Research Directions: Biotechnology Design

www.cambridge.org/btd

Results

Cite this article: Alima N (2024). BioForms: 3-D printed mycelium wall panel systems. *Research Directions: Biotechnology Design*. **2**, e18, 1–9. https://doi.org/10.1017/btd.2024.9

Received: 27 December 2023
Revised: 25 April 2024
Accepted: 24 May 2024

Keywords:
mycelium; 3D printing; robotics; computational design

Corresponding author:
Natalie Alima; Email: alimanatalie@gmail.com

BioForms: 3-D printed mycelium wall panel systems

Natalie Alima

School of Architecture and Urban Design, RMIT University, Melbourne, VIC, Australia

Abstract

BioForms integrates sacrificial formworks, agent-based computational algorithms and biological growth in the generation of biodegradable internal wall panel systems. These wall panel systems are intended to minimize material waste, utilize local botany and generate a symbiosis between the artificially made and the naturally grown. This is achieved by utilizing local waste as a structural compressive core, mycelium as the binder, and recycled pellets as the architectural skin. Leveraging mycelium's structural, acoustic and thermal properties, this exploration delves into unique methods of incorporating fungi and waste into architectural construction. The motivations for this research stem from the need to address the building industry's contribution to climate change, by considering the lifecycle of our materials. BioForms aims to retrofit existing buildings by replacing foam insulation and MDF (medium-density fiberboard) wall panels with biodegradable and recyclable 3D-printed skins embedded with a mycelium core. Analysing mycelium's reaction to BioForms I, the second iteration, BioForms II, evolves in design complexity and materiality. BioForms II explored robotically fabricated wood-based polylactic acid plastic (PLA) composite materials. Within the second iteration of this research stream, mycelia was both embedded within the compressed fabricated skins and on the external surface. Whilst BioForms explored the generation of biodegradable wall panel systems, the broader aims of this research is aimed at infiltrating biological matter into human-occupied spaces, completely omitting the use of synthetic building materials within the construction industry and advancing the architects relationship to nature in the generation of form.

Introduction

According to 'The Global Status Report for Buildings and Construction' 2018, the building industry has been a significant contributor to global warming (Global Alliance for Building and Construction, 2018). The construction industry, responsible for 39% of total CO_2 emissions, faces considerable pressure to find sustainable alternatives to commonly used synthetic materials (Madurwar et al., 2013). These materials, including glass, concrete and plastics, pose hazards that deplete natural resources and pollute our air, land and water (Jones et al., 2020). Similarly, internal wall panel systems are commonly made of synthetic materials, such as MDF, with internal foam panels acting as insulation and absorbing sound (Kawasaki and Kawai, 2006). Although comprised of wood, an organic material, the binding agent of MDF boards is comprised of formaldehyde, a toxic gas that may be omitted from the material and has been proven to be linked to cancer and respiratory diseases (Lee et al., 2020). Based on polystyrene, the internal foam panel is utilized in many sandwich panel systems that not only clog landfills but take hundreds of years to biodegrade (Arifin and Yusuf, 2013). Additionally, the production of a single cubic metre of polystyrene consumes the equivalent of 1.5 L of oil (Jones et al., 2020). For these reasons, 'made with nature' materials and bio-fabrication are considered a highly sustainable replacement for many petrochemical materials, in line with a cradle-to-cradle approach (Kopnina, 2018; Severis and Rech, 2019).

Over the past few years, a vast amount of research and development has been attributed to the efforts to convert biological matter, into a material fit for architectural building standards and regulations. Through developed research, mycelium, in particular, has showcased astounding results in its ability to absorb sound. This can be attributed to the organism's porous, fibrous nature, which has been scientifically proven to show an acoustic absorption of at least 75% at 1000 Hz, which is the typical frequency of road traffic noise. Companies such as Mogu have commercialized this material in the production of mycelia-based eco-friendly acoustic panels. In addition to the organism's ability to absorb sound, mycelium composites are rich in natural phenolic polymers, such as lignin, and naturally occurring or synthetically produced silica (SiO_2). These features enable the organism to showcase improved thermal degradation levels and fire reaction properties. Due to the organism's ability to release water vapour during combustion, mycelium has obtained a fire class B-s1, d0 in comparison to the

