

Adaptive fungal architectures

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With an estimated 3.8 million species, fungi are amongst the most numerous creatures in the world. They started, shaped and maintained Earth ecosystems. Fungi also act as forest internet allowing trees to communicate with each other and with microbial populations. Fungi can sense everything humans can sense. Fungi demonstrate a high degree of proto-intelligence and show evidence of a long distance communication within their extended bodies that includes decision making. Fungi are also used as furniture, building and decoration materials. Taking into account all these unique properties of fungi we decided to produce a living and ‘thinking’ house made of fungi. Here we discuss our first steps towards the biofabrication and implementation of our fungal architecture.



Fig. 1. Fungal architecture in the post-apocalyptic world. Installation by Irina Petrova (<https://www.irina-petrova.com/>). Printed with kind permission of Irina Petrova.

In 1953 the 25 year old Robert Sheckley published “Specialist”,⁶ a short science fiction story that depicts, presumably for the first time, a galactic bio-ship driven by a crew comprised of members of diverse intelligent species that had to cooperate symbiotically forming the different parts of the craft; Engine, Thinker, Eye, Pusher, etc. After Sheckley’s first conceptualisation, the idea of living and sentient bio-ships

has been growing in the sci-fi imaginary. Bio-ships are made of biological components and most can be considered lifeforms of their own. Like other living beings, bio-ships can sense their environment and respond to it, searching for food sources, fighting and regenerating damaged parts, growing and reproducing their kind, and most-likely protecting and nurturing their cargo, usually members of other

species working for mutual benefit. Despite their organic nature, sci-fi bio-ships can be gigantic, sturdy and able to travel harsh deep-space conditions. An organic real-world material able to offer some of these protective characteristics is chitin, one of the most abundant polymers on earth forming the shell of insects, crustaceans and fungal cells.

Wild sci-fi is one of the best motors of scientific research pointing to possibilities far beyond the current state of the art, or more precisely, beyond our state of mind (Fig. 1). Visualising a bio-ship can be helpful to understand the relationships within a forest or any given self-sustaining Earth’s ecosystem, including the human body. Moreover, we can find parallels between the internal works of a bio-ship and the intention and the rationale behind a project such as FUNGAR, acronym for Fungal Architectures, a EU Horizon 2020 research project that seeks to develop a fully integrated structural and computational living monolith by using fungal mycelium. The goal: to advance towards the realisation of full-scale intelligent bio-buildings and other functional bio-structures. In this short paper we introduce the state of the art of fungal biofabrication technology and report on the progress done by the partners involved in the FUNGAR project.

Fungal Biofabrication

Biofabrication can be defined as the production of complex living and non-living biological products from raw materials such as living cells or molecules. In the long term, biofabrication can dramatically transform traditional industries becoming a new paradigm for 21st century manufacturing. A fast evolving and growing branch of the biofabrication field is led by fungal-derived biomaterials and the researchers behind them. At the current moment, several private companies, public universities, artistic and scientific organizations worldwide have embraced fungal biofabrication as a subject of study, research and development,⁷ including MOGU S.r.l, Utrecht University, CITA based at Royal Danish Academy and University of the West of England, the four FUNGAR partners in charge of the different fungal biofabrication and functionalization efforts.

Fungal bio-based materials (Fig. 2), or shortly mycelium materials (MMs), are considered an emerging family of environmentally friendly composites and natural polymers of fungal origin mainly based on chitin and glucan fractions, the main components of the fungal cell walls.⁸ Although the usage of fungal-sourced materials is not new in human history,⁹ their production, transformation and distribution following modern biotechnological and commercial processes is an industry in its very infancy.

MMs are currently commercialised as packaging and construction elements, acoustic insulation panels, furniture and decoration pieces, automotive upholstery and also as leather-like non-woven fabrics in the form of flexible fungal mats.¹⁰ In contrast to their petroleum-based counterparts, MMs are fully biodegradable, moreover their production process is simple and economical, requiring a minimal knowledge of fungal biology and a basic set of tools normally used in other fungal biotechnological activities, such kitchen fermentation processes (e.g. tempeh, koji) or mushroom cultivation operations.¹¹

