Figure 1. Kintsugi, the art of mending broken pottery by valuable elements (Image Credit: Motoki Tonn)

Controlling the Uncontrollable

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Abstract

Throughout the history of architecture, new design, fabrication, and production paradigms have arisen from industrial revolutions. The three revolutionary eras of mechanical, electrical, and electronic engineering have led to three principal paradigm shifts in architecture. Now, in the fourth industrial revolution era, another change in the perspective seems necessary. This era, distinguished by climate change, environmental problems, and biodiversity, offers the possibility of returning to nature and taking advantage of biomaterials. The increasing interest among scholars and industries in using nonindustrial timber, bamboo, bacterial cellulose, algae, and mycelium shows the importance of this return to nature. However, working with bio-based materials as living organisms challenges the designers in a multitude of ways. These materials are intrinsically uncertain, mostly weaker than common materials in mechanical behavior, and thus, more unstable while prepping and functioning in different environmental conditions. These challenges call the designers and the existing traditional methods of design, fabrication, and production into question. Working with these materials goes beyond the straightforward studies on forming the material and even the relationship between form and matter. On the one hand, these materials are cultivated by designers so that they control the material properties as part of the design process. On the other hand, the intrinsic uncertainty of these materials may enable the design process with unexpected discoveries. In other words, the fourth dimension of time is involved in working with these materials. Thus, unlike traditional materials, the outcome is imposed not only by the designer but also by a dialogue between the designer and the material. This paper discusses how these novel biomaterials are uncertain and, thus, unstable in their prepping and curing processes and the importance of the interrelationship between the designer and the material to cope with this uncertainty with prototypological frameworks. This paper presents a study on mycelium-based composites as a specific case to contextualize the broader research.

What is the 'MATTER'?

Due to the climate emergency, our world changes almost daily. This unstoppable change affects every aspect of our lives. As architects and designers, we must conform to the change and shift our design and manufacturing paradigms accordingly. Materials, as Janet McGaw (2018) describes them, are the stuff to make architecture, in contrast to words that make the discourse. The importance of materials and their role in the design and manufacturing of any physical object is undeniable. Our approaches to using and forming materials might be the key to conforming to the ever-changing world.

In contrast to the common understanding of the relationship between form and matter in design and making, Benay Gürsoy, in her extensive study on approaches to making, states that there is a less-practiced approach that values the uncertainties in the processing of materials. In this approach, the *hylomorphic* model of creation is challenged. In *hylomorphism*, form is the substantial part of making, which gives the essence and identity to the matter, while in this approach, the form and matter are not separated (Gursoy, 2016). From an ordinary point of view, materials can be shaped to meet the performance requirements resulting from a design proposal. Nevertheless, it is also possible to develop new materials to respond to highly particular design problems that the designer has redefined (Gourdoukis, 2015). For such an approach, we must rethink the matter and the technique to form the matter.

Throughout history, we adapted novel materials and technologies from other disciplines and shifted our design and manufacturing paradigms. In the past three centuries, parallel to Industrial Revolutions, the architecture, engineering, and construction (AEC) industry revolutionized. Mechanical and materials engineering in the eighteenth century, electrical engineering in the nineteenth century, and electronics and information technology (IT) in the twentieth century have affected architecture and design from different aspects, including how form and matter are linked. After the Industrial Revolutions, the main structure of buildings changed. The first industrial revolution introduced novel materials in mass-produced amounts shifting from masonry to cast iron and steel. The second shift happened right after the omnipresence of electricity. The buildings got taller as elevators started to work, and artificial lighting possibilities have instigated architectural changes. Then, after electronics and IT stepped in, the concept of mass customization instead of mass production (Wang and Duarte, 2002) and using digital technology to generate unprecedented design ideas raised and modified the building industry. The interconnection between digital design and digital tools to deliver an exact physical model out of the digital world also became possible. However, at this point, a new challenge started to show up: The digital design and fabrication protocols, while allowing designers to rediscover the idea of form and matter through standardization and simulation, began to eliminate the emergence and unpredictability that characterize processes that harness materiality (Gourdoukis, 2015; Gursoy, 2018).

Now, at the gate to the fourth industrial revolution, we should look for another revolutionary paradigm shift in our design and manufacturing. Park and Bechthold (2013) suggest that the fourth revolutionary change in the building industry may happen soon with a return to nature. So, biomaterials in the built environment can be a possible answer to the main challenges of our era, like climate change, environmental problems, and unprecedented population growth.