European fire rating classification of UNI EN 13501-1 B-s1-d0 (Haneef et al., 2017). In addition to the material's fire retardant and acoustic properties, hemp-based fungi composites have been scientifically proven to have high termite resistance and low mass losses resulting from termite infestation over four weeks (16–53 wt %) (Haneef et al., 2017). Due to the organism's material properties, mycelium has become an ideal bio-alternative material to replace synthetic materials such as foams, insulation and acoustic panels for internal building applications. This is due to the amount of air contained within and between the often porous and loosely packed substrate filler (Haneef et al., 2017). Mycelium insulation panels are able to achieve a thermal conductivity of 0.024 W/m.K., surpassing the values that can be achieved by market-leading but unsustainable materials, such as glass fibre (0.032–0.044 W/m.K), mineral wool (0.032–0.044 W/m.K), expanded polystyrene (0.036 W/m.K) and extruded polystyrene (0.029–0.036 W/m.K) (Jones et al., 2020). Leveraging fungi's compressive strength, acoustic damping properties and thermal insulation capabilities, companies such as Evocative Studio are now developing naturally grown insulation panels such as MycoBoard (Pelletier et al., 2013), with the ambition to generate sustainable internal wall panel systems. In this case, mycelium is grown between two pine boards adopting the geometry between the two wall panels. Extreme heat is then applied to the organism, to ensure that it no longer grows beyond its set boundaries (Pelletier et al., 2019). This methodology of utilizing mycelium to replace synthetic materials, such as foam insulation, has been tested and commercialized in order to meet the tight requirements of lightweight design, environmental-friendliness and load-carrying functions (Wong et al., 2019).

Advancing this existing research further, BioForms aims to replace MDF wall panel systems with 3-D printed skins and foam insulation, with mycelium-grown acoustic panels. In order to minimize material waste, the wall panels are 3-D printed from bio-based plastics that have been reused and re-purposed. This methodology builds on the cradle-to-cradle concept, where waste may be converted into a new product lifecycle (Sherratt, 2013).

BioForms I technical workflow

In order to generate a direct dialogue between the fabricated skins and mycelium, the form was generated to encourage mycelium growth and stability. To address this question, a series of experiments were conducted to test how mycelium reacts to various textures. These experiments aimed to determine which textures provide the mycelium with an appropriate surface to latch onto, while also maintaining adequate aeration, temperature and humidity necessary for its growth. A series of small-scale experiments were initially conducted to test the organism's compatibility with the fabricated skin's width distance, internal void size, geometry, skeleton and texture. The goal was to determine the ideal form for the mycelium to latch onto and provide sufficient oxygen and nutritious substrates to grow. Once the mycelium was grown over the fabricated form, a visual inspection was then applied to determine which of the coarseness–density measures was more successful in supporting the mycelium's latching. *Pleurotus ostreatus* was utilized as it not only grows at a rapid pace but produces fascinating patterns of growth when searching for nutrients. From the set experiments, it seemed that mycelium was most attracted to intricate textured geometries rather than smooth surfaces. Scientific research has demonstrated that hyphae (the mycelium's forming structure) can sense the texture of surfaces and detect grooves half a micro-metre deep. Furthermore, if hyphae are confronted with an obstacle, they will divert themselves around it by branching out and then back together (Sheldrake, 2020). By studying the organism's behavioural patterns of growth, this research posits a strategy in which empirical observational knowledge becomes an input into the form-making process. Mycelium's growth aesthetics is therefore converted into a language for architects to design with, catalysing a synergy with the biological. As a result, mycelium growth is utilized as a design generator and also for the fabrication of living, breathing architectural forms (Figure 1).

In order to computationally generate intricate and textured surfaces, an algorithm based on swarm intelligence was deployed. This algorithm was specifically utilized to array and organize hundreds of components across the wall's surface. Swarm intelligence is based on the collective behaviour of self-organized systems (Chu et al., 2011). This behaviour is evident in natural systems such as ant colonization, birds flocking and wasps building nests. Computationally, algorithms based on the logic of swarm intelligence seek to mimic the robustness, adaptivity and efficiency of these systems, which emerges as a result of multiple interactions between simple components (Buus, 2006). A number of agents therefore act according to very simple rules, governing the construction of large architectures. In order to generate rippled, intricate surfaces, each component (which are referred to as scales) was modelled at the dimensions of 70 mm height, 50 mm width and 20 mm depth. Through a swarm intelligence algorithm, these scales arrayed across the wall's surface to simultaneously give the allusion of rippled skins and encourage both biological growth and mycelium's adhesion to the fabricated skins. The wall's surface was designed in varying degrees of coarseness, to support the mycelium's ability to latch onto the skins. High-resolution intricate scales were arrayed across the fabricated skins at three contrasting levels of densities: low – scales at 50 mm apart; medium – scales at 20 mm apart; and high density – scales next to each other. Figure 2 presents these scale-like structures at the three density levels. Through observations, the growth and the reaction of the mycelium to the fabricated skins were monitored.

