Bio-Modules

Mycelium-Based Composites Forming a Modular Interlocking System through a Computational Design towards Sustainable Architecture

Abdelhady, Omar; Spyridonos, Evgenia; Dahy, Hanaa

Published in:
Designs

DOI (link to publication from Publisher):
10.3390/designs7010020

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

designs

Article

Bio-Modules: Mycelium-Based Composites Forming a Modular Interlocking System through a Computational Design towards Sustainable Architecture

Omar Abdelhady [1], Evgenia Spyridonos [2,*] and Hanaa Dahy [2,3,4]

1 IUSD Master's Program, Ain Shams University, 1 El-Sarayat Street, Cairo 11517, Egypt
2 BioMat@Stuttgart: Bio-Based Materials and Materials Cycles in Architecture, Institute of Building Structures and Structural Design (itke), University of Stuttgart, Keplerstr. 11, 70174 Stuttgart, Germany
3 BioMat@Copenhagen: Bio-Based Materials and Materials Cycles in the Building Industry Research Centre-TECH-Technical Faculty for IT & Design, Planning Department, Aalborg University, Meyersvænge 15, 2450 Copenhagen, Denmark
4 Department of Architecture (FEDA), Faculty of Engineering, Ain Shams University, Cairo 11517, Egypt
* Correspondence: evgenia.spyridonos@itke.uni-stuttgart.de

Abstract: In a resource-constrained world, raising awareness about the development of eco-friendly alternative materials is critical for ensuring a more sustainable future. Mycelium-based composites (MBC) and their diverse applications are gaining popularity as regenerative, biodegradable, and lightweight alternatives. This research aims to broaden the design potentials of MBC in order to construct advanced systems towards a novel material culture in architecture. The proposed design method intends to explore the design and fabrication of small-scale components of MBC to be applied in modular systems. Mycelium-based modular components are being developed to fulfill the geometrical requirements that allow for the creation of a lightweight system without additional reinforcement. The modules are linked together using an interlocking system. Through computational design and form-finding methods, various arrangements of the modules are achieved. An initial prototype of five modules is created to demonstrate the ability of the system to form various geometrical configurations as a result of the used workflow. The proposed application aims to expand the scope of the use of mycelium-based composites in modular systems and to promote architectural applications using bio-based composite materials.

Keywords: bio-based materials; mycelium; composites; modular system; computational design; growing materials; sustainability

Citation: Abdelhady, O.; Spyridonos, E.; Dahy, H. Bio-Modules: Mycelium-Based Composites Forming a Modular Interlocking System through a Computational Design towards Sustainable Architecture. *Designs* **2023**, *7*, 20. https://doi.org/10.3390/designs7010020

Academic Editor: Hicham Benhayoune

Received: 13 December 2022
Revised: 11 January 2023
Accepted: 17 January 2023
Published: 1 February 2023

1. Introduction

1.1. Relevance and Challenges

The demand for building habitats continues to rise as the population grows. The high consumption of resources and energy from the construction sector, the scarcity of natural resources, and the acknowledgment of climate change and severe environmental challenges have prompted incentives to improve material efficiency, consider the complete life cycle of buildings and their components, and search for alternative resources in place of conventional ones [1–3].

Bio-based materials have emerged as a popular biodegradable, regenerative, and low-cost source of using natural biological mechanisms and low-energy fabrication methods to produce composite materials [4,5]. They have numerous facets of sustainability, aiming to reduce, reuse, recycle, and recover waste and encouraging the further following of the circular economy model of closing the loop of resource use and controlling the material lifecycle.

Emerging material research and applications of bio-based composites are gaining attention as a prevalent ecological solution and a design tool capable of producing free-form geometries and building elements with a low energy use and carbon footprint, achieving more sustainable products within the building industry [6,7]. Bio-based composite materials are applied and can often be validated through small-scale demonstrators as a proof of concept [8].

1.2. Mycelium-Based Composites

Mycelium is the vegetative part of fungi that grows in and on soil, consisting of long hyphal filamentous structures responsible for growth. Mycelium-based composites (MBC) are bio-based composite materials relying on the growth of mycelium that colonizes plant-based substrates and binds them into a unique matrix [9,10]. At present, grown plant-based materials such as mycelium-based composites are emerging as eco-friendly solutions that are within reach for designing and manufacturing sustainable objects. This is because their main constituents contain plant-based waste materials and demand low energy during production, and their product characteristics are strengthened by their ability to be readily recycled and easily disintegrated into the soil.

Mycelium naturally decomposes organic matter by binding onto surfaces rich in carbon to form three-dimensional networks. Agriculture fiber residues such as hemp, straw, and sawdust are commonly used as substrates, and they are selected depending on the chosen fungal species and design criteria. Substrates provide nutrition for mycelium, because their cellular structures are composed of cellulose content embedded in a lignin and hemicellulose matrix, enabling them to bind strongly and form a composite material [11]. Temperature, light, and relative humidity are all factors that influence the pace and maturity of cultivation. There is a wide range of MBC products with distinct properties delivered to the building sector, including insulation panels with low thermal conductivity, high acoustic absorption, and fire protection properties, as well as biodegradable and lightweight substitutes to conventional materials [4,12,13]. MBC characteristics include highly compressive mechanical properties and impact loads compared to its self-weight, as well as durability, fire-resistance, and acoustic and thermal insulation. Additionally, the properties of the composites can be easily customized to specific applications [14].

The ability to choose the fungal species and substrate characteristics changes the environmental parameters, drying, and post-treatment methods as well as the mechanical properties [15]. As the composites grow in molds, they also become more flexible in shape. The types of fungi and substrates influence the morphological characteristics of MBC, as they control the hyphae growth, thickness, density, and surface topography, which affect their acoustic, thermal, and mechanical performance [16].

The mechanical properties of MBC depend on the substrate characteristics including the particle's size and density, the fiber orientation, and post-treatment methods; these parameters can be modified to achieve better results [9,17]. Hemp is a compatible substrate demonstrating strength and stiffness and achieving a strength ranging between 29 and 93 kPa [18,19]. Post-treatment methods such as hot and cold pressing also increase the elastic and flexural modulus, thereby obtaining higher properties [20,21]. Additionally, adding two external layers of lignocellulosic material to be incubated by fungal skins results in a sandwich composite, which provides resistance against planar and lateral bending loads, as well as shear loads [22].

The properties of MBC have led to applications in insulation, paneling, packaging, and furniture products. MBC possess properties that qualify them for further applications in the building industry. However, its adoption is limited due to the challenging fabrication process, a significant part of which lies in growing the material and controlling its parameters [17,23]. New methods and tools for working with the material are still being developed. MBC have strong hygroscopic properties due to their porous nature, which prohibits their use in high-moisture external environments.

