FROM NATURE TO STRUCTURE:

Exploring a Bio- Integrative Design Framework for Architectural Design

ORLAGH CASEY

RIED at Queens University, Belfast
ocasey03@qub.ac.uk

ABSTRACT

The field of architectural design is undergoing a profound transformation catalysed by the rapid advancements in smart material systems. This paradigm- shifting journey is marked by the integration of innovative materials, capable of responding to environmental stimuli and adapting their properties, thereby challenging traditional architectural framework. Within this innovative landscape, mycelium-based materials have emerged as sustainable construction materials. This research introduces a novel Bio- Integrative Design Framework (BIDF) to guide the incorporation and understanding of living matter in architectural design.

The integration of generative design software, inspired by evolutionary developmental principles, further enhances the potential of mycelium-based materials in architectural design. The RIED (Re-Imagining Engineering Design) engine embraces nature's principles, enabling designers and engineers to explore an extensive design space, resulting in a vast array of optimised solutions. The integration of the BIDF-RIED engine can introduce a new level of adaptability and sustainability to architectural projects. The RIED engine transcends conventional design methodologies, emphasising adaptability, design growth, and intelligent learning systems. Fostering a novel design engine with emerging living materials offers a vast design space, considering functionality, material behaviour, structural ability, and environmental constraints.

KEYWORDS

Biodesign, Formability, Mycelium, Computational Architecture

SESSION

MATERIALIZE & BUILD

1. INTRODUCTION

The field of architectural design is in the midst of a profound transformation, driven by the rapid advancements in smart material systems. These innovative materials, capable of responding to environmental stimuli and adapting their properties, are challenging the traditional paradigms of architecture. The integration of smart materials into architectural design has the potential to not only enhance the functionality and sustainability of built environments, but also redefine the very essence of what architecture can be.

Architects and designers have long been in pursuit of designs that seamlessly interact with their surroundings, occupants, and changing conditions. The evolution of design practices has been marked by a continuous quest for improved efficiency, sustainability, and occupant use and comfort. Smart material systems offer a ground-breaking opportunity to make these aspirations a reality. Whether its self-healing concrete that repairs its own cracks (Wang, 2014), or adaptive façade systems that optimise energy usage (Bui, 2020), these materials promise to fundamentally shift the way buildings and structures are conceived, constructed, and inhabited.

The integration of smart materials invites architects to think, not only in terms of form and function, but also in terms of dynamic and responsive systems that are intertwined with the environment and user needs. This evolving landscape prompts the essential question: How should design practices adapt to harness the full potential of smart material systems in architectural design? To address this question, exploration of novel computational design methodologies must be sought out, delving into the multifaceted aspects of technological, structural, and aesthetic dimensions. This study investigates the potential of mycelium- based materials as sustainable construction materials and introduces a novel Bio-Integrative Design Framework (BIDF) to guide the incorporation of living matter in architecture focusing on how to design with this emerging material group.

Combining the fields of nature and technology calls for a collaborative understanding, and thus a shift in software design. This paper explores evolutionary developmental principles and generative design techniques within software, creating the most optimal outcomes for architectural material systems. The integration of living materials into architecture design presents a revolutionary shift in the construction industry, which therefore presents a shift in software and hardware understanding. This calls for a new framework to guide the incorporation of living matter in architecture, resulting in biodesigned architecture.

2. RESEARCH BACKGROUND

Mycelium, the vegetative network of fungi, offers unique attributes including rapid growth, adaptability, and biodegradability, positioning it as a sustainable alternative to some traditional building materials. The mechanical properties of mycelium-based composites (MBC) warrant detailed analysis, as they form the foundation for those composites' architectural viability. Mycelium, when cultivated on organic substrates, undergoes self-assembly, resulting in a network of hyphal threads that bind particles together. This inherent cohesion gives rise to a composite material with commendable compressive strength, providing a solid basis for load-bearing applications.