Most MMs listed above are normally manufactured through solid state fermentation (SSF) methods involving the propagation of pure fungal cultures on lignocellulosic substrates such as sawdust, wood-chips, straws, hulls and similar side-and waste-streams from agroindustrial activities.¹² The fungal hyphae grow on these substrates, forming a fibrous matrix, the mycelium, surrounding, covering and binding together all the substrate particles forming a composite solid material that sometimes can feel foamy. Once harvested, these composites are normally dried using convection ovens to stop fungal activity, action that aims to ensure the preservation of the object by avoiding a total digestion or decomposition of the substrate. Alternatively, liquid state fermentation (LSF) techniques have been developed to produce pure fungal biomass that can be further processed into functional materials such as mycelium-based papers and leather-like mats.¹³ Such LSF protocols have been adapted from well-established fungal enzyme production processes (e.g. penicillin, citric acid or mycoprotein production). Although these and other

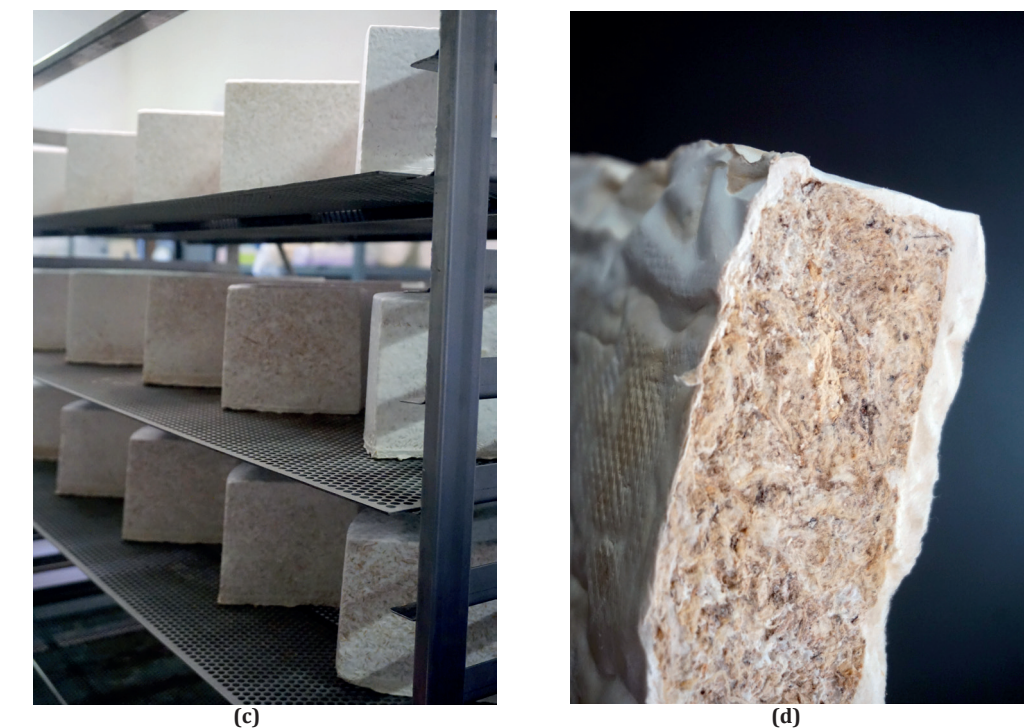


Fig. 2. (a) Mycelium of a lamentous fungus growing on Potato Dextrose Agar (PDA). (b) Antlers or elongated primordia of *Ganoderma lucidum* seeking for light and higher oxygen concentrations. (c) Composite MMs in form of bricks made by growing fungal mycelium on hemp shives. (d) Transverse cut of a mycelium brick grown on cotton waste.