The advantages of MBC have already been explored in architecture applications, with the most common method being producing mycelium structures in small segments assembled into larger structures [24]. All the presented structures have compression-based geometries in common, as mycelium has good compression mechanical properties. On a large scale, a correct form, a design for the reinforcing system, and a stable formwork are critical for growing successfully. One of the earliest large-scale examples is the Hy-Fi tower constructed from ten thousand mycelium bricks to form three intersecting cylinders, which was displayed at the 2014 MoMA PS1 Young Architects by The Living Firm and ARUP [25]. The 13 m tall structure was built using modular MBC brick elements stacked on top of each other. This project showcases MBC bricks' potential application as modular components to create large-scale structures. A successful example of MBC applications is the MycoTree by the Karlsruhe Institute of Technology, the Block Research Group at ETH Zurich, and the Future Cities Laboratory at Singapore-ETH, which was exhibited at the 2017 Seoul Biennale of Architecture and Urbanism (Figure 1a). To achieve stability and create a performative structure, the project used the 3D graphic statics method and computational tools to design the form and geometry of the components to load the material, utilizing its compressive structural capacity [26]. During the cultivation process, bamboo endplates and metal dowels were integrated into MBC components to work as joints. The advantage is that the system is easily assembled, obtaining clean connections and transferring the loads from one component to the other.

(**a**) (**b**)

Figure 1. State of the Art: (**a**) The "MycoTree" at the Seoul Biennale of Architecture and Urbanism, 2017; photo by Carlina Teteris [26]; (**b**) "The Circular Garden" at the Milan Design Week 2019; photo by Marco Beck Peccoz [27].

An existing work of a large-scale structure using continuous MBC is The Circular Garden by Carlo Ratti Associati (Figure 1b). To enable the growth of MBC in a continuous format, this project used the hanging chain form-finding method to create a catenary shape. This was possible by hanging a series of suspended catenary formworks while growing mycelium on it [27]. Sixty arches of four meters were cultivated in two months. The final structure pushes the boundaries of using continuous MBC for compression structures. However, large-scale components require a longer growth time, greater material quantities, special formworks, a profound design of the components, and assembly strategies at an early design stage.

In architecture, various concepts of interlocking modular assemblies have been explored, where repetitive shapes are combined to form various configurations. The modular pieces have connection slots that allow them to join and lock together at different angles. The structural integrity of the interlocking system is achieved by distributing forces through the elements without the use of additional binding materials. Nguyen Khac Phuoc Architects and Dang + Partners created Module+, a permeable structure in rural Vietnam made up of 2000 cross-shaped modular wooden components. Each module has slots that allow the components to connect with one another [28]. This interlocking system relies on friction, without the need for additional fixtures, resulting in a self-supported system. Here, the configuration options are limited because the slots are located only along the components' horizontal and vertical axes. A medium-scale demonstrator of Interlocking Particles was designed by Markus Hudert and exhibited at the 2017 Aalto Festival in Espoo, Finland [29]. It consists of six plywood panels that are connected on an orthogonal spatial pattern. This concept is based on a spatial arrangement of 145 × 145 cm modular panels with integrated slots. Each slot is one-fifth the length of the panel's edge length deep. The structural performance of the global system was analyzed using finite element analysis (FEA). The resulting sculpture explores the fundamentals of interlocking modular assemblies in architectural contexts.

1.3. Scope

Because of the nature of mycelium and its growth process, the final product will function best when fabricated in smaller fragments. In terms of growth and environment, smaller elements are easier to control, lowering the risk of contamination. The porous surface and material composition make it much more challenging to build large continuous blocks and structures. As a result, most mycelium applications focus on small-scale elements, such as thin components or combinations of small modules or blocks for forming larger structures. In architectural applications, mycelium products are expected to obtain a higher preference for modular applications.

The approach of this study focuses on the design of small-scale modular components for architectural applications. The development of mycelium-based composites involves exploring the geometry, size, thickness, interlocking strategy, and growing time of a unit. Developing a functional integrated interlocking system for connecting the modules is crucial for a successful modular system using only mycelium components. The modules are designed with finger joints for the elements to interlock beneficently to minimize contamination from the requirement of making perforations for additional fixations, formwork, and scaffolding. The concept of easy assembly and disassembly is also considered to offer geometrical flexibility and rigidity and to enable the creation of various configurations. A computational design workflow is being used to test and optimize the design and variety of connections.

This type of system is characterized by the low production costs required to create fully biodegradable units, using only agricultural waste products that can be sourced regionally. This modular system is an eco-friendly solution to the commonly used conventional materials aiming to produce less waste, considering the complete life cycle of buildings and their components and fulfilling the circular economy model in the building industry.

On an architectural scale, a geometric case study is proposed and demonstrated by creating small-scale prototypes that showcase the material's feasibility in the proposed system. As an outcome, the prototypes demonstrate the design's functionality, expanding the application of MBC and promoting a novel materials culture. This paper focuses on the development of mycelium modules including the design concept of the studied geometry and its production process. The material and its properties have not been thoroughly addressed or examined but are nevertheless understood in terms of thickness, component size, interlocking techniques, and growth time.

2. Materials and Methods

The first challenge is to define and understand the tolerances and criteria of the shaping of these materials, with an emphasis on the geometric and joining properties of the component. In the first phase, a material study is conducted to produce mycelium modules, and the workflow is broken into four main parts: (1) identifying key factors which influence the performance of the modular components, such as the geometry, size, thickness, interlocking strategy, and growing time of the component, (2) designing the global geometry and its finger joints, (3) integrating the design process into the computational design workflow, and (4) realizing physical prototypes.

After gaining sufficient knowledge of mycelium's growing behavior, processes, and favorable conditions, the cultivation process of the organism begins. To obtain a culture, the process of inoculation is required by making first-generation grain spawn and incubating it using a fungal strain. This study focuses on the design of mycelium modules, and, thus, the inoculation process was discarded because of the lack of a contained environment with proper sterility, as well as the imposed long growing period required to achieve a mature culture. One commonly used method for fabricating mycelium modules is to grow them using a mycelium growing kit, which is based on Do-it-Yourself practices and can be customized for personalized product applications (Figure 2). Mycelium growing kits are becoming available on the market, making the material accessible to the public and allowing users to grow their products. Several companies introduced growing kits and made them easily accessible for regular users, such as the mycelium growing kit from the company Grown.bio (Heerewaarden, The Netherlands), which is used in this study to produce all the physical prototypes [23]. The kit contains 3 L of moistened hemp substrate particles of 5–15 mm inoculated with active mycelium. This growing kit grows to fill a volume of 3398 cm^3 and achieves a composite property, a density of 121.74 kg/m^3, a compressive strength at 15% compression of 0.1246 N/mm^2, and a flexural strength of 0.234 N/mm^2 [30].