Figure 1 Mycotecture

Figure 2 Hy-Fi

Earlier works on mycelium structures employ traditional construction techniques, such as 2009 project 'Mycotecture'. (Mok, 2018), Figure 1, and 2014 project 'Hy-Fi (Benjamin, 2015), Figure 2. Work on adapting the material for use in 3D and 4D printing allows us to explore new structural capabilities through generative design software technologies. However, the prototyping stage of mycelium based material structures has been prolonged due to their lack of structural properties. With reference to the Hy-Fi project, Figure 2, the mycelium bricks are stacked in a traditional offset formation; this construction technique is usually combined with masonry. According to Granta CES Edu Pack, the traditional clay brick has a compressive strength of 69-140 MPa, when compared to the mycelium brick with a compressive strength of 0.35-0.75 MPa (Bitting, 2022). These values are significantly different, but due to the undulating design of the brick formation in the Hy-Fi project, the structure is able to support itself, demonstrating successful architectural design implementation, showing the importance of both material and design systems. Most conventional materials like steel and concrete are designed to be strong by increasing their stress limits. Mycelium-based materials are eco-friendly because they can reduce waste, decompose naturally, and be recycled easily, but they are not found to be strong when undergoing tension or bending. To use these materials for large-scale structures, the shape of the structure matters more than the strength of the material. By using computational design tools, stable structures can be made without compromising safety and stability.

Environmental considerations underscore the allure of mycelium-based composites. The growth process of mycelium relies on organic waste materials, converting them into functional building components through biodegradation. This symbiotic relationship with waste management aligns with contemporary sustainability goals. The low energy input during cultivation, coupled with the capacity for end-of-life composability, bolsters mycelium's eco-friendly profile. Moreover, the cultivation process sequesters carbon dioxide, thus contributing to mitigating the carbon footprint associated with construction.

The incorporation of living matter into the design and build process becomes an essential component, enhancing the function of a work through the organisms' natural abilities. This can be done on the design side by learning from organism behaviour, such as organism growth patterns, or on the construction side through organic matter manipulation and enhancement for material creation for different uses; also known as 'biofabrication'. Biodesign, unlike current 'sustainable' or 'green' approaches looks beyond the bio- inspired and instead looks at the bio- integrated. This design paradigm deals with the technical transformation and application of structures, procedures, and developmental principles of biological systems.

Biodesign has brought to fruition the possibilities of nature- integrated design. Nature can thus become embedded within the fabric of architectural practice, creating a dynamic relationship between living matter, energy and information when creating a new environment. Through this approach, a new object to consider can be introduced, a living one, resulting in buildings that would live and, in a way, come alive. Designers, engineers, and architects alike have begun to explore this emerging new design paradigm. Designer and architect Neri Oxman created the Krebs Cycle of Creativity III, (Oxman, 2020), adapted from Krebs cycle- the sequence of reactions by which organisms generate energy. Oxman's adaptation, represents the collaboration of Art, Science, Engineering and Design, as we begin to understand this field further. In the Krebs Cycle of Creativity, Oxman asks us to think of how 'science converts information to knowledge; engineering converts knowledge into utility; design converts utility into cultural behaviour and context; and art takes context and questions our perception of the world' (Oxman, 2016). Biodesign considers the complex interrelations between design parameters, such as structure, performance, aesthetics, and ecology. By learning from nature and applying computational methods, biodesigners can explore new possibilities for architectural expression and function, as well as address the urgent environmental issues of our time.

2.1 THEORETICAL FRAMEWORK

The architectural implications of mycelium-based composites encompass a spectrum of possibilities. The material's formability during growth permits customisation, enabling designers to shape structures that align with aesthetic, functionality, and spatial requirements. Case studies demonstrate the feasibility of using mycelium composites for diverse architectural elements, including wall panels, insulation panels, and lightweight load-bearing components. Notably, the integration of living matter introduces an element of temporal evolution, as structures continue to evolve post-installation, adapting to changing environmental conditions.

This paper introduces a novel approach for designing with living matter in architecture, termed "Bio-Integrative Design Framework"(BIDF), Figure 3. BIDF transcends conventional design methodologies by embracing the dynamic nature of living materials. It integrates principles from biology, architecture, and engineering to guide the design process, emphasising adaptability, coevolution, and synergistic relationships between the built environment and living organisms. BIDF is underscored by iterative prototyping and testing, allowing designers to coalesce biological growth and architectural form.

