular components to integrated geometries, future compatibility is only reliant on the building data. This can be retrieved through 3d scanning or through integrated data on the life cycle of buildings, such as the system proposed in the Durable Architectural Knowledge project [28]. Fabrication strategies such as 3d printing allow for future repairs, alterations or additions to be seamlessly integrated into the pre-existing built environment. Compatibility is thus not achieved through strict adherence to predetermined standards, but rather through adaptable and fluid software relationships.

Fig. 5 "Nimis" sculpture by Lars Vilks. Photo by Erik Daugaard, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=3521923

Feedback and adaptation

The timeline of biofabrication (in the range of days to weeks for mycomaterials) can be a disadvantage when compared to other construction materials (though concrete constructions often require similar timespans to fully cure). However, if the relationship between construction and inhabitation is reconsidered as parallel rather than linear, urgency loses meaning. Instead, a building's inhabitation coexists continuously with the growing and remaking of the building itself. These types of construction paradigms are not unheard of, and are well illustrated in Esfahak village (Fig. 4) or the contemporary artwork Nimis (Fig. 5), which are both examples of structures that have been constructed and inhabited in parallel over long time frames.

Such a slow, interactive process brings two distinctive advantages to the built environment that can increase its performance and sustainability. First, it allows the raw materials to be produced from local sun and rain, and second, it enables adaptivity and change.

Raw material sourcing

When habitation and construction are separated, the construction phase must be as short as possible to maximise the use of the building. In this scenario a centralised system is highly beneficial as it allows for resources from a large area to be intensely applied to a limited focus with high effect. Here economies of scale are critical, and standardisation of materials follows.

If a more organic growth model of building construction is made possible, the material sourcing has the potential to be solved locally. For materials such as clay or soil, resources can be found in redundant building parts or by ground excavation. Biological raw materials can be grown on or near the building and be used together with local waste and compost to feed fungal bioreactors producing stock for 3d printing of new building components.

Over time, such systems may even evolve and diversify as the biological flora adapts to the particular local habitat, and a controlled genetic adaptation of fungal strains can carry local cultural as well as performative significance.

Fluid buildings

Animals often build shelters of some kind and here construction, design, and inhabitation are inseparable [29]. A termite mound is constantly being rebuilt. Not only does it expand over time as the colony increases in size, but it also varies over the seasons. In the rainy season, food and moisture are abundant, and this is where the metabolism of the colony is at its maximum. During this time, the homeostatic zone, the volume with an actively regulated internal climate, grows and the mound increases. This is followed by a period of dryness and reduced metabolic activity, during which the homeostatic zone decreases, and the mound falls in disrepair [30]. This cycle is repeated every year over the lifespan of the colony and contributes to the adaptability and flexibility of the mound. In fact, the behavioural algorithms that drive the mound morphogenesis appear to be *dependent* on constant disturbances to function properly [31]. Considering this, the capacity to adapt with a new organization to changes is a crucial aspect of resilience.

If buildings are continuously remade, maintained, and adapted, similar fluidity can be achieved in architecture. The overlay of timescales in the cyclical change of a termite mound can be replicated to accommodate changes in use and inhabitation, as well as changes to the building's "habitat"—whether seasonal or due to climate change. Rather than design buildings as static containers, they should be homeodynamic environments, full of variable spaces fit for different activities and weather [32].

By bringing several examples of local adaptation, Alexander [33] refers to emergence as a geometric process driving biological development as well as vernacular buildings. He points out that decentralization and stretching over time contribute to adaptation which reduces mistakes in the resulting configuration. He highlights that the complexity of structures necessary for their adaptation results from a high density of internal relationships in every direction [ibid, p188].

Agent construction in biology and architecture

The common parameter between the principles outlined above is interdependence and interaction between physical and conceptual parts. Such interdependence gives rise to nonlinear behaviours which provide significant design challenges. Peter Bentley writes in *Climbing through complexity ceilings*:

> "When designing complex systems, we have to worry about complexity theory and chaos. A complex system has too many interacting components to be predictable using conventional mathematics. Each component affects too many others, each of which affect yet more (including themselves). The network of interactions may also be dynamic as the behaviour of components changes over time, defined by other interactions. Like the 'butterfly effect', if one component is poorly designed and fails, it may affect the whole system in a cascade of terminal interactions." [16]

At this point design systems based on top-down control and omniscience of the designer break down. Instead, designers should embrace a computational design and construction paradigm which is built on the morphogenetic logic of biological design. Such systems are procedural rather than formal, and based on the local action of different agents, human or otherwise.