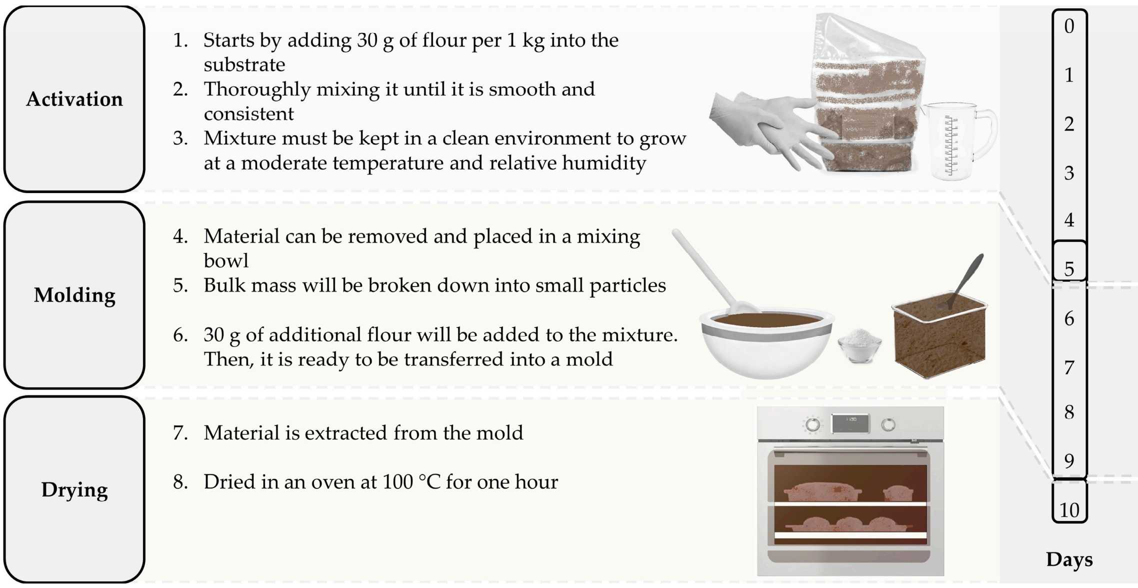


Figure 2. Mycelium growing kits processes Adapted from [30].

The mycelium growing kit includes a recipe and step-by-step instructions for making your own pieces at home. A fast-growing mycelium strain is included, which reduces the production time and infection risk. The growing process starts by adding 30 g of flour per 1 kg into the substrate and thoroughly mixing it until it is smooth and consistent. Then, the mixture must be kept in a clean environment to grow for four to five days at a moderate temperature and relative humidity. After the white mass has formed, the material can be removed and placed in a mixing bowl, where the bulk mass will be broken down into small particles. At this point, 30 g of additional flour will be added to the mixture. Then, it is ready to be transferred into a mold and left to grow for another four to five days. The material is then extracted from the mold and dried in an oven at 100 °C for one hour. Following these steps, a finished product can be achieved within ten days, promoting possibilities for material experimentation and hands-on practice.

2.1. Modular Unit Design Exploration and Analysis

Experimentation on the fabrication process, growing time, thickness, size, and interlocking strategies of the component was conducted to obtain sufficient knowledge about the growth behavior of mycelium for designing modular components.

2.1.1. Geometrical Shapes and Interlocking Strategies

In the first experiment, five modules of different shapes were studied, testing the component geometry and conceptualization (Figure 3). The aim was to achieve a viable design solution of the unit's geometry that allows the modules to be connected to form a modular system without the need for additional fixations. Each sample is designed within 100 cm^2 and a density of 221 kg/m^3, integrating one to four joints. Plastic molds were prefabricated and filled with the material, which was then left to grow for five days.

Figure 3. First experiment: modules of different shapes with embedded finger joints.

After the samples were grown and dried, they were examined. They were evaluated based on their geometric appearance and how effectively the finger joints allowed for connection and maintained the connected modules' stability. The joint's geometry and number became a crucial design factor in inheriting the interlocking capacity without the need for additional reinforcements but relying on inheriting an existing material's characteristics, such as surface roughness, and connecting multiple parts more sustainably. By integrating three or more joints, the elements were able to form multiple compositions.

Several issues were observed in the interlocking process, which affect the stability of the overall system (Figure 4). The manual molding process resulted in inaccuracies and deformations of the edges and groves of joints, an inadequate thickness-to-aspect ratio, and an ineffective distribution of the material. When interlocked with other samples, this resulted in most connections being unstable. Furthermore, the joint's geometric control is lacking, resulting in a weak friction force between two parts [31].

Figure 4. Interlocking physical testing.

2.1.2. Size and Thickness

In the second experiment, four 9 × 10 cm rectangular samples were developed, with various thicknesses ranging from 0.3 to 6 cm, to determine the most suitable ratio between the thickness and size in order to obtain a suitable friction force between two parts. There is an interdependent relationship between the thickness and the ability of the modules to successfully connect to each other. Based on the pervious experiment, the aim was to develop modules with a thickness that can provide the joints relative freedom to slide among each other with adequate friction and provide interlocking strength. An additional factor that influences the global form involves maximizing the material quantity around the edges of the joint and in the center of the component [32]. The hemp substrate consisting of 5–15 mm particles was incrementally compacted and distributed in multiple layers along the coplanar flatter side of the components to increase the density of the composite. This process allowed for arranging fiber particles horizontally along the face onto which the loads will be applied.

To test and evaluate the effect of the compacting process on the elements' strength, each sample was tested physically under different loads of 0.2, 0.5, 0.67, and 1–3.63 N/mm^2 and loaded gradually by adding the accumulation of loads onto the horizontal face to determine their maximum capacity (Table 1).

Table 1. Results of the interface between the thickness and sample size ratio for mycelium modules.

Sample Size (cm)	Density (kg/m^3)	Thickness (cm)	Physical Loads (N/mm^2)
10 × 10	221	1	<3.63 $^+$
10 × 10	332	0.3	<0.20 $^+$
10 × 10	407	0.5	<0.25 $^+$
10 × 10	110	6 [1]	-

$^+$ Growth Failed.

The sample with a thickness of 1 cm and a density of 221 kg/m^3 could bear weights up to 3.63 N/mm^2 compared to samples with a thickness of 0.3–0.5 cm and a density of 332–407 kg/m^3, which instantly broke under lighter loads. They also showed a light geometric transformation from a linear to a convex form as a result of shrinkage and a loss of water after being dried. The sample with a thickness of 6 cm and a density of 110 kg/m^3 did not grow successfully because of its excessive thickness in relation to its size, which limited gas exchange and prevented the organism from developing. A correlation can be observed regarding the interdependent relationship between thickness and strength. The material thickness and density contribute to the success of the interlocking system and can also affect the strength and stability of the module. Structural and mechanical strength has not yet been fully considered, as it is not the primary focus of this research. The goal of this study emphasizes the design concept for mycelium modules and its developed geometry, its thickness, the size of the component, its interlocking strategies, and its growing time. However, mechanical testing would need to be conducted in future work to assess the maximum load-bearing capacity.

2.2. Design Concept

The benefits of such material are important from an ecological perspective. However, it may also be challenging in terms of both design and production methods. The goal was to create mycelium modules while considering their fabrication characteristics and limitations such as growth time, size, and thickness, all of which must be analyzed. Because of its simplicity, a cross-shape was chosen as the fundamental form for designing the modules. Furthermore, the form's design was adjusted to satisfy the material's growth and construction criteria, resulting in mycelium modules that may organize different configurations, grow independently, and be joined to form a complete system. The geometry and design of the module have become an essential aspect of the success of the modular system's growth and functional features, as well as the material emerging as successful and suitable in giving a promising approach for construction employing modular mycelium components.

The design workflow was handled in the Rhino/Grasshopper computational design environment to facilitate the design process and obtain control over the chosen geometrical parameters. Geometrical variations of the cross-form size of 20 × 20 × 2 cm were generated and tested, with the highest number of joints, while the global geometric stability was maintained (Figure 5a). This is an important step for obtaining connection flexibility and generating complex compositions.