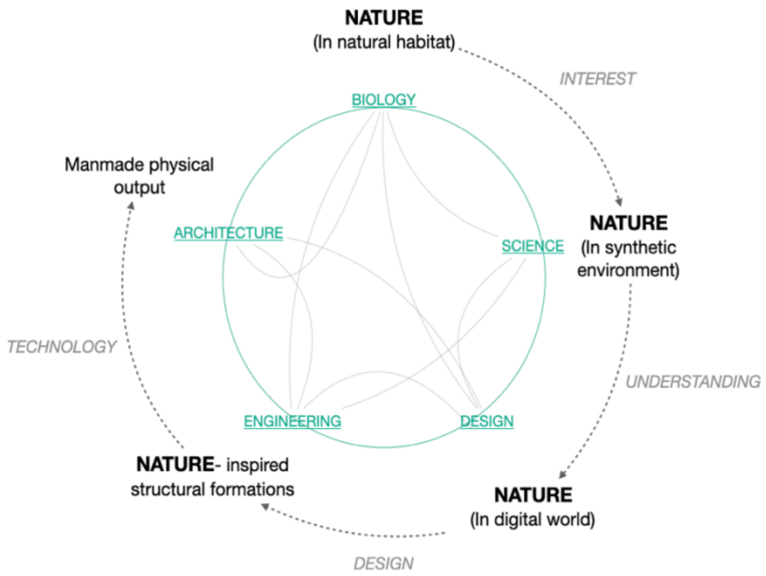

Figure 3 Bio-Integrative Design Framework by Author

Creating a system of evolutionary development learnt from nature's principles explored through generative design softwares allows for several advanced structural outputs that otherwise would not be realised. Evolutionary architecture is an innovative approach to architectural design that draws inspiration from nature's form, generating processes, and uses computational tools to emulate and enhance them. By applying evolutionary algorithms to virtual models, designers can explore a vast range of possibilities and select the best solutions for different contexts and criteria. The use of generative design within architecture offers a tool to predict and optimise material behaviours within a final product, presenting a more efficient design approach to solving complex and dynamic problems. Using these software systems offers the opportunity to create advanced outcomes that would otherwise not occur in nature.

Generative design software, such as nTopology, Fusion 360 and Solidworks, play a pivotal role in the integration of living matter in architecture, aligning with the principles of Evolutionary Development (Evo-Devo). Evo-Devo, a scientific field exploring how genes drive developmental processes and evolution, informs this architectural approach. The software employs algorithms inspired by natural evolutionary processes, generating diverse design iterations based on predefined criteria, akin to genetic variation. Designs are then assessed for their fitness, much like natural selection in Evo-Devo, focusing on factors like sustainability, material behaviour, and aesthetics. This iterative and data-driven process optimises architectural solutions, mirroring the evolutionary refinement seen in biological development. Generative design software thus bridges biology engineering and architecture, fostering innovation and adaptive, efficient architectural outcomes in harmony with living matter.

The optimisation of living materials for architectural application can be explored through advances in software technologies and design practices. Research carried out within the RIED (Re- Imagining Engineering Design) research team at Queens University, Belfast challenge the current generative design process by exploring the concept of nature, learning from its principles with respect to functionality, form, growth, and aesthetics- all of which may play into each other. This, coupled with evolutionary developmental principles, generates masses of possible formation outcomes, suitable for the predefined criteria. To reimagine our approach to design through nature, in conjunction with soft and hardware technologies, pushes the boundaries further presenting endless opportunities.

This integration of biological material systems calls for the employment of evolutionary developmental and generative design approaches. Here we can introduce a design framework that amalgamates evolutionary developmental principles and generative design systems to enable the conceptualisation, optimisation, and realisation of living material- based architectural solutions. Playing a pivotal role in this framework, generative design facilitates the creation of complex design solutions. Through parametric modelling, and algorithmic design techniques, a vast design space can be explored, considering not only aesthetics but also the biological, structural, and environmental constraints of a living material. Additionally, these tools allow for the optimisation of architectural forms that promote the symbiotic relationship between the building, and its living components.