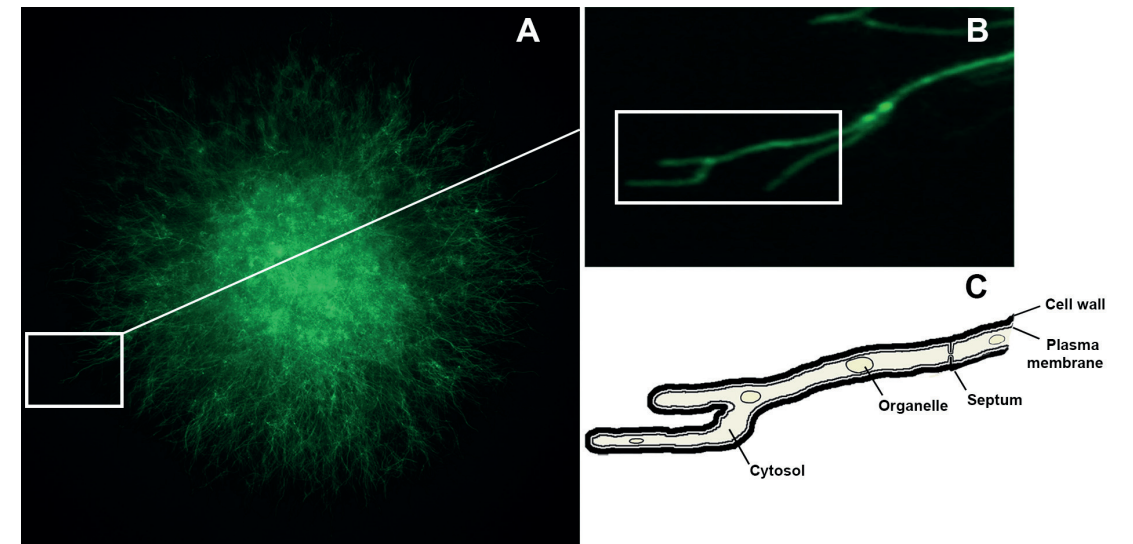


Fig. 3. An example of a fungal colony (a) and hypha (b) and its corresponding schematic diagram (c).

methodologies and applications for fungal biofabrication have been recently made available, there is a long way to go regarding the improvement of the cultivation systems and the mechanical properties of the materials, as well as the overall biosafety of the art.

One of the challenges in FUNGAR will be to grow a large living fungal structure in the metre length scale; more specifically a self-supporting and self-sustaining biocomputing monolith. This bio-structure will serve as proof of concept prior to implement complete fungal architectures in the near future, such as housing and other functional buildings. The fungal monolith will consist of a superstructure of interconnected fungal threads or mycelium growing on a nutritive woody scaffold. The active living threads of the fungal mycelium will carry information, sensing its immediate environment and responding to it. This concept will result in the development of new cultivation and life-sustaining protocols for living fungal networks. The success of such an undertaking will be measured by the active growth of the mycelium on selected substrates and its capacity to remain alive, healthy and ultimately sentient to the external conditions, whether it is provided by the natural elements, by touch or by electrical stimuli directly applied by micro-controllers

and *in silico* computing units as described in the following sections.

Conductive Functionalisation of Fungal Mycelium

A mycelium consists of a network of hyphae (Fig. 3a). Fungal hyphae are thread-like structures that can have a length in the centimetre range under laboratory conditions. Hyphae are highly polarised. They grow at their apex and form lateral branches in sub-apical regions (Fig. 3b). For instance, in the case of the mold *Aspergillus niger*, growth occurs within the first 25 μm of the hyphae, while the first branch is made after 150 — 300 μm ¹⁴ (Fig. 3c). This polarisation is the result of developmental and environmental cues.¹⁵ Hyphae of the most species rich groups of the fungal kingdom, the ascomycetes and the basidiomycetes, are compartmentalised by cross walls called septa. These septa have pores that allow streaming of cytosol and even organelles from one compartment to the other and from one hypha to another. These septa are placed at regular distances. In the case of *A. niger* and the mushroom forming fungus *Schizophyllum commune*, septa are placed every 50-100 μm ¹⁶ (our data unpublished). By closing the pores,¹⁷ these fungi can isolate hyphae or compartments enabling

them to specialise.¹⁸ For instance, some hyphae at the outer part of the mycelium of *A. niger* release proteins in the medium, while others are more resistant to heat. Hyphae have a width of about 2-10 μm . The cell wall is the outer part of the hypha. It protects the underlying plasma membrane, that in turn envelopes the cytoplasm. The latter consists of a cytosol with organelles like nuclei, mitochondria and vacuoles. Depending on the culture conditions

conductivity. Current propagated along a hypha did not leak into the medium surrounding the mycelium,²² indicating that the cell wall and cell membrane are good insulators as was described previously.²³ Thus, the cytosol is the main conductive part of the hypha. Septa of *Neurospora crassa* do not seem to exacerbate voltage attenuation. However, the septa in this fungus seem to be generally open, enabling uninterrupted cytoplasmic flow.²⁴ In contrast, a