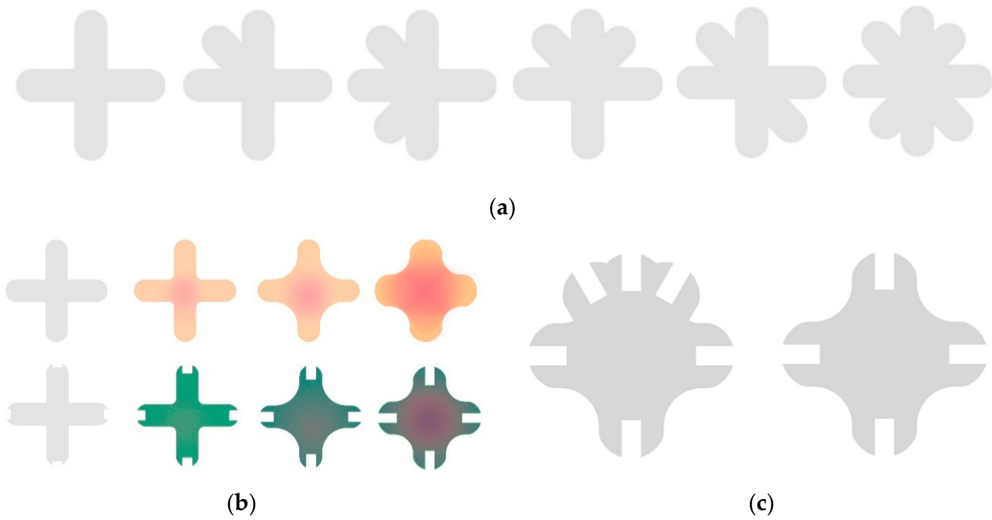


Figure 5. (a) Process of form generation incorporating the maximum number of joints, (b) Interlocking aspects and material reinforcements applied to the selected modules, (c) Parametrically generated options of two modules with four and six joints with 60- and 90-degree angles.

Each iteration included interlocking aspects, the number of joints, and material reinforcement criteria while maintaining the interdependent relationships between all parameters, including joint geometries, thicknesses, and the sample size ratio (Figure 5b). To provide appropriate friction between two pieces, rectangular joints with an aspect ratio of 25% of the length of the longest side were designed, with a clearance range of 0.3 mm. The global geometry was then optimized, reinforcing the areas around the edges of the joint, between neighboring joints, and in the middle of the space. By incorporating these numerous parameters into the design, it becomes evident that the geometry of the module and the material are interconnected parts that complement each other in achieving a higher potential based on their inherent interdependent properties while repurposing their combined properties to achieve one component with functional capacities, allowing MBC to be used for further applications in architecture.

Alternative assemblies were explored using different interlocking slots to construct various configurations of the modules. Initially, the modules were connected orthogonally. However, most of them are rigid and have limited possibilities because the slots were located only on the horizontal and vertical axes (Figure 6). Two modules with four and six joints and 60- and 90-degree angles were introduced, allowing for the assembly of more configurations. The developed modules are easy to assemble and disassemble. The resulting systems are self-supported due to the interlocking joints, the amount of the contact surface, and the arrangement of modules that form a robust cluster.

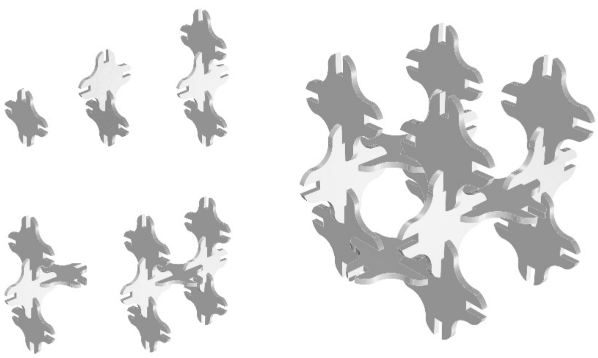


Figure 6. Assembly systems for three-dimensional configurations using 90-degree orthogonal angle slots.

2.3. Computational Design

An integrative computational design workflow was adopted to optimize the developed geometry and to test various assembly possibilities (Figure 7) by incorporating a form-finding method, an assembly strategy of the modular components, and an optimization process [33]. After experimenting with numerous geometrical modifications of the basic module, an optimal shape was chosen and transferred to the digital model to be used as the primary input for the assembly strategy process. Various assembly logics and constraints for connections were developed, guiding the modules to interlock with each other by defining the slots and specifying the center points of the interlocking modules. To conduct the simulation, all the constraints were gathered and added to the aggregate setup. A catenary arch was modeled to optimize the aggregation process and arrange elements based on a target. An arch-shape global geometry was chosen to evaluate the capabilities of the components' assembly in a proposed architectural case study. The arch is an inverted catenary shape, an optimized form determined by its weight which works under compression.

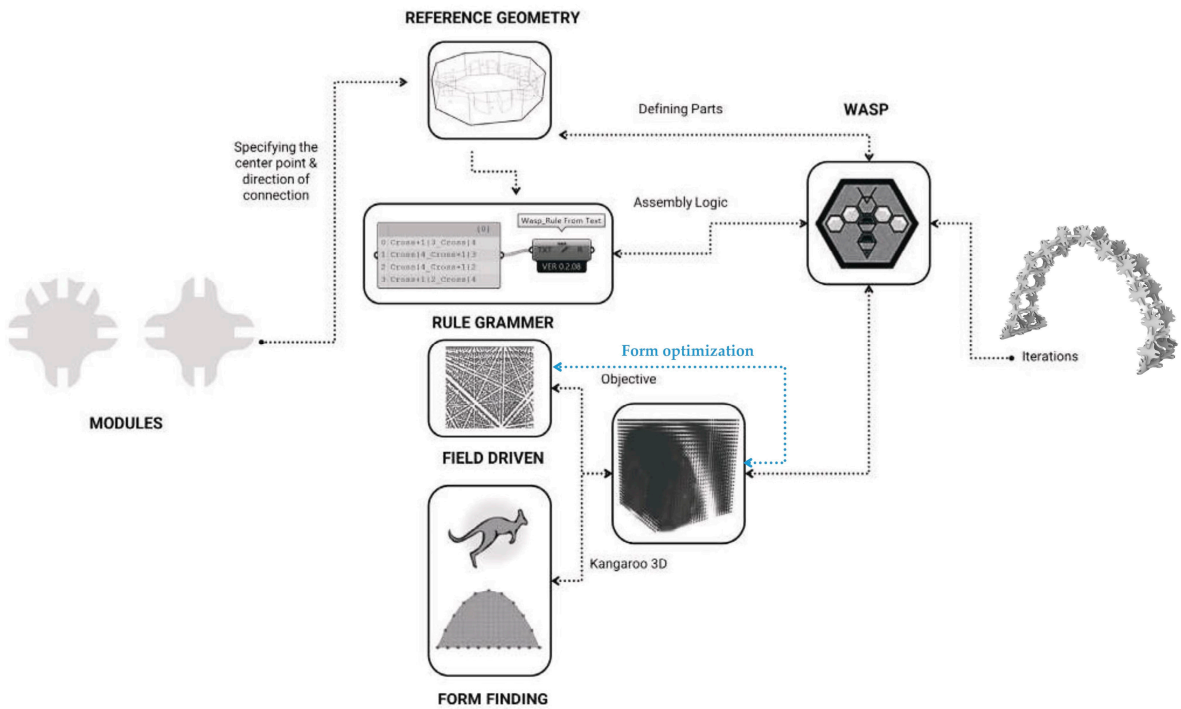
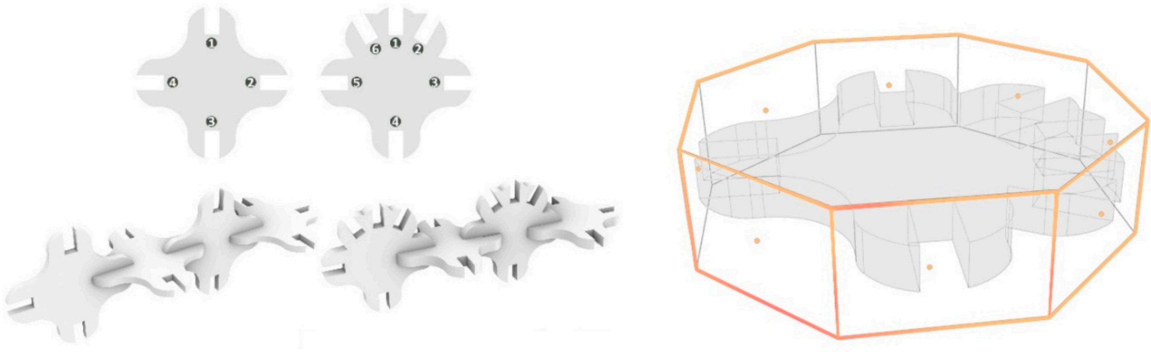