To enhance the tensile strength of the wall panel system, a methodology was developed by which external passageways were computationally designed to house fibre composites and provide additional tensile strength. As demonstrated in Figure 3, Fibre hemp ropes were laced within grooves prefabricated within the scaffold. These natural fibre ropes are 6 mm in diameter and with a breaking load of 285 kg, thus appropriate for adding the required tensile support. These grooves were then sealed and coated with a bio-resin, which is a plant-based non-toxic resin.

With the rise of machines and access to technology in our vicinity, robotic fabrication has become a widely accessible tool within the design and construction industry. Evident in 'SensiLab' and RMIT's Building 515 project, Roland Snooks has proven that 3-D printing has now shifted from the small-scale prototyping stage into the commercialization of viable building products (Snooks, 2021). With this technology now meeting building codes and fire regulations, architects are retrofitting existing buildings with 3-D printed facades and wall panel systems to minimize material waste and decrease human labour. The downside however to utilizing this innovative technology is the common use of petroleum-based materials such as polyethylene or polypropylene (Lee et al., 2020). With the motivation to reduce and reuse synthetic materials such as PETG, this research re-uses and re-purposes existing building materials. Designed by Roland Snooks, 'Floe' was comprised of seventy robotically fabricated PETG panels

https://doi.org/10.1017/btd.2024.9 Published online by Cambridge University Press

Figure 1. Prototype 01: Mycelium growing inside recycled PETG skins.

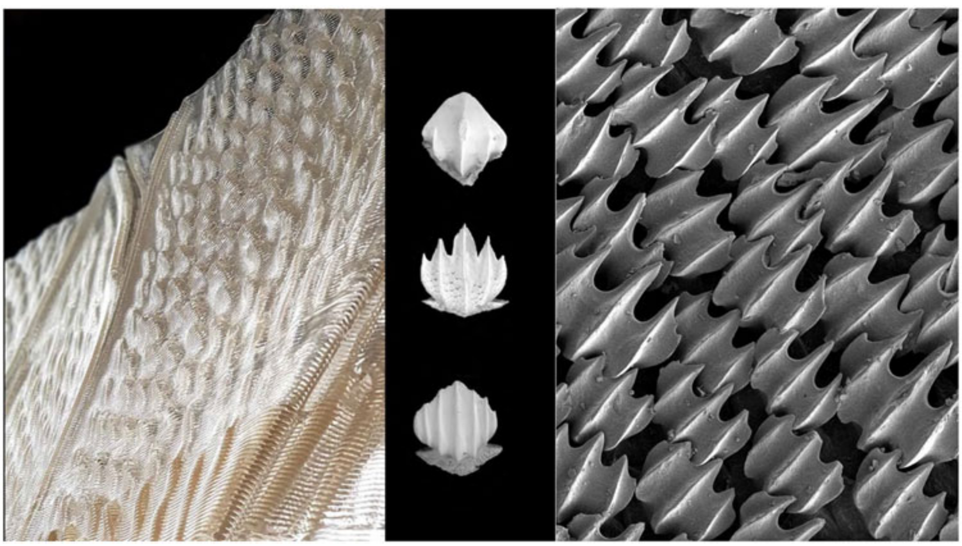

Figure 2. An algorithm based on swarm intelligence was developed to array components across the surface, generating a reptile scale-like texture.

and presented at the National Gallery of Victoria (NGV) in 2018 (Snooks, 2021). In order to reuse and repurpose this plastic, each panel was ground into the form of pellets, which were then melted and extruded through a large-scale industrial robot – the Kuka KR150 robot. This same plastic was then utilized to 3-D print BioForms, a two-metre high wall panel system.