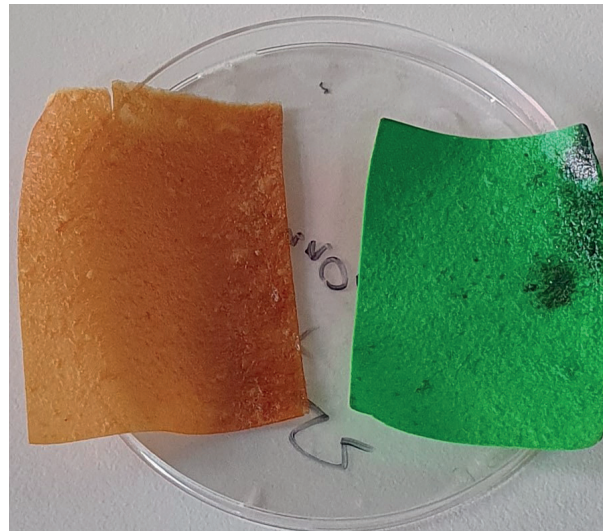


Fig. 4. Films of dead mycelium that was chemically treated to increase electrical conductivity. The lm on the right-hand side has been doped with Cu^{2+} and is six times more conductive than the lm on the left-hand side.

the cell wall thickness varies, but as a thumb of rule it is about 0.20 μm ¹⁹ while the plasma membrane is about 15 nm thick²⁰ (Fig. 3c). A mycelium can be considered heterogeneous. Hyphae at the outer part of the colony grow and colonise the substrate, while most hyphae in the central zone of the mycelium do not grow. In fact, they may have even lost their cytoplasm. The heterogeneity of the mycelium as well as the heterogeneous structure of the hypha along its length and width makes it challenging to produce a conductive material made from fungus, as a hypha is only as conductive as the strongest resistor in said hypha and not all hyphae are interconnected. Hyphae of some fungi have been shown to be sensitive to electrical fields, growing either toward or away from the cathode or anode. In addition, hyphal branching could be increased by an electrical field.²¹ These data show that fungal hyphae, or parts thereof, show some degree of

high percentage of septa of other fungi like the mushroom forming fungus *S. commune* or the molds *A. oryzae* and *A. niger* are closed.²⁵ The question is whether this will also diminish current flow in the hyphae. It should also be noted that even in *N. crassa* a voltage attenuation was observed of 70 % after 0.49 mm.²⁶ This would make fungal hyphae good resistors. The current observed in *N. crassa* leads to the prediction that conductivity of a mycelium happens mostly in the form of electrolytic conductivity. Indeed, when mycelium of the fungus *S. commune* is dehydrated, material resistance exceeds 20 MO compared to 1.5 MO when the mycelium is still living (our unpublished results). This is equal to the electrical resistance that was previously found in the living mycelium of the fungus *Pleurotus ostreatus*.²⁷ The high electrical resistance of dehydrated mycelium does not mean it cannot be used in electrical appliances. High resistance materials