Figure 7. Computational design workflow overview: form-finding defining the assembly strategy of modular components and the optimization process for generating aggregation.

A catenary structure was explored to achieve equilibrium. The physics simulation plugin Kangaroo3d in Rhino/Grasshopper was used to simulate a form of a 2.4 m height arch [34]. The form-finding process was initially defining the length of a curve—here, 3.7 m. The curve was then subdivided and assigned with anchors and boundaries for the simulation to start. Subsequently, the engine built a relaxed state of the system and resolved the form until an equilibrium state was achieved. A catenary curve was obtained as a result of this setup, and it could be then used for testing arrangements of modules along its thrust line.

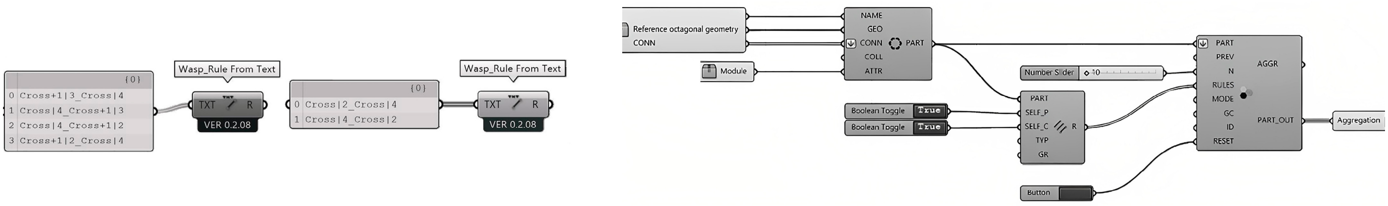
2.3.1. Defining the Assembly Strategy

To design the assembly strategy for the elements, the Grasshopper plug-in Wasp was used inside the Rhino/Grasshopper environment [35]. The setup involves defining the rules and guidelines for connections by specifying which modules can interlock with each other via which slots (Figures 8a and 9a). First, the center points of the interlocking slots need to be located. An octagonal prism of the modules' boundaries was used as the reference geometry to simplify the geometric shape (Figure 8b). The center points of the slots' faces were then located. Interlocking aggregation can be accomplished in several ways. The first method is to use a "rule generator," which automatically generates all possible connection outcomes based on the defined center points of interlocking slots for random aggregation. A different method involves the use of a text string, which allows for the direct conversion of text into rules for generating controlled aggregation. Finally, all parameters are put into the aggregation setup, which is then executed to build aggregation (Figure 9b).



(**a**) (**b**)

Figure 8. Defining the assembly logic: (**a**) Interlocking modules with four slots (1,2,3,4) and six slots (1,2,3,4,5,6), (**b**) Octagonal prism of 20 × 20 × 4 cm used as the reference geometry of the six slots module.



(**a**) (**b**)

Figure 9. Defining the assembly strategy in the Rhino/Grasshopper environment using: (**a**) rules from the text component for the assembly rules and guidelines, which are fed into (**b**) the aggregation component.

2.3.2. Generating Aggregation

A parametric workflow was adopted to optimize the aggregation process by placing parts based on an objective, given a suitable form and rules of assembly (Figure 10). Any geometry can be transformed into a field of points, allowing the modules to be positioned accordingly. The optimized catenary form was converted into a high-resolution boundary filled with points. The position and coordinates (x,y,z) of all points were extracted (Figure 10b). These points were then referenced with a numeric value between 0 and 1, indicating their distance from the geometry.

Points with lower values (numeric value closer to zero) were closer to the arch, which means there was a high probability of placing parts, and points with higher values (numeric value closer to one) were found further away, meaning less portability. As a result of this process, a list of numeric values referring to the three coordinates (x,y,z) could be extracted and fed into the aggregation component, along with the defined assembly rules, the geometry of the modules, and the number of parts for controlling placing parts iteratively without collisions.

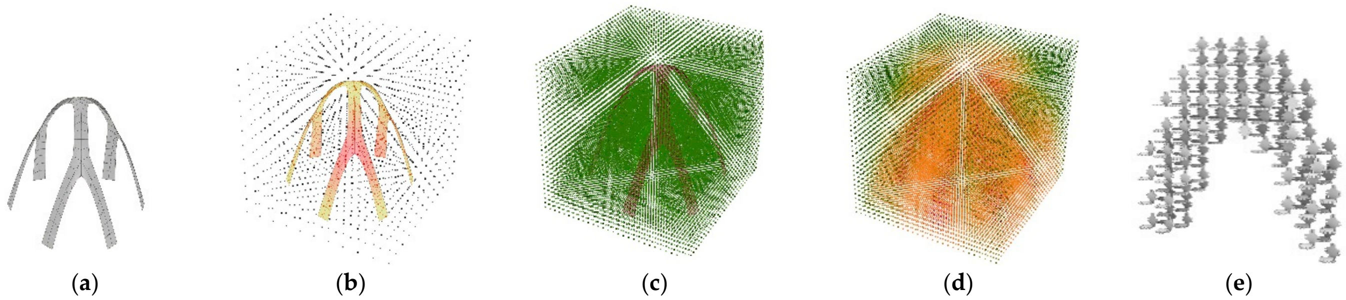


Figure 10. Parametric workflow: (**a**) defining the aggregation objective using a global form, (**b**) creating a boundary of points, (**c**) locating and culling the tangent points—dark green, (**d**) extracted list of tangent points, (**e**) assembly result.