The final generated form was 3-D printed using recycled PETG. As demonstrated in Figure 4, a large-scale industrial robot, the Kuka KR 150, was used for 3-D printing. The form's dimensions were 2000 mm in height, 800 mm in length and 30 mm in width. The skin thickness was 2 mm, and the internal gap was 80 mm. The fabricated skins were then painted with gradients of blue to visually enhance the form's rippled, scaled and textured surfaces.

Once 3-D printed, the robotically fabricated skins were ready for the application of the mycelium. The mycelium was then mixed with upcycled agricultural waste comprised of mycelium 60%, coffee 5%, paper pulp 25%, hemp seeds 5% and flax seeds 5%. This mixture was found to be effective in providing nutrients for the fungus's growth. The scaffold was incubated for 14 days in a specially built greenhouse, keeping the humidity at 85% and the temperature at 30 °C, with natural light and airflow. The final form was left uncapped to encourage further growth of the mycelium. As the mycelium was kept alive, it continued to grow and fruit beyond the scaffold's framework, forming long cylindrical tubes of oyster mushrooms. As demonstrated in Figures 5 and 6, the external fruiting of the fungus flourished and grew over time. During this process, mycelia began to form tiny networks of living labyrinths, filling all the available space between the fabricated skins. After a 14-day period, the fungi and nutrients formed a solid structure, as the organism adopted the shape and adhered to the two fabricated skins. Aesthetically, the organism embodied a thick cumbersome texture, mimicking the texture of foam.

Exhibited as part of the 2021 NGV's 'Melbourne Design Week', BioForms I was presented as part of the Printed Tectonics exhibition, displayed at the RMIT design archives window. The exhibition explored the positive environmental impact of building-scale 3-D printing and its implications for architectural design.

BioForms II technical workflow

Reflecting upon the BioForms I designed form, a few insights were revealed, which informed the development of BioForms II. First, it appeared that the plastic-based PETG scaffold was too smooth in texture for allowing successful latching of the mycelium. It was only in the high density of scale-coarseness that the mycelium was able to latch onto the skin. Thus, the final outcome did not appear as a unified form, but rather as loosely integrated, where the internal mycelium core seemed unstable as it was unable to successfully grip onto the surrounding fabricated skins. The

Figure 3. Fibre hemp ropes laced within grooves prefabricated within the scaffold for additional tensile strength.

Figure 4. The final fabricated wall panel system, 3-D printed from the Kuka KR150 robot.

findings also reveal that aesthetically, structures at a macro-scale of metres inhibit the expression of the fungus's patterns of growth.

To address this problem, there was a need to turn to other materials, leading to the experimentation of wood-based skin solutions. When researching ideal materials to host mycelium growth, the earth's natural nutrient cycles and processes of upscaling organic waste were explored. According to existing scientific research, fungi naturally consume nutrients contained in lignocellulosic biomass, which is the dry plant matter. These are often found in agricultural waste and fibrous substances such as straw, paper pulp, tree bark and sawdust (Kavanagh, 2005). To digest these materials, the fungi release enzymes from their hyphal tips, which result in intricate tapestries of growth (Jones et al., 2020). Converting this scientific research into the architectural field, wood–plastic composites (WPC) were utilized in order to provide nutrients for the organism to consume and eventually degrade. Wood-based scaffolds seemed appropriate, as this material is used as a natural substrate for fungus, and it has a more penetrable surface. Reflecting on the first research stream BioForms I, from an aesthetic perspective, by enclosing the mycelium between the skins, it adopted a thick cumbersome foam-like appearance. Its intricate labyrinth patterns therefore became lost in the sheer volume of the material. To address this problem, there was a need to allow the mycelium to grow externally and contribute to the aesthetics of the overall formation. In summary, three main changes were made when progressing from BioForms I to II. These were changing in skin material, creating scaled textures at high density across the entire surfaces of the skin and allowing the mycelium to form its patterns of growth external to the wall panel. In BioForms II, the following changes were implemented in the creation of the form: (i) The scaffold was made of wood–plastic composites (WPC), composed of corn starch (PLA [60%]), and wood cellulose (40%); (ii) the scaled density was now set to be high and uniform across the skins; (iii) mycelium culture was infused on the external skin and not only applied to the interior of the skin; and (iii) the shape of the structure advanced past the standardized wall panel system into baroque rationality through high-resolution organic forms that further exposed my architectural design aesthetics. These changes were derived as outcomes from reflecting on the design outcome of BioForms I.