BIO-MATTER

Biomaterials are materials made from living organisms that frequently exhibit exceptional mechanical and more sustainable qualities compared to the weak components from which they are generated (Zolotovsky, 2018). Because they require little energy to function and cause the least amount of waste, these materials are typically considered sustainable (Vincent 2012). However, there are certain obstacles towards using biomaterials in the AEC sector: Because many of them cannot be used as raw materials, and their large-scale uses are still underdeveloped, they need to be processed (Derme et al. 2016). The hierarchy, self-assembly, and self-healing capabilities of biomaterials are among their most significant characteristics. The exciting options for various kinds of expression that can be realized and the potential to redefine production paradigms to find more sustainable solutions are the driving forces behind incorporating biomaterials into design and construction (Karana et al., 2018). Katia Zolotovsky suggests dividing these materials into three groups based on their performance. When a product is concluded, the first group of biomaterials employed in the fabrication process is killed or, at the very least, hibernated. The second group reacts to their surroundings after manufacture and acts as a component of the living system and a piece of the finished building. The final group consists of structures fully activated by living organisms interacting with their surroundings and responding to stimuli.

She refers to these three groups as "bio-based," "bio-responsive," and "bio-active" materials, respectively (Zolotovsky, 2018).

Innovative technologies that can improve the qualities of biomaterials with the least amount of alteration to their natural behavior are needed to advance them in the AEC industry. Different techniques are employed to create matter that can be used to produce bio-based products. "Some need standard procedures like baking, molding, and mixing, while others will demand more radical techniques like cultivating, breeding, raising, or farming" (Hebel and Heisel, 2017).

To start engaging nature as a collaborator in design techniques, we need to stop viewing it as a model to be merely imitated. Instead, we should emphasize co-construction principles. We emphasize that design output is the consequence of a co-evolution, assuming nature is an active participant within architectural processes (Marinelli, 2020). However, when seeing nature as a collaborator, the fourth dimension, time, enters the scene, and the idea of the temporality/instability of matter shows up.

Temporality/instability of MATTER

Like everything else in our world, materials are also subject to change. This change causes a temporality and, in a broader sense, instability for the materials. The material lifecycle is the most plausible notion of time for materials in architecture. Since every material has a shelf life and eventually begins to deteriorate, we can classify all materials as temporal. Arts like *Kintsugi* (Figure 1), which is to repair broken pottery by mending the areas of breakage with valuable elements like platinum and gold, show the importance of time within the objects and matter. Acknowledging the passage of time within the lifetime of an object helps the audience of artwork or habitants of habitat to experience something different. As architects and designers, we mean to let people face new experiences. While two pots manufactured in the same manufacturing line may seem perfectly the same to people's eyes, when they break, they break differently. If mended by Kintsugi, they will not be similar anymore. Each of them, after this breakage, has a unique look and story. So, the idea of the time passage can completely change the users' perception of the object.

However, the idea of time in this research is slightly different. The source of temporality/instability in this research is the prepping and curing of materials. Concrete, the most used construction material worldwide, is an example of temporal material in this sense. While studying the characteristics of different concrete mixtures, scholars evaluate their material properties at different ages, such as the third, seventh, and twenty-eighth days of the curing process. This change in the material's properties and behavior shows how time affects the material and the construction. In more focused studies, the time has a more prominent role in novel manufacturing techniques such as additive manufacturing. The setting time of the material has the primary role in designing and developing the toolpath for extruding the material (Li et al., 2020; Ashrafi et al., 2021). As layers of the extruded concrete sit upon each other, it is of the highest importance for the designers and manufacturers to know when they can extrude the next layer and modify the design accordingly.

While concrete, as an example of conventional materials, shows the temporality/instability related to the prepping and curing, most unconventional materials, especially biomaterials, exhibit more time-dependent behaviors regarding their inherent uncertainties. The fourth dimension of time has a prominent role in designing and manufacturing these materials, and coping with it requires novel frameworks and paradigms.

Controlling the Uncontrollable

Alison Gopnik used a metaphor in her book, *The Gardener and the Carpenter*, about children's development. While a carpenter has a predefined roadmap or set of instructions to form the material, the gardener must conform to a plant's day-to-day changes and adjust the workflow according to the outcome of previous work. With the same analogy, working with biomaterials tends to be a gardener's work more than a carpenter's. When working with conventional materials, the designer and the manufacturer can use standards and instructional codes to design, develop, and build an object. However, working with uncertain and unconventional materials needs more flexibility, conformation, and a fast-paced response to how the material behaves.