Complex geometries were possible using this parametric workflow. Due to the computational complexity of the aggregation process, the model was broken up into smaller sections to maximize the placement of parts within a pre-defined boundary along a geometry thrust line (Figure 11). First, the curve was divided into eight segments, with a tangent line generated at each resulting point. These tangent segments were then extruded into surfaces to form boundaries, allowing the modules to be placed where they intended to be. The planes were subdivided into grids to guide the placement of the modules in space. The grid was used to maintain a distance of 10×10 cm to distribute the points sufficiently within the rectangular boundary and ensure that the gaps between parts could overlap once all modules were oriented onto the tangent planes (Figure 12). It could also serve as a geometric reference for the parts placement and keep track of the distance between interlocking sections.

A numeric list was extracted, which included the points of the tangent planes, along with the geometry of the modules and their orientation. The list was then fed into the aggregation component to control the parts' placement, following the workflow discussed in the previous section. The algorithm of the aggregation component could then generate the configurations while maintaining the planarity of the modules. The gaps and the discontinuity of the parts from each iteration were compensated by overlapping layers of modules over each other to create a continuous system. Furthermore, redundant elements were removed, ensuring that there were no loosely linked modules. The resulting final aggregation was a compact self-supported system.

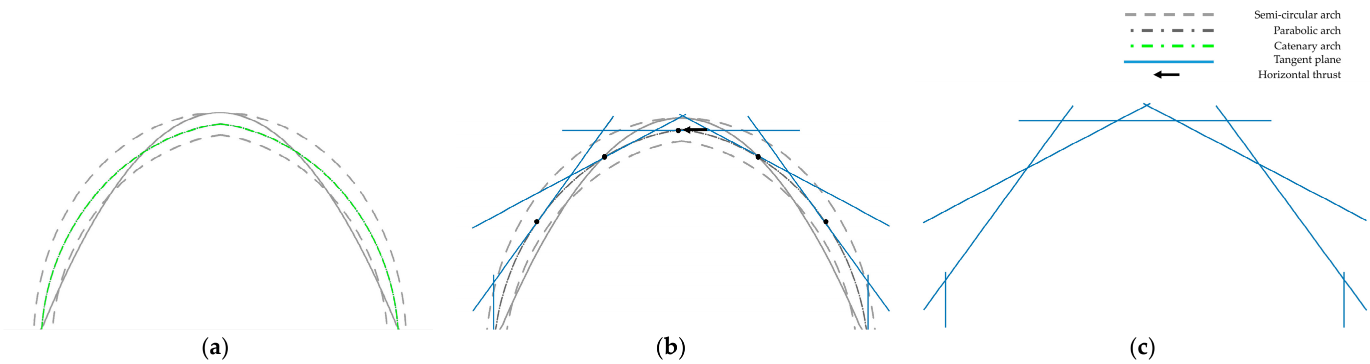


Figure 11. Discretization process of the model: (**a**) Catenary curve through obtaining (**b**) points on the curve, converted into (**c**) tangent segments.

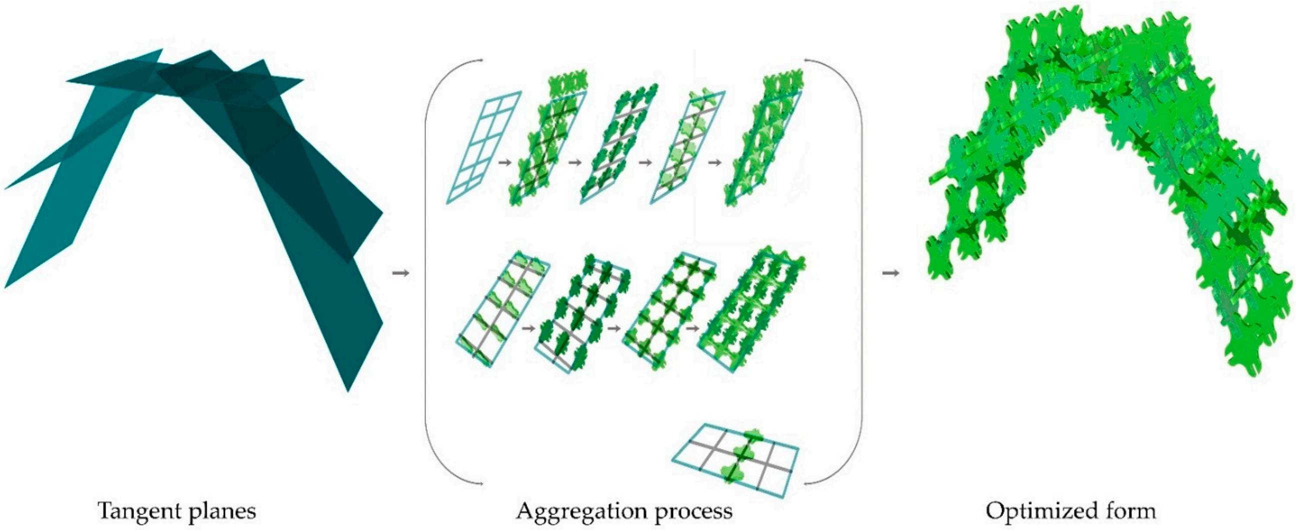
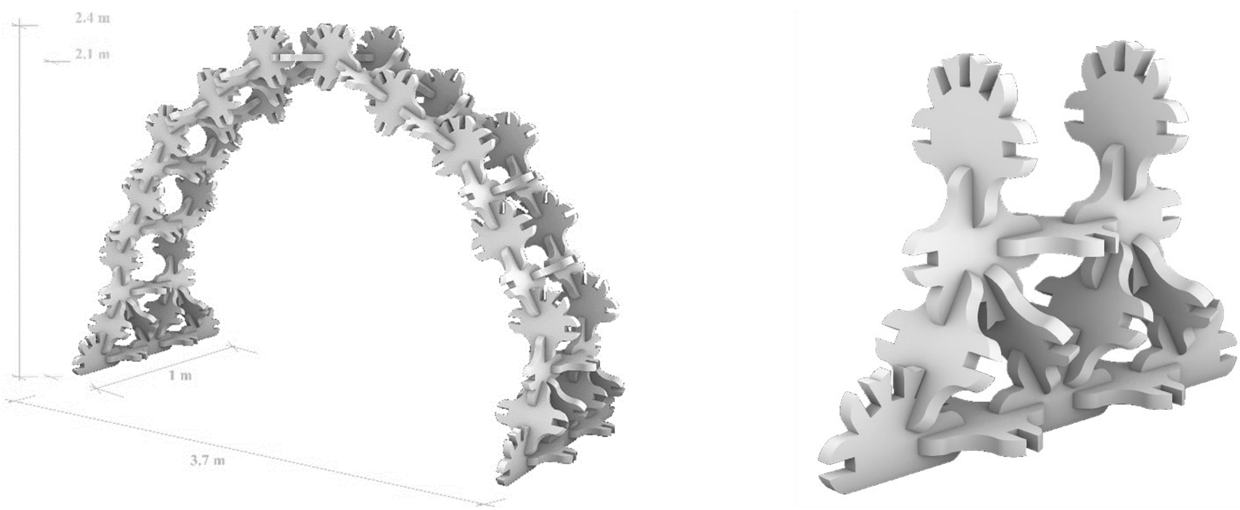


Figure 12. Discretization and aggregation workflow overview.