In order to enhance the organism's adhesion to the designed surface, skin textures were amplified, providing coarseness for the organism to latch onto. Rather than arraying scales across the external surface wall, a new algorithm was generated which morphed the surface both internally and externally. Utilizing an algorithm based on cellular growth, complex organic structures were generated to create intricate groves and textured pathways for the organism to seep through and spread its hyphae tips. As demonstrated in Figure 7, through these heterogeneous skins, form varied in areas of intensity, sparsity and scales, generating pathways for the organism to seep through and expose its agency of growth. The developed algorithm utilized the principles of differential growth, developed by Alan Turing in his paper 'The Chemical Basis of Morphogenesis'. Here, a computational cell receives nutrients from its environment, which alters its overall

https://doi.org/10.1017/btd.2024.9 Published online by Cambridge University Press

Figure 5. Mycelium growing inside the wall panel system.

Figure 6. Mycelium growing inside the two-metre high wall panel system.

network topology (Turing, 1990). Structures were created from interconnective cells with rules for the forces between the cells and for how the cells accumulate internal nutrients. When the nutrient level in the cell is given a threshold, the cell splits into two and reconnects with its immediate neighbour (Lomas, 2014). Results show an incredible similarity to biological organisms, which were specifically tailored to embody a sharp contrast between smooth and intricate areas. As a result, a catalogue of intricate, textured surfaces were computationally designed to simultaneously encourage mycelium growth and expose my architectural aesthetic of baroque formations and amplified resolution. These intricate forms not only operate performatively as they enable mycelium to grow and adhere in certain ways but also expose the architects' design aesthetics of high resolution and delicate complexity. These heterogeneous skins transitioned from smooth into highly detailed surfaces, embodying organic forms that are ordinarily seen in nature. These skins were intentionally restricted to a 40-degree angle to ensure successful printability on the robot.

https://doi.org/10.1017/btd.2024.9 Published online by Cambridge University Press

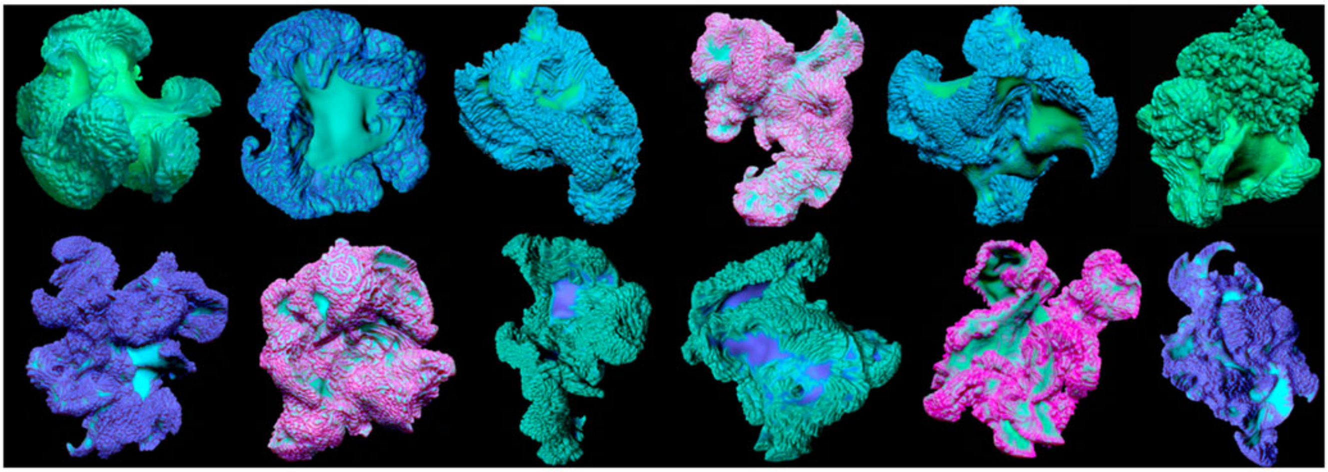

Figure 7. A catalogue of intricate, textured surfaces computationally designed to simultaneously encourage mycelium growth and expose my architectural aesthetic, utilizing an algorithm based on cellular growth.