The code built within RIED coupled with the need for further understanding of living materials within architecture presents a newfound approach to design with intelligent material systems. The concept of this framework can be understood through the analogy for biological development, Figure 4 (RIED, 2022). The RIED engine employs nature analogous processes where designs grow from 'cyber seeds' which holds information needed to create the design. These designs adapt and learn as they develop, showcasing the potential for intelligent, self-organising systems that we often find in nature's behaviours. The development of intelligent computational systems in conjunction with structural designs for nature based architectural materials will exhibit the potential, and much needed change, within our approach as contributors to the built environment, in both engineered product design and architecture. While broad in its scope RIED is currently largely focused on more traditional mechanical systems, and so there is an excellent opportunity to add new capabilities and knowledge to the RIED system with the exploratory work identified in mycelium-based materials.

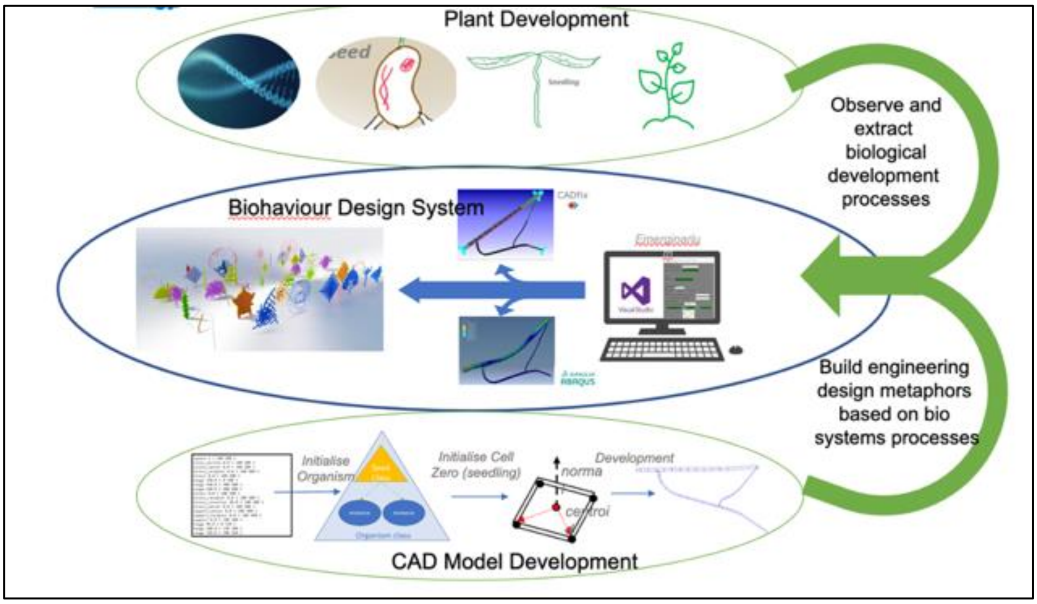

Figure 4 Generative Design for Additive Manufacturing Using a Biological Development Analogy (RIED)

The BIDF is an extension of the RIED framework. The BIDF-RIED, Figure 5, looks at all stages of the design process and how understanding of each has an impact on each stage retrospectively. The BIDF, in particular, looks at biodesign within architecture and considers a new material parameter, a living one, MBC (mycelium-based composites). This research will further understand the possibilities of MBC within structural architectural outputs, coding the material parameters of such, to result in intelligent outputs through an evo-devo inspired generative design system. i.e.- the design outputs can hold complex geometries which can only be realised physically through advanced manufacturing technologies such as AM (additive manufacturing), although, there are limitations to the 3d printing technologies which will affect the software design process as well as the material used during this manufacturing process.

The software can define any material with known parameters. To date RIED has explored typical engineering materials, e.g., Steel 8620 and Aluminium6061. Extending the system to model and simulate organisms made from MBC's could further expand the design space for even more novel organisms, designed with and by bioinspired materials and processes. Designing structural formations through algorithms that understand and respond to the material properties and the environment create ease when working with AM techniques for the next stage of production.