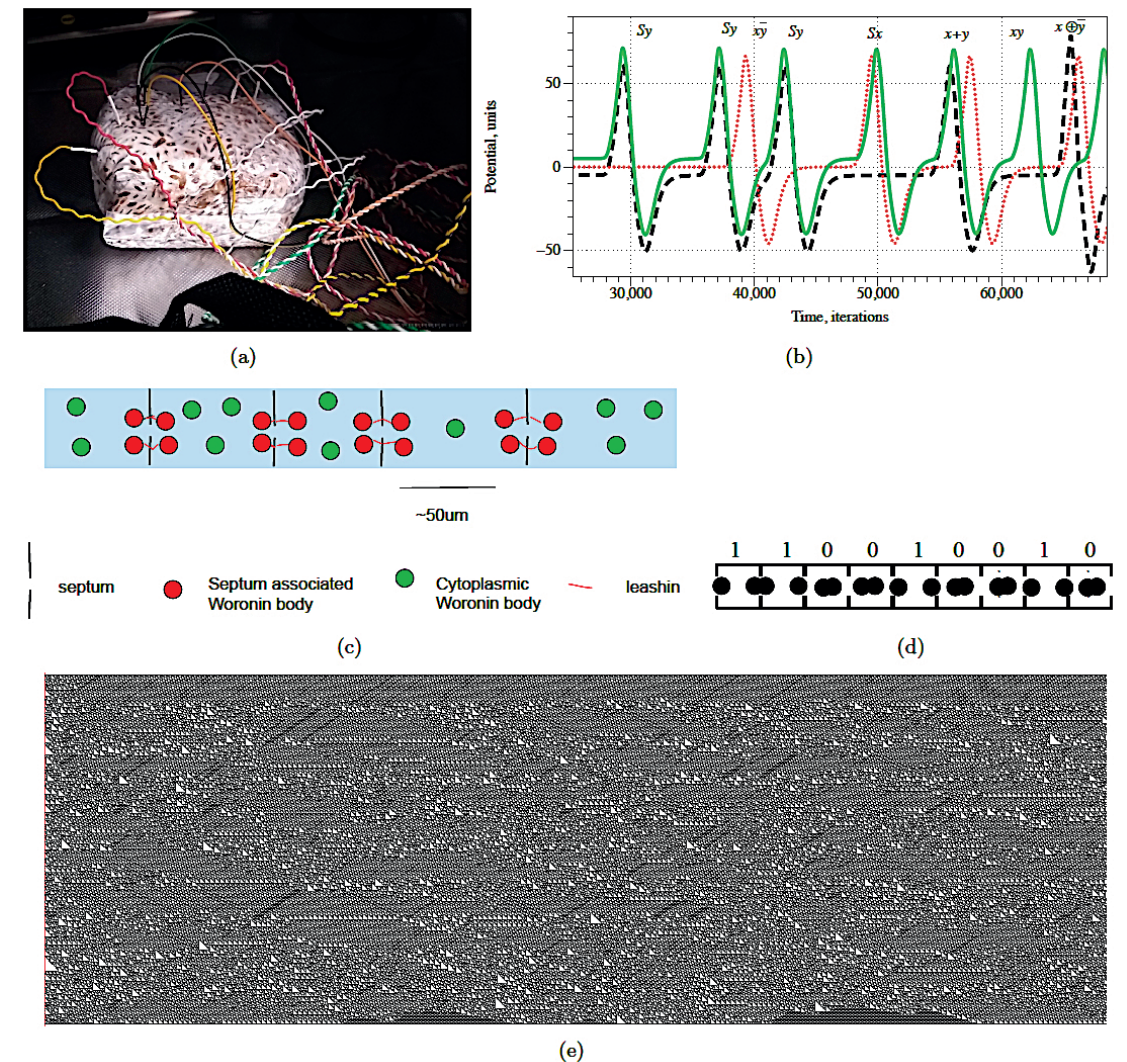


Fig. 5. Towards fungal computing. (a) Exemplar setup of recording electrical activity of mycelium of *Pleurotus ostreatus*. (b) Example of Boolean gates implementation with computer model of spikes travelling in a fungal colony. Fragment of electrical potential record in response to inputs (01), black dashed line, (10), red dotted line, (11), solid green line, entered as impulses.²⁸ (c) A biological scheme of a fragment of a fungal hypha of an ascomycete, where we can see septa and associated Woronin bodies.²⁹ (d) A scheme representing states of Woronin bodies: '0' open, '1' closed.³⁰ (e) Exemplar evolution of a one-dimensional fungal automaton: the arrays of nite state machines is vertical and time increases from the left to the right.³¹

can be used as a capacitor (see above) or to convert electrical energy to heat. To expand the electrical functionality of fungal mycelium it has to be modified (Fig. 4). This can be achieved by functionalisation or by changing the inherent properties of a mycelium. The largest contributor to fungal mycelium electrical resistance seems to be the cell wall and the cell membrane.³² This can be an advantageous property as an insulating outer layer can keep an electrical current inside a hypha. A hypha would then need to

be modified in such a way that both the apical and distal parts of a hypha are conductive. A conductive living wire would be obtained with an increase in cytoplasmic conductivity. To increase cytoplasm electrolytic conductivity a fungus would need to be more tolerant to high concentrations of conductive ions. Several fungal species display a high transition metal tolerance (our unpublished results). These metals may be taken up and stored in special organelles in the cytosol. In this case, they will not likely increase conductivity significantly. It

may also be that the metals are pumped out of the cell continuously, maintaining a higher but non-toxic level in the cytosol. This would contribute to the conductivity of the hyphae but its extent needs to be determined. Finally, metals may not enter the cytosol, but instead bind to the cell wall. Binding of metals to the cell wall may enable yet more electrical applications as alternating conductive and insulating layers are useful in transmission of high frequency electrical signals (e.g. coaxial cables or high-voltage cables).