To test the ideal scale, a series of wall panels were designed with contrasting gap sizes between surfaces. The question posed was: What gap size between the two fabricated skins is appropriate for obtaining maximum structural support for the form while maintaining the mycelium's properties of growth? The appropriate gap was determined as such when it ensures the adhesion of the mycelium and its compact enclosure between the skins, supports the mycelium's weight and allows oxygen to permeate the model, so as to not suffocate the mycelium. In addressing this question, I experimented with various gap sizes. The three trailed gap sizes were 50 mm, 40 mm and 20 mm. Sections were extracted from each computational model and fabricated on a small-scale 3-D printer in order to test these qualities on an accurate scale. The skins were 3-D printed using a Prusa 3-D printer, with a printing bed size of 300 mm × 300 mm × 30 mm. This printer is suitable for small-scale projects, as in my three trial experiments. The WPC type used in this printer is polylactic acid or polylactide (PLA) derived from fermented starch (Lamm et al., 2020). The filament was extruded through a 0.8 mm nozzle to prevent the wooden fibres from clogging the extruder.

Once the form was fabricated, I used a liquefied culture of mycelium for infusing on the external skins. The form was then incubated for 14 days, as the mycelium grew within the internal gap as well as on the external textured surfaces. Figure 8 demonstrates mycelium's growth in the enclosed gap between the two fabricated skins and its exposure on the skins' high-resolution textured surface. Internally, the organism embodies a thick cumbersome texture, while externally the organism exposes its intricate agency of wispy fibrous growth. It was therefore found that the dual applications of using WPC to create the scaffolds and applying scales-texture at high density across the entire surfaces were effective in improving the latching of the mycelium onto the skins. Aesthetically, the organism exposed its wild patterns of growth as it flourished through the uncapped voids in each digitally fabricated model. The findings revealed that the appropriate width of the gap is 40 mm, met the requirements of an adhesion of the mycelium and its compact enclosure between the skins, supported the mycelium's weight and allowed oxygen to permeate the model, as to not suffocate the mycelium.

Building on these results, these initial tests were then scaled up to create the final form to the scale of metres. The final computational form was designed as a team, incorporating these findings of high-resolution skins and internal gap size to encourage mycelium growth. Here, the geometry embodies textured grooves for the organism to latch onto, and internal pathways to seep through, exhibiting coral-like (Cnidaria) formal qualities, often seen in marine environments. Here once again, the Kuka KR 150 robot was used for 3-D printing the skins. To do so, WPC pallets were dried at 100 °C for 4 hours to reduce the moisture content to 2%. This ensured that no air bubbles were formed during the extruding of the material. Once inserted into the printer, the material was further heated at 170 °C for 3-D printing. Arbitrary geometries were initially generated in order to test the fibrous material's flow rates, melting temperature, layer heights and compatibility with the Kuka KR 150's extrude.

Similar to the inoculation process of BioForms I, mycelium was grown within the internal walls of BioForms II, acting as a natural binder to adhere the fabricated skins. Thus, BioForms II was successful in demonstrating the formation of a unified wall panel, where the mycelium acted as the internal natural glue, bonding the fabricated skins together to form a sandwich-style panel system. However, being kept alive, the fungus often strayed away from the pre-designated enclosures, affirming its own sense of agency and volatility. Unlike the growth within the internal surface of the skins, which was homogenous, appearing as a thick cumbersome foam, the examination of the external walls revealed entirely different aesthetics. Here a rich heterogeneous silhouette of formations were apparent, presenting a catalogue of geometric features, such as high-resolution textured surfaces, mesh mutations and internal folds. As demonstrated in Figure 9, the form embodies features of organic growth, aesthetically blurring the architectural intention by infusing the fungus's autonomous agency into the pre-determined design of the wall panels. It was therefore found that the dual applications of using WPC to create the scaffolds and applying scales-texture at high density across the entire surfaces were effective in improving the latching of the mycelium onto the skins.

While the fabricated solid surfaces were 2 mm thick, the organism at times burst through these solid surfaces and began to fruit, exhibiting a wispy delicate texture. Finally, there was a need to address the challenge of scaling up and controlling the mycelium's growth. Here, the following question was posed: To what extent can the mycelium's growth patterns be scaled up and controlled

https://doi.org/10.1017/btd.2024.9 Published online by Cambridge University Press

Figure 8. Mycelium growing inside the 3-D printed wooden wall panel system.