3. Results

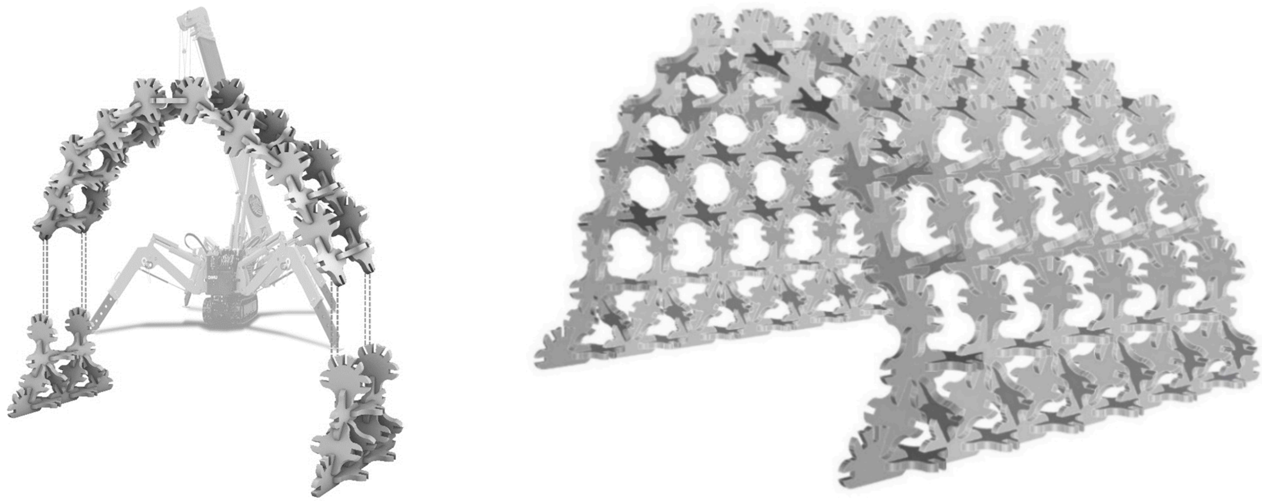
3.1. Forming an Arch

Seventy-three modules of 20 × 20 × 2 cm were joined in equilibrium along a catenary curve to form the final articulation of an arch structure: 2.4 m high, 3.7 m long, and 1 m wide (Figure 13a). This initial design showcases the potential of the developed system in a full-scale architectural application. Two support anchors, each made up of 28 modules, were designed to support the structure, acting as buttresses for transferring loads and ensuring overall stability. In two triangular arrangements, 14 modules were joined to form a cluster (Figure 13b). Two customized modules with a flat base were built for this layout to provide the foundation with extra strength. As a result of this configuration, loads could be transferred from one element to another, achieving equilibrium in the system. Similarly, large-scale applications can also be achieved by connecting multiple arches, using additional lateral horizontal modules as supports to form a vault (Figure 14).



(**a**) (**b**)

Figure 13. (**a**) Digital model of the arch structure with the best aggregation outcome, (**b**) Triangular configuration of the support cluster.



(a) (b)

Figure 14. (**a**) Digital model of the assembly with the help of a crane for large-scale applications, (**b**) Example of multiple arches connected to the form of a vault.

3.2. Fabrication

To demonstrate the applicability of the developed system, five modules of 20 × 20 × 2 cm were produced as a small-scale demonstrator to further understand the physical limits, properties, and potential of the system as an initial design phase. To prepare for the manufacturing, the 3D model was converted into 2D drawings. Prefabricated plastic molds were CNC-cut from recyclable plastic sheets and used to assemble the walls of the mold in order to obtain clean edges after demolding. Based on the results of the experiments, this fabrication procedure was chosen to achieve a clearance range of 0.2–0.6 mm, thereby increasing the friction between the parts and improving the system stability. Additionally, the vertical plastic walls were CNC-cut as a continuous strip, glued, and dried in place before the material filling process began for additional support. Three 3L growing kits of mycelium material were used to produce the modules (Figure 15). The molds were assembled and filled with the material using an incremental compacting process to ensure even distribution [17,26]. Following the growth procedure, which was previously explained, the growing process was accomplished.

(a) (b) (c)

Figure 15. Production process: (**a**) Prefabricated molds filled with the growing material, (**b**) Incremental compacting for a higher density, (**c**) Grown samples ready to be dried in an oven.

3.3. Physical Prototypes

The design and fabrication process were materialized on a prototypical scale. The final prototype consisted of five modules which were able to form different geometrical configurations, resulting in the utilized workflow (Figure 16). Each module weighted 0.39 N and had a density of 50 kg/m^3, including two modules with four and six joints, as well as a density of 100 kg/m^3 for the special module with a flat base; thus, it could support a weight more than two thousand times higher than its self-weight. These initial prototypes were then capable of holding the weight of an average adult (80 kg), resulting in a deflection of 0.2 cm The fabrication process and the adequate distribution of the material resulted in lightweight modules which could be assembled in various configurations (Figure 17). The finger joints were fabricated with clean edges and enough of a contact surface, which provided the joints relative freedom to slide among each other with adequate friction, resulting in a sufficient interlocking mechanism. Alternative assemblies using different interlocking slots of the modules could be possible, and various scenarios were tested for assembling vertical, horizontal, and diagonal configurations. The developed modules are also easy to assemble and disassemble.

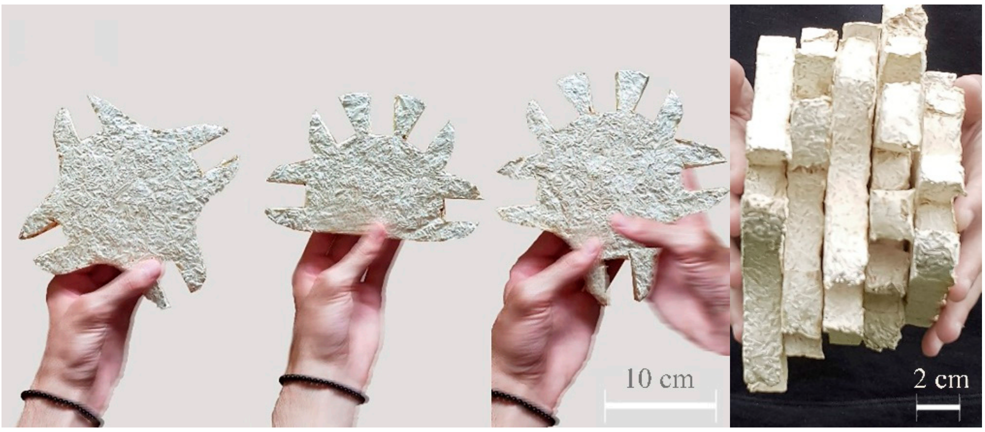


Figure 16. Final prototypes of the modules.

Figure 17. Final prototypes are assembled in various configurations.

4. Conclusions

The purpose of this research was growing materials experimentation by demonstrating the development of MBC in the form of modular components which could result in multiple geometrical configurations that do not require the use of extra pieces for fastening. This was accomplished by including numerous criteria into the design, ensuring proper material distribution via the molding and compacting processes, and applying computational design to optimize the geometries. Hemp substrate was chosen and found to be compatible with mycelium, achieving greater stiffness [9,17]. The compacting and material distribution that was used for the cultivation process increased the density of the composite and arranged fiber particles horizontally, thereby improving the modules' stability.