From another perspective, working with these materials allows us to consider them as our co-designers. Due to the inherent uncertainties of these materials, the design process may result in unexpected findings. This potential is because designers cultivate the materials to control the material properties as part of the design process. In contrast to traditional materials, the output is dictated not only by the designer but also through the dialogue between the living matter and the designer. The title of this paper, *controlling the uncontrollable*, never means limiting the uncertain materials. It means working with these materials requires knowing

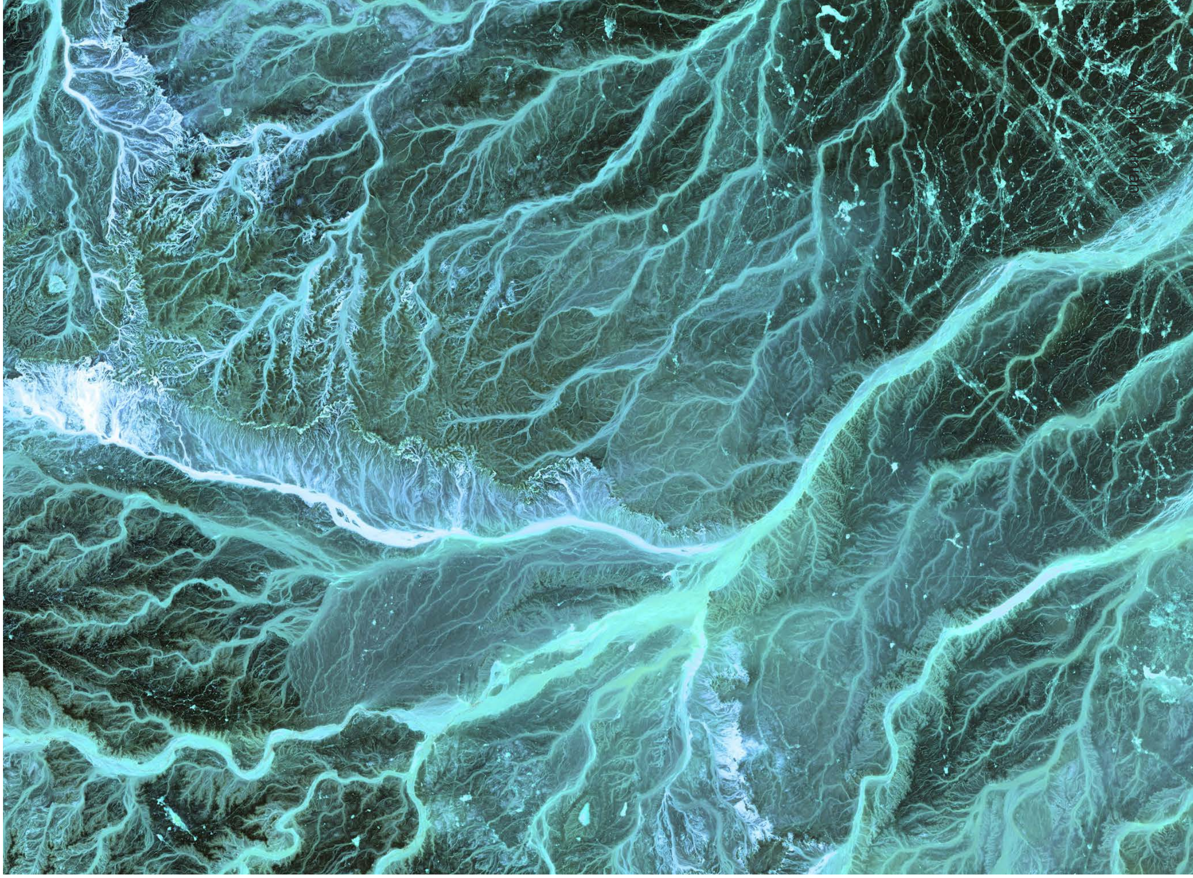

Figure 2. Mycelium, the vegetative root system of fungi (Image Credit: United States Geological Survey)

the materials' properties, identifying the affordances and limitations, and designing and developing *prototypologies* to take a step forward in using them.

Prototypologies, as Heisel and Hebel (2019) describe them, are "full-scale applications that holistically discover all connected aspects and address unknowns of a specific question" while being a part of a more extensive and systematic test series of such different typologies with similar characteristics but varying parameters. The *prototypological* methodology can help the designers find the best practices for utilizing a novel material, technique, or combination. A prototypology is not a model but a passing stage of an evolutionary process. The objective of prototypologies is to identify and validate the knowledge and skills incorporated with the materials and techniques rather than the formalistic and aesthetical perspectives (Heisel and Hebel, 2019). Thus, the prototypological methodology advances research on novel and unstable architecture subjects, specifically unconventional materials. It means the precedent works, with the material and technique, inform the researchers and designers on some aspects of the performance, and the line of the evolutionary research process continues from where it has ended in the works of others.