Figure 9. Mycelium growing throughout the 3-D printed wooden skins exposing contrasting biological patterns of growth.

through fabrication, while keeping the mycelium alive and thriving? In relation to scale, it was found that once scaled up to metres, aesthetically the mycelium takes on a thick, cumbersome form, masking its intricate details that were once visible at the micro-scale. Similarly, the living organism maintains its volatility, regardless of attempts to control it. The experiments revealed that regardless of applying rigid computational guidelines and imposing digitally fabricated enclosures, the fungus could not be completely controlled. While there were some sections in the living prototype that were successful in controlling the mycelium, in other parts, it strayed away from these rigid guidelines, asserting its own agency. Figure 10 demonstrates the fungus's self-assertion as it deviates from the set frame.

Conclusion

BioForms has shown that 3-D printing recycled PETG and biodegradable wood–plastic composites may be applied at a building scale by developing computational algorithms based on swarm distribution and mesh expansion. This applicability was particularly demonstrated in relation to developing textures that enclose and encourage the growth of mycelium through complex forms with external passageways. The findings from BioForms reveal that the mycelium was able to latch successfully to WPC-based skins, with a 40 mm gap in between, with skins presenting high-density, scale-textured surfaces internally and externally. Furthermore, the fabricated skins can be used successfully as a

https://doi.org/10.1017/btd.2024.9 Published online by Cambridge University Press

Figure 10. Mycelium bursting through the 3-D printing framework, asserting its own agency within the generated form.

permanent formwork to support the application of mycelium as an internal wall panel. The findings also reveal that aesthetically, structures at a macro-scale of metres inhibit the expression of the fungus's patterns of growth. This was particularly apparent in the internal structure and, to some extent, also in the external growth. The findings suggest that by enabling mycelium's response to architectural forms to drive the design process, novel co-creational relationships and interspecies forms may emerge. By giving more design autonomy to the fungus and creating forms at a scale closer to that of the hyphae, further aesthetic formations may be created, expanding the affordances of the mycelium to architectural design.

While BioForms explored the generation of biodegradable wall panel systems, the broader aims of this research are aimed at infiltrating biological matter into human-occupied spaces and completely omitting the use of synthetic building materials within the construction industry. To evolve this research further, applications may expand to building facades, ceiling panels and floors. With the ambition to have entire buildings and cities fabricated out of biological matter, this methodology references Kevin Kelly's philosophy that buildings, much like nature, should function as dynamic entities capable of growth, adaptation, healing and evolution (Kelly, 1994).

Data availability statement. Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Acknowledgements. BioForms I was a collaborative research project done by the Tectonic Formation Lab RMIT. Team members included Natalie Alima, Roland Snooks and Hesam Mohammed. BioForms II was a collaborative research project done by the Tectonic Formation Lab RMIT. Team members included Natalie Alima, Roland Snooks and Hesam Mohammed and Dasong Wang.

Author contributions. The author read and approved the final manuscript.

Financial support. No funding has been received to conduct this research.

Competing interests. The author has no competing interests to declare that are relevant to the content of this article.

Ethics approval and consent to participate. Not applicable.

Consent for publication. Not applicable.

Connections references

Dade-Robertson M (2023) Can we grow a building and why would we want to? *Research Directions: Biotechnology Design* **1**, e1. https://doi.org/10.1017/btd.2022.2.

References

Arifin, YH and Yusuf, Y (2013) Mycelium fibers as new resource for environmental sustainability. *Procedia Engineering* **53**, 504–508. https://doi.org/10.1016/j.proeng.2013.02.065.

Buus D (2006) *Constructing Human-like Architecture with Swarm Intelligence.* January.

Chu SC., Huang HC, Roddick JF, Pan JS (2011) Overview of algorithms for swarm intelligence. In Jędrzejowicz P, Nguyen NT, Hoang K (eds.) *Computational Collective Intelligence. Technologies and Applications. ICCCI 2011.* Lecture Notes in Computer Science 6922. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-23935-9_3.