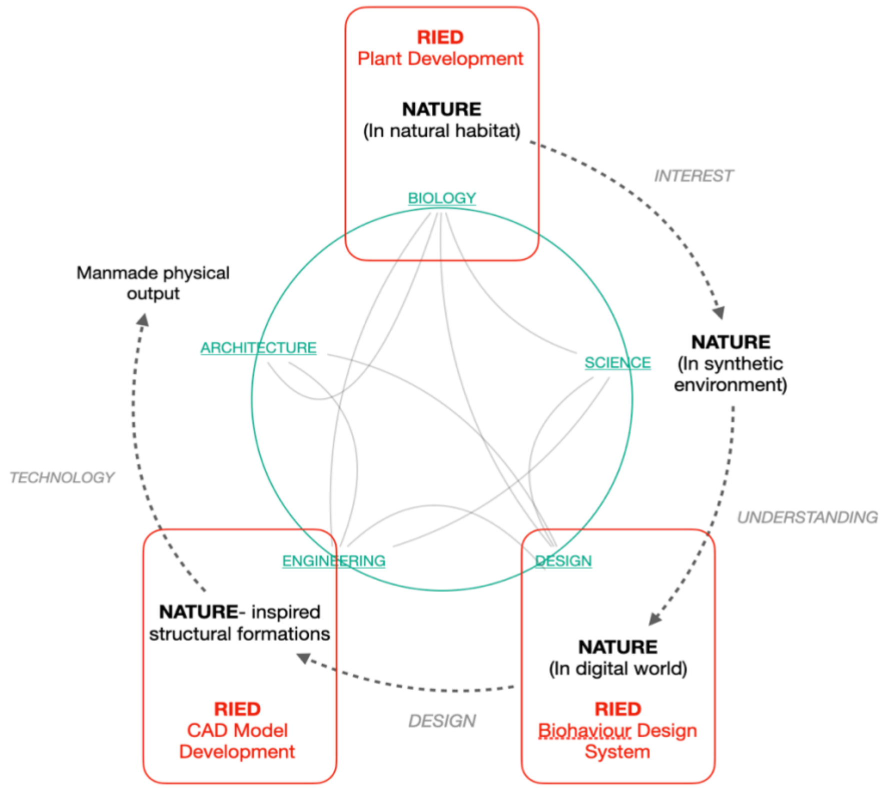

Figure 5 BIDF-RIED by Author

By employing generative design algorithms, inspired by natural evolutionary processes, RIED generates diverse design iterations based on predefined criteria. These iterations are then rigorously evaluated for their fitness, addressing sustainability, material behaviour, and aesthetics, much like natural selection in evolutionary biology. This iterative and data- driven approach optimises architectural solutions, mirroring the refinement observed in biological development.

The software's potential is not limited to traditional materials but extends to the dynamic exploration of mycelium- based materials. RIED's adaptability allows for the introduction of new parameters to mimic different mycelium-based materials, enhancing our understanding of their structural and design capabilities. Designing structural formations through algorithms that understand material properties presents a more efficient approach to solving complex and dynamic architectural problems.

2.2 METHODOLOGY

The unique behaviours and characteristics exhibited by mycelium have inspired innovative design possibilities in the realm of structural architectural components. Drawing inspiration from mycelium's growth patterns, self-assembling nature, and adaptability, architects and designers can explore novel ways to reimagine building forms, functions, and aesthetics. By leveraging mycelium-based materials, these design approaches are reshaping architectural paradigms, fostering sustainability, and embracing the dynamic interplay between living matter and the built environment.

Mycelium's expansive growth and branching structures offer a blueprint for biomimetic design. Employing these growth patterns in design, creates structures that mimic the efficiency of mycelial networks. These biomimetic designs optimise material usage, enhance load-bearing capacities, and distribute stresses effectively, thus achieving structural integrity while minimising waste.

In essence, mycelium's behaviours and the innovative use of mycelium-based materials have broadened the horizons of architectural design. From biomimetic structures to adaptive environments, architects are embracing the inherent qualities of mycelium to craft buildings that harmonise with nature, promote sustainability, and challenge traditional notions of construction. As the exploration of mycelium's potential continues, the architectural landscape is poised to witness a transformation that merges biology, engineering, and design, leading to structures that are not only functional but also in harmony with the dynamic forces of the natural world, and thus employing the idea of biodesigned architecture.