Among all unconventional and uncertain materials, this paper focuses on research on mycelium-based composites. It investigates how to proceed with the limitations and affordances of a lightweight, bio-based, and biodegradable material.

The Mycelium Case-study

“Fungi have an undeniable role in shaping our world. In addition to creating food and medicines, they also digest rock and create soil, digest contaminants, help feed plants, control animals' behavior, and modify the composition of the Earth's atmosphere” (Sheldrake, 2020). The fungi kingdom, which is as broad as the animal or plant kingdoms, is more known for the mushrooms, their fruiting bodies. However, the infrastructure of this kingdom is based on mycelium. The vegetative root system of fungi is called mycelium (Figure 2), which is made up of hyphae. Merlin Sheldrake (2020) describes “hyphae as tiny tube structures that branch, fuse, and entangle to form the chaotic filigree of mycelium.” The most prevalent fungal habit, a curious, irregular inclination, is described by mycelium, which is better understood as a process as opposed to a physical object. Fungi eat through mycelium. Some creatures, like photosynthesizing plants, produce their nourishment. Some creatures, like most animals, collect food from the environment and bring it into their bodies for digestion and absorption. Fungi employ a different approach. They incorporate food into their body after digesting the surrounding environment. “Animals put food in their bodies, whereas fungi put their bodies in food” (Sheldrake, 2020). As the mycelium digests the organic matter surrounding it, no two mycelial networks are alike, a phenomenon known as “developmental indeterminism” (Sheldrake, 2020). It means we can shape this material in the ways that we desire.

There is a multitude of advantages to working with fungal materials. They are easy to grow, and less energy is required to cultivate them, as they can grow on various organic materials, and transferring materials is minimized. They also use little resources since they can be produced with byproducts or waste from other industries. As a biomaterial, the fungi-based matter is compostable and produces less waste than its competitors. When alive, they can be used as active materials, and after ceasing life, they exhibit some passive features such as insulation and fire retardancy. The extensive discussion about this material, the precedents of using this material in architecture and design, and the technological ways to enhance the material's performance are published in another paper (Ghazvinian and Gursoy, 2022a).

The inherent uncertainty of mycelium-based materials opens different opportunities for designers. First, as the designers can cultivate the material, they can modify it through the cultivation parameters. The idea of graded materials is not novel. The building industry uses different steel and concrete grades for various functions in every project. However, while working with a bio-based material, the grading and the accessibility to multiple grades are controlled by the designer (Ghazvinian and Gursoy, 2022b; Elsacker et al., 2021). One of the cultivation parameters affecting the production of mycelium-based composites is the cultivation time. The longer the fungi grow, the lighter and mechanically weaker the composite will be (Ghazvinian and Gursoy, 2022b). It is, to some extent, because of the change in the microstructure of the composite. In longer cultivation times, the more organic substrate is digested, and the product becomes more fungal, so its mechanical properties change and weaken. The idea of time as a grading parameter can also be seen in the two-phased growth of the material. As the mycelium first grows in bulk (most potentially in bags) and then in the desired forms (formwork, additive manufacturing, or subtractive manufacturing), we can see the role of time in each of these phases, too (Ghazvinian and Gursoy, 2022b). Other cultivation parameters, such as the substrate mixture, the fungal species used, and the additives to manipulate the process's outcome, may also be affected by time. For example, *Ostreatus* spawns thrive faster than *Ganoderma* spawns (Ghazvinian and Gursoy, 2022a).

The next opportunity here is related to the different methods of shaping the material. Mycelium networks have no shape than the shape of the nutritional substrates they digest. As designers, we can shape the substrates as we desire and let the mycelium bind them together. However, as discussed throughout the paper, there are always limitations with uncertain materials, and we need to find the proper forms to use mycelium in architecture and design. The extensive literature review on mycelium-based materials in architecture has studied these forms and how each informs the prototypological research (Ghazvinian and Gursoy, 2022a). From the very first architectural effort with mycelium-based materials by Phil Ross, the Mycotectural Alpha, to the most recent projects, the role of the temporality of the material is undeniable. Phil Ross used the living *Ganoderma* bricks to fabricate the Mycotectural Alpha project, and at the end of the exhibition, he used those bricks for brewing herbal tea (McGaw, 2018). In the Shell Mycelium project by Yassin-Arredia and Beetles 3.3, the mycelium has been used in-situ as claddings for a triangular timber network, and the cultivation of the mycelium was the key to enabling a semi-monolithic shell.