Haneef M, Ceseracciu L, Canale C, Bayer IS, Heredia-Guerrero JA, and Athanassiou A (2017) Advanced materials from fungal mycelium: fabrication and tuning of physical properties. *Scientific Reports* **7**(1), 41292.

International Energy Agency: (IEA) (2018) Towards a zero-emission, efficient and resilient buildings and construction sector. In *Global Alliance for Building and Construction. Global Status Report.* Paris: IEA. https://www.iea.org/reports/2018-global-status-report.

Jones MP, Mautner A, Luenco S, Bismarck A, and John S (2020) Engineered mycelium composite construction materials from fungal biorefineries: A critical review. *Materials and Design* **187**, 108397. https://www.sciencedirect.com/science/article/pii/S0264127519308354.

Kavanagh K (2005) *Fungi: Biology and Applications.* Hoboken, NJ: John Wiley & Sons, Inc.

Kawasaki T, and Kawai S (2006) Thermal insulation properties of wood-based sandwich panel for use as structural insulated walls and floors. *Journal of Wood Science* **52**(1), 75–83. https://doi.org/10.1007/s10086-005-0720-0.

Kelly K (1994) *Out of Control. The Rise of Neo-Biological Civilization Addison.* Wesley Publishing Company.

Kopnina H (2018) Circular economy and Cradle to Cradle in educational practice. *Journal of Integrative Environmental Sciences*, **15**(1), 119–134. https://doi.org/10.1080/1943815X.2018.1471724.

Lamm ME, Wang L, Kishore V, Tekinalp H, Kunc V, Wang J, Gardner DJ, and Ozcan S (2020) Material extrusion additive manufacturing of wood and lignocellulosic filled composites. *Polymers* **12**(9), 2115. https://doi.org/10.3390/polym12092115.

Lee TC, Mohd Pu'ad NAS, Selimin MA, Manap N, Abdullah HZ, and Idris MI (2020) An overview on development of environmental friendly medium density fibreboard. *Materials Today: Proceedings* **29**, 52–57. https://doi.org/10.1016/j.matpr.2020.05.679.

Lomas A (2014) Cellular Forms: An artistic exploration of morphogenesis. In *Proceedings SIGGRAPH '14 Cellular Forms: An Artistic Exploration of Morphogenesis*. https://doi.org/10.1145/2619195.2656282.

Madurwar MV, Ralegaonkar RV, Mandavgane SA (2013) Application of agro-waste for sustainable construction materials: a review. *Construction and Building Materials* **38**(1), 872–878.

Pelletier MG, Holt GA, Wanjura JD, Bayer E and McIntyre G (2013) An evaluation study of mycelium based acoustic absorbers grown on agricultural by-product substrates. *Industrial Crops and Products* **51**(November), 480–85. https://doi.org/10.1016/j.indcrop.2013.09.008.

Pelletier MG, Holt GA, Wanjura JD, Greetham L, McIntyre G, Bayer E and Kaplan-Bie J (2019) Acoustic evaluation of mycological biopolymer, an all-natural closed cell foam alternative. *Industrial Crops and Products* **139**(June), 111533. https://doi.org/10.1016/j.indcrop.2019.111533.

Severis RM, Rech JPPB (2019) Cradle to cradle: An eco-effective model. In Leal Filho W, Azul A, Brandli L, Özuyar P, Wall T (eds.) *Responsible Consumption and Production. Encyclopedia of the UN Sustainable Development Goals*. Cham: Springer. https://doi.org/10.1007/978-3-319-71062-4_62-1.

Sheldrake M (2020) *Entangled Life : How Fungi Make Our Worlds, Change Our Minds & Shape Our Futures.* New York: Random House.

Sherratt A (2013) *Encyclopedia of Corporate Social Responsibility*. Berlin: Springer.

Snooks R (2021) *Behavioral Formation: Volatile Design Processes & the Emergence of a Strange Specificity*. New York: Actar Publishers.

Turing AM (1990) The chemical basis of morphogenesis. *Bulletin of Mathematical Biology* **52**, 153–197. https://doi.org/10.1007/BF02459572.

Wong YJ, Arumugasamy SK, and Mustapha KB (2019) Development of a computational predictive model for the nonlinear in-plane compressive response of sandwich panels with bio-foam. *Composite Structures* **212**(January), 423–33. https://doi.org/10.1016/j.compstruct.2019.01.039.