Many different iterations of mycelium-based materials have been created and tested within recent years, with many more emerging. In order to complete a comprehensive analysis and design output of the potentials of different variations of mycelium material structures there must be an analysis regarding their composition, manufacturing methods, and mechanical properties. ‘A comparison of mycelium- based materials to standard materials’, Figure 6 (Bitting, 2022), illustrates just this, showcasing the mechanical strength of MBC and PMM (Pure Mycelium Materials), in which some fall close to material properties of concrete (Bitting, 2022). Understanding material characterisation e.g., young’s modulus can help identify the material’s potential and limitations when designing for structural outputs. Validation of system accuracy will be tested by comparing design outcomes using mycelium-based materials, to industry standard materials. The output of these comparisons should present different formations to accommodate for the varying material characteristics and purpose of intended design.

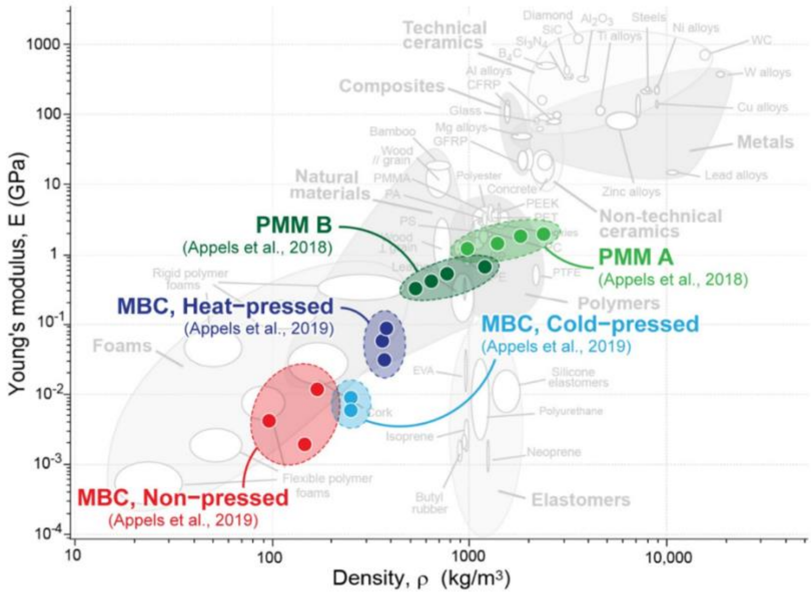

Figure 6 Comparison of mycelium- based materials to standard materials

Within the RIED engine 2D structural designs are explored. For example, a truss bridge-like organism is defined in an environment, with supports and a loading condition. Material properties, Steel8620, are assigned to the solid members of the organism. The variable parameters during the development process are the position of the connecting points on the organism, which can move in 2D space, this altering the stress distribution within the organism. Initial tests,
Figure 7, ran through the RIED engine showcase the different solutions that satisfy the objective of attaining a stiff lightweight structure. Further tests will accommodate for previous discussion around mycelium-based materials.