Fungal computing

There are three ways of making sensing and computing devices with fungi: morphological computation, spikes based computation and conventional computing with fungi as organic electronic devices.

The morphological computation would represent data with spatial distribution of attractants and repellents. A mycelium network developed in these gradient fields would represent a result of the computation. This method is well tested and proved to be successful in the implementation of slime mould based computing devices.³³ The morphological computation is slow because it is based on a physical growth of the creatures. Thus we turned to a computation with electrical phenomena.

Whilst oscillation of electrical potential of fungi have been reported once in 1970s³⁴ and once in 1990s³⁵ by intra-cellular recording, only recently did we discover that the oscillation can be equally well recorded extra-cellularly by inserting electrodes in fruit bodies³⁶ or even in a substrate colonised by fungi (Fig. 5a). Several modes of spiking have been discovered and electrical responses of fungi to thermal and chemical stimulation have been analysed.³⁷ We previously³⁸ proposed that fungi Basidiomycetes can be used as computing devices: information is represented by spikes of electrical activity, a computation is implemented in a mycelium network and an interface is realised via fruit bodies. In an automaton model of a fungal computer, we have shown how to implement computation with fungi and demonstrated that a structure of logical functions computed is determined by mycelium geometry.³⁹ In

the FUNGAR project, the automaton model was perfected by using the FitzHugh–Nagumo model to imitate propagation of excitation in a single colony of *Aspergillus niger*. We developed techniques of encoding Boolean values by spikes of extracellular potential. We represented binary inputs by electrical impulses on a pair of selected electrodes and record responses of the colony from sixteen electrodes. We demonstrated that the colony can compute by deriving sets of two-inputs-one-output logical gates implementable (Fig. 5b).⁴⁰ Ratios of the gates found matches well the ratios of the gates discovered in other living systems, in the case of the simulated fungal colony the ratios was the gates were or 0.13, select 0.56, xor 0.04, not-and 0.11, and 0.15. Preparations for implementation of fungal computing with real living mycelium is underway. In the meantime, we have developed an abstract model of fungal computing based on some particular features of mycelium—the fungal automata.⁴¹

Two types of fungal automata were proposed: 1D and 2D. In the 1D automata we studied models of information dynamics on a single hyphae.⁴² Such a filament is divided in compartments (here also called cells) by septa (Fig. 5c). These septa are invaginations of the cell wall and their pores allow for the flow of cytoplasm between compartments and hyphae. The septal pores of the fungal phylum of the Ascomycota can be closed by organelles called Woronin bodies. Septal closure is increased when the septa become older and when exposed to stress conditions. Thus, Woronin bodies act as informational flow valves (Fig. 5d). The 1D fungal automata is a binary state ternary neighbourhood cellular automata, where every compartment follows one of the elementary cellular automata rules if its pores are open and either remains in state '0' (first species of fungal automata) or its previous state (second species of fungal automata) if its pores are closed. The Woronin bodies closing the pores are also governed by automaton rules. We also analysed a structure of the composition space of cell-state transition and pore-state transitions rules, complexity of fungal automata with just a few Woronin bodies, and exemplified several important local events in the automaton dynamics (Fig. 5e).⁴³

Inspired by the controllable compartmentalisation within the mycelium of the ascomycetous fungi, we designed 2D fungal automata: cellular automata where communication between neighbouring cells can be blocked on demand.⁴⁴ We found that these automata are computationally universal. This has been proved by implementing sandpile cellular automata in 2D fungal automata. We reduced the Monotone Circuit Value Problem to the Fungal Automaton Prediction Problem, and constructed families of wires, cross-overs and gates to prove that the fungal automata are P-complete.

Architectural design

As reported above in the “Fungal Biofabrication” section, MM’s have entered the building industry through products such as acoustic insulation panels and flooring tiles – applications that permit their incorporation into conventional construction approaches and building systems. Speculative constructions, in which MM’s play a central role in the construction logic or building system, have been recently demonstrated in the form of full-scale temporary constructions.⁴⁵ Here, one of the primary foci has been on exploring and exploiting their structural (load-bearing) capacities. The study of MM’s for application as primary construction material for architectural structures is accelerating and diversifying in productive ways, for example, finding intersection with 3D print technologies to achieve highly intricate geometries that are not reliant on molds.⁴⁶ In one speculative design proposition, 3D printing becomes a mechanism for exposing the contaminated soil of an inner urban site and exploiting the remediation capabilities of *Pleurotus* and *Trametes*.⁴⁷ Such a proposition calls into question orthodox understandings of what architecture is, what roles it performs and what its objectives are – seeking new and expanded relationships that promise a more ecologically engaged practice. With its core objective of developing a living construction material with computational capabilities from mycelium, the FUNGAR project aims to contribute to this widening of architectural scope with extension to design practices and new construction logics.