Following these efforts, Jonathan Dessi-Olive investigated the potential of this material for bulk and monolithic structures (Dessi-Olive, 2018). Pouring around one ton of fresh material when it is alive and finding ways to let it breathe and cultivate seems impossible if one's knowledge is insufficient for the living material. The idea of coping with uncertainty goes to the next level when the technique is less predictable. After finding out that by increasing the surface-to-volume ratio, the mycelium grows faster, more complex formwork systems and additive manufacturing efforts in shaping mycelium-based materials have begun (Modanloo et al., 2021). As discussed earlier, materials' temporality gets more critical even with conventional materials like concrete. Now, with living material, this relationship with time enables infinite scenarios. From simple extruded biomass (Bhardawaj et al., 2020) to smart geometries that can bear loads (Modanloo et al., 2021), and recently, projects that combined the living and the machine to co-create with humans, fungi, and robots (Alima et al., 2022), the idea of forming this uncertain material with a precise but at the same time, the unpredictable technique is being investigated. Now, after approximately a decade of experimenting with different ideas for shaping this material for architectural functions, researchers started to experiment with some radical strategies, such as reinforcing the material with clay (Jauk et al., 2021) or wood-veneer (Ozdemir et al., 2022), or forming it with Rattan frameworks (Nguyen et al., 2022), or organic textile formwork systems (Hoenerloh et al., 2022).

Concluding Remarks

This research discusses how the temporality, instability, and uncertainty of unconventional biomaterials affect the design process, focusing on mycelium-based materials. It lays the ground for broader research in which we intend to enhance the material characteristics of mycelium-based composites and find the best practices for forming these composites to perform as load-bearing components in temporary structures. The overall framework in this research is based on the prototypological methodology described earlier. After an extensive literature review on this biomaterial and the built precedents (Ghazvinian and Gursoy, 2022a), we focused on specific aspects of the material and its forming process. First, the idea of graded materials regarding the controllable parameters in the cultivation process has been studied (Ghazvinian

Figure 3. MycoCreate 2.0 Pavilion (Image Credit: Tom Daly)

and Gursoy, 2022b). The outcomes of this study revealed the design opportunities that emerge with studying the cultivation process. Then, regarding the limitations found in precedents, a prototypology, the MycoCreate Pavilion (Figure 3), has been defined to address some of the challenges of working with mycelium-based composites (Ghazvinian et al., 2022). These challenges are related to the use of plastics in the formworks, the necessity to compact the mycelium paste inside complex and irregular formworks, and allowing enough air for the mycelium to breathe during cultivation. As explained before, prototypologies address some challenges, but they also bring new challenges to the attention of designers. The most crucial questions raised while working on the MycoCreate prototypology are how to cope with the contamination of mycelium, particularly with other fungal organisms such as molds, and how to control the shrinkage of the material during the curing process.

In future studies, for the former, there is a discussion about multi-organism systems. In his infamous book, *Entangled Life*, Merlin Sheldrake states that talking about individuals makes no sense anymore. Instead, biology has transformed into ecology. “The former is the study of living organisms, while the latter is the study of the relationship between living organisms” (Sheldrake, 2020). Along these lines, one strategy to address the contamination issue is to utilize the other organisms and create an ecosystem. Although, it is crystal clear that the presence of a new player changes the instability status of the material during its preparation stages. For the latter, other shaping and processing methods might be the answer. Again, modifying the parameters of the material to minimize shrinkage and changing the way the material is formed are the two potential ways of coping with the raised challenge.

The discussion about how materials are unstable and how this instability opens several opportunities for designers to experience unprecedented scenarios and see unexpected results cannot be limited to one material and one paper. The unconventionality of living matter proposes novel ontological and epistemological frameworks for design. Iterative processes between material preparation, experimentation, design, and fabrication are required to enable the practical use of unstable materials. Still, the outcome may deliver some unexpected features, and in this stage of the learning curve, these unprecedented results are more than welcome. This paper barely touched the surface of a profound concept that lets us see some novel outcomes and let the audience of the built environment experience it. This field of research seems promising and undeniable for shaping the future of materials and architecture. Although most of the outcomes are experimental and way out of the architectural scale, as discussed earlier, the change is undeniable, and if we do not conform to it, there will be more challenges soon.

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