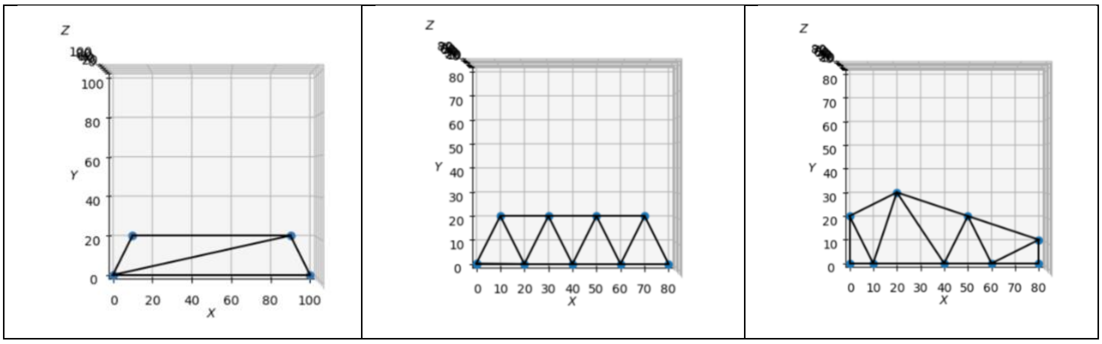

Figure 7 Beam Experiment Tests by Author

These initial experiment solutions indicate very promising design explorations.
The ongoing experiments within the RIED engine have provided a solid foundation for the exploration of design possibilities. The 2D solutions generated, although focused on steel as the primary material, offer a glimpse into the potential for innovation. The adjustment of parameters, such as specific organism characteristics, e.g., thickness, point positions, cross-section type and area offer a glimpse into the internal properties that can be adjusted during development, whilst the definition of the environment, e.g. loads and boundary conditions, opens up the possibility of exploring a changing environment and as such the response of the organism to this. These promising results

lay the groundwork for extending the capabilities of the RIED engine to encompass mycelium-based materials, aligning with the growing interest in sustainable and eco-friendly construction practices. The initial experiment outputs not only reflect the adaptability of the system but also inspire optimism for future design explorations that can shape the future of architecture, offering innovative and sustainable solutions.

2.3 CONCLUSION

The potentials of mycelium-based materials offer a paradigm shift in architectural design, redefining materiality, sustainability, and interaction with the environment. This study underscores the exploration of advanced software designing for nature inspired and integrated solutions for the built environment. Furthermore, the proposed Bio-Integrative Design Framework introduces a pioneering methodology that bridges the gap between biology, engineering, and architecture, facilitating innovative design solutions. As the architectural landscape embraces living materials, an era of transformative, adaptable, and sustainable structures beckons, reshaping the future of architecture, this framework feeds into how we begin to design at different stages, focusing here on the software design stage.

The ongoing experiments within the RIED engine have provided a promising start for the integration of mycelium-based materials into the architectural design process. While initially focused on steel, the adaptability of the system and the generation of varied outputs when adjusting parameters demonstrate the platform's potential to extend its capabilities to accommodate mycelium-based materials, furthering the exploration of sustainable and innovative design solutions. RIED represents a fusion of biological knowledge, engineering, and architectural innovation. The software system's ability to bridge biology, engineering, and architecture fosters innovation, allowing architects to create structures that harmonise with nature, adapt to changing conditions, and challenge traditional design paradigms.

In conclusion, the RIED software offers unprecedented potential for architectural and engineering design. It provides a glimpse into a future where intelligent material systems and generative design principles reshape the architectural landscape. By fostering a dynamic relationship between living matter and the built environment, RIED opens new horizons for innovative, sustainable, and adaptive architectural solutions.

3. REFERENCES

Benjamin, D., 2015. *Hy-Fi.* [Online]
Available at: https://www.holcimfoundation.org/projects/hy-fi
[Accessed 2023].
Bitting, S., 2022. Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication. *Biomimetics*, 7(44), p. 5.
Bitting, S., 2022. Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication. *Biomimetics*, 7(44), p. 15.
Bui, D.-K., 2020. Enhancing building energy efficiency by adaptive façade: A computational optimization approach. *Applied Energy,* Volume 265.
Mok, K., 2018. *Mycotecture: Building With Mushrooms? This Inventor Says Yes.* [Online]
Available at: https://www.treehugger.com/mycotecture-mushroom-bricks-philip-ross-4857225
[Accessed 2023].
Oxman, N., 2016. *Age of Entanglement.* [Online]
Available at: https://jods.mitpress.mit.edu/pub/ageofentanglement/release/1
[Accessed 2023].
Oxman, N., 2020. *Mission.* [Online]
Available at: https://oxman.com/mission
[Accessed 2023].
RIED, Q., 2022. *Nature-Inspired Design and Manufacture – including "Lessons from Nature for fully integrated, concurrent design and manufacture",* s.l.: s.n.
Wang, J., 2014. Self-healing concrete by use of microencapsulated bacterial spores. *Cement and Concrete Research,* Volume 56, p. 139.