The material basis of the FUNGAR project presents many novel construction challenges to the realisation of architectural outcomes. Two key challenges are: 1) cultivating MM’s at meter lengths scales; 2) achieving structural capacity with MM’s that are living and therefore continually altering in their chemical and mechanical properties. To address these primary challenges, we are investigating a novel construction concept that employs stay-in-place scaffolds produced using a sparse Kagome weave pattern (Fig. 6).

Kagome is a resilient triaxial weave based on a regular hexagonal lattice. It is also a very versatile weave that allows complex morphologies to be realised through the judicious application of simple topological transformation principles.⁴⁸ These local changes of topology – referred to as singularities, or lattice disclinations – govern the production of double curvature by generating out-of-plane stresses in the weaver material. Kagome therefore provides a principled approach to the production of scaffolds that can achieve architectural scales (meter length), act as porous containers for MM ‘s to grow within and provide structural capacity for MM’s that are in continuous states of chemical and mechanical transformation. This novel construction method contributes a bio-hybrid approach in which technical elements and living complexes are synergistically combined to achieve design intentions and support architectural objectives.

Working with living complexes offers an opportunity to enrich the palette of orthodox architectural objectives. Tasks such as boundary creating, framing, filtering and staging have the potential to be reimagined by coupling them with attributes such as growth, adaptation and metabolism. The project’s aim, of producing a living computing substrate that can be used as construction material, will provide novel capabilities embedded at the scale of material. This presents the fascinating design challenge of determining how the spatial distribution and organisation of that material can influence the computation – how the space of an architecture assists in its computation. The idea that spatial form languages emerge from targeted objectives is familiar and perhaps most

tangible through structural performance, as in the case of membrane architectures and compression-only shell structures. The compelling promise of working with actively computing living substrates is that new form languages and spatial characters will be invented. This is quite tangible and achievable, for example, through the informed design of geometries and

volumetric parameters of material to influence spikes based computation, or contained regions of discrete mycelium networks organised through differentiated structural elements to create parallel computing units that can exchange information.



Fig. 6. Early prototype component exploring the compatibility of mycelium composite grown within a rattan Kagome weave. The weave acts as a combined stay-in-place formwork and reinforcement.

Discussion and future challenges

Despite a growing pool that estimates a total of approx. 3.8 million species from which only about 120.000 are currently identified,⁴⁹ just a few dozen basidiomycetes are currently being used in the manufacturing of MMs. Therefore, basic screening and selection efforts are required to identify more species with features of interest. In parallel, new developments in fungal genetic engineering using tools like CRISPR⁵⁰, or user-friendly cloning frameworks such as the FungalBraid⁵¹, could lead to fast-prototyping of new metabolic pathways and phenotypes, allowing new unforeseen properties and functionalities. Moreover, such genetic engineering efforts could lead to establishing new symbiotic or co-protective relationships between fungi and other living beings, mimicking relationships already observed in nature such as the fungus-growing ants and termites, and allowing the deployment of truly engineered living materials that can survive on their own and respond to external stimuli. Furthermore, we can imagine that SSF, LSF and combined (hybrid) manufacturing technologies will continue to be improved, providing fruitful synergistic results and making MMs manufacture ready for mass production and functional application across industries and households.

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Quantum Computing: Coping with Underpowered, Inaccurate, but Astonishing Quantum Computers

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Why quantum computing?

Gordon E. Moore’s 1965 law is the empirical observation stating that the number of transistors on a chip doubles about every two years. This prediction has defined the trajectory of computing technology and, in some ways, it marked the progress itself.

In early 1990s talks about the eventual decay of Moore’s law lead to the question: what

happens when Moore’s Law (inevitably?) ends? Among various possibilities, the advance of new models of computation, called *unconventional*,² was one. At that time there was a widespread belief that the P vs. NP problem – currently still open – will be solved in the negative before the end of the century. This motivated the need to find fast algorithms to solve NP problems, a computational challenge