The emphasis on local action and sensing is paramount and forms the basis for agents in biological systems. Agent construction principles appear repeatedly in biological design, such as the interplay of osteocytes and osteoclasts that control the formation and adaptation of bone in our own bodies. Through their interplay emerges a dynamic system where bone is optimised for the loads it experiences without the need for a central template. There is no global coordination of the cells, instead each individual senses its immediate environment and acts accordingly [34].

Mound-building termites function in a similar way, though with a more complex set of inputs and outputs. A colony consists of a few million termites, and each individual belongs to a certain caste (e.g., minor and major workers) with its own set or operating procedures. The coordination of the termites' actions take place through *stigmergy*, where individual agents coordinate their actions through the physical environment. The actions of one agent influences the environment and the resulting change is picked up by nearby agents. These modify their own behaviour based on the signals received with coordinated action as a result [35, 36]. The individual agent only needs to sense its immediate environment, both in space and time. This radically reduces the complexity of the individual agents and eliminates or limits the need for a global or centralised hierarchy and communication system. A benefit of agent systems apart from their ability to navigate complex design tasks is that the design outcome is never static, but constantly renegotiated in response to changing surroundings.

Computational simulations based on the physical and biological world can be used to design the built environment in a generative fashion. Like biological organisms, generative simulations are at their base a code or program that describe a series or behaviours or reactions depending on contextual input [37]. A building must incorporate the code for its own transformation into the unpredictable. Through physical agents, be them humans, swarm robots, or 3d printers, data is collected, and physical interventions are made continuously.

Thus, the role of the designer or architect must necessarily change. Andrasek and Andréen [38] write:

> "The designer's role changes to that of the programmer, who sets relationships and fundamental behavioural rules, manipulating them in the pursuit of the desired outcomes, which are not simply built but which arise in dynamic equilibria. The designer shifts attention, one could say, from only the visible, formal representation, to extend it into a domain of the invisible: the underlying logic and procedures."

Conclusion

From the making of *Protomycokion* it became evident that biodesign in architecture comes with challenging propositions for the construction industry and for the architectural designer, and that business as usual is not a convincing option. The link between biological design and biodesign is both direct and indirect. Direct in the way that incorporation of living organisms requires consideration to be taken to the ongoing processes that sustain the life of the organisms and that must be accommodated in the built environment where they live. But also indirectly, in that the possibilities of what can be accomplished through design is increased when biological principles make it possible to engage with higher levels of interconnectedness and complexity.

The four principles we suggest here are: *diversity*, *complexity and specificity (of form)*, *durability through resilience*, and *feedback and adaptation*. These strategies are not necessarily novel in themselves—it is the way architecture has been created over the ages before the invention of the modern construction industry with its engineering prowess and rationalisation. Vernacular architecture, both ancient and contemporary, incorporated much of these strategies.

The challenge moving forward is to integrate these approaches into the requirements of contemporary society. This means achieving high levels of performance (cultural as well as functional) and efficiency, as well as accommodating lifestyles that are more global, diverse, and specialised. While human interaction with buildings is an important aspect of adaptive architecture, building inhabitants are no longer able to dedicate the amount of time and skill that is required to maintain much vernacular architecture. A new synthesis between old and new, biology and engineering is called for. The distinction between high tech and low tech is perhaps unfortunate since it implies a sense of progression from "low" to "high". Instead of an opposition between the two we see a more productive future where they are combined: Bulk material is sustainably sourced and processed, and it is complemented by high-energy, high-performance materials that are employed more selectively and with greater criticality.

The reality is that much has been sacrificed when moving to the industrial paradigm, but equally much has been gained. At the current time we face unprecedented challenges, but we are also fortunate to possess knowledge that may prove to be crucial for a transition to the future: insight into the unsustainability of the current approach, and a new understanding of the world and a new set of tools that is uniquely suited for addressing these challenges.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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