Five prototype modules were created and assembled in various configurations to demonstrate and validate the system's geometrical feasibility, interconnecting possibilities, and applications. The embedded finger joints allowed the mycelium modules to interconnect and form a biodegradable modular system. These developed prototypes can be respectively scaled up for larger architectural applications. The main limitation is the need for excessive control over the growing and cultivation time, molding, and production process. The main goal of the prototypes was to test the interlocking system while considering upscaling in an architectural context for future studies. The physical prototypes demonstrated the interlocking and the system capacities needed to build a modular system in various configurations. However, more research on the structural capabilities of the joints and reinforcement strategies is required.

In the future development of this work, it is intended to perform mechanical tests to explore the strength and stability of the interlocking joints in different loading scenarios by applying a gradual compressive loading in a set-up of two or more connected modules, as well as to understand the material properties and the structural behavior. The integration of different materials, such as wood, into the molding process is also considered. Wood could bind with mycelium and act as a reinforcement, increasing the compressive strength and flexural properties. This could speed up the fabrication process while also increasing the strength of the composite and making the molding process more resource-efficient. It is important for structural analysis simulation to be integrated into the computational design workflow to provide optimum shapes based on force flows and loads distribution. Furthermore, bio-based coatings need to be studied and considered to be integrated into the composite to increase the rigidity and water resistance by lowering water absorption. This can enhance the mechanical properties and create opportunities for the use of MBC in external applications (Figure 18).

(**a**) (**b**)

Figure 18. Concept for the self-supported interlocking system in (**a**) an interior application and (**b**) an external environment.

In future work, producing the complete structure will demonstrate the full potential of the system's capabilities. The process itself promotes further material experimentation and design explorations. It highlights the importance of understanding and identifying the characteristics and properties of the materials, studying potential growing methods, and supporting the use of computational design in developing complex geometries in an architectural context. This research has presented methods for expanding the scope of the use of mycelium-based composites in modular systems and promoting architectural applications using bio-based composite materials.

Author Contributions: The conceptualization, design, methods, presentation, prototyping, and testing, as well as the writing of this paper, were carried out by O.A. This paper was supervised and reviewed by H.D. and E.S., and both gave prerequisite knowledge, support, and guidance to the

author in the field of biocomposites and sustainable architectural building elements. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the Fachagentur Nachwachsende Rohstoffe e. V. (FNR, Agency for Renewable Resources) under Bundesministeriums für Ernährung und Landwirtschaft (BMEL, Federal Ministry of Food and Agriculture) throughout the research project LeichtPro: Pultruded load-bearing lightweight profiles from natural fiber composites (FKZ:22027018), managed by Hanaa Dahy, director of the BioMat Department at ITKE, University of Stuttgart. The work was also partially supported by Krown-Design BV, Hogewaard 21D, 6624 KP Heerewaarden, Netherlands, the company from which the mycelium growing kits were purchased.

Data Availability Statement: Not applicable.

Acknowledgments: This paper was part of a Master's Thesis of Ain Shams University, which was supervised at the BioMat Department of the University of Stuttgart by Hanaa Dahy and tutored by Evgenia Spyridonos.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Dahy, H. Efficient Fabrication of Sustainable Building Products from Annually Generated Non-Wood Cellulosic Fibres and Bioplastics with Improved Flammability Resistance. *Waste Biomass-Valorization* **2019**, *10*, 1167–1175. [CrossRef]
2. Hebel, D.; Wisniewska, H.M.; Heisel, F. *Building from Waste: Recovered Materials in Architecture and Construction*; De Gruyter: Berlin, Germany, 2014; ISBN 978-3-03821-375-8.
3. United Nations Environment Programme; Global Alliance for Buildings and Construction. *2020 Global Status Report for Buildings and Construction: Towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector—Executive Summary*; UN Environment Programme (UNEP): Nairobi, Kenya, 2020.
4. Jones, M.P.; Huynh, T.; Dekiwadia, C.; Daver, F.; John, S. Mycelium Composites: A Review of Engineering Characteristics and Growth Kinetics. *J. Bionanoscience* **2017**, *11*, 241–257. [CrossRef]
5. Dahy, H. Biocomposite Materials Based on Annual Natural Fibres and Biopolymers–Design, Fabrication and Customized Applications in Architecture. *Constr. Build. Mater.* **2017**, *147*, 212–220. [CrossRef]
6. Dahy, H. Towards Sustainable Buildings with Free-Form Geometries: Development and Application of Flexible NFRP in Load-Bearing Structures. In *Biocomposite Materials: Design and Mechanical Properties Characterization*; Hameed Sultan, M.T., Majid, M.S.A., Jamir, M.R.M., Azmi, A.I., Saba, N., Eds.; Composites Science and Technology; Springer: Singapore, 2021; pp. 31–43, ISBN 978-981-334-091-6.
7. Dahy, H. 'Materials as a Design Tool' Design Philosophy Applied in Three Innovative Research Pavilions Out of Sustainable Building Materials with Controlled End-Of-Life Scenarios. *Buildings* **2019**, *9*, 64. [CrossRef]
8. Rihaczek, G.; Klammer, M.; Başnak, O.; Petrš, J.; Grisin, B.; Dahy, H.; Carosella, S.; Middendorf, P. Curved Foldable Tailored Fiber Reinforcements for Moldless Customized Bio-Composite Structures. Proof of Concept: Biomimetic NFRP Stools. *Polymers* **2020**, *12*, 2000. [CrossRef] [PubMed]
9. Girometta, C.; Picco, A.; Baiguera, R.M.; Dondi, D.; Babbini, S.; Cartabia, M.; Pellegrini, M.; Savino, E. Physico-Mechanical and Thermodynamic Properties of Mycelium-Based Biocomposites: A Review. *Sustainability* **2019**, *11*, 281. [CrossRef]
10. Elsacker, E.; Vandelook, S.; Wylick, A.V.; Ruytinx, J.; Laet, L.D.; Peeters, E. A Comprehensive Framework for the Production of Mycelium-Based Lignocellulosic Composites. *Sci. Total Environ.* **2020**, *725*, 138431. [CrossRef]
11. Dicker, M.P.M.; Duckworth, P.F.; Baker, A.B.; Francois, G.; Hazzard, M.K.; Weaver, P.M. Green Composites: A Review of Material Attributes and Complementary Applications. *Compos. Part A Appl. Sci. Manuf.* **2014**, *56*, 280–289. [CrossRef]
12. Attias, N.; Danai, O.; Abitbol, T.; Tarazi, E.; Ezov, N.; Pereman, I.; Grobman, Y.J. Mycelium Bio-Composites in Industrial Design and Architecture: Comparative Review and Experimental Analysis. *J. Clean. Prod.* **2020**, *246*, 119037. [CrossRef]
13. Abhijith, R.; Ashok, A.; Rejeesh, C.R. Sustainable Packaging Applications from Mycelium to Substitute Polystyrene: A Review. *Mater. Today Proc.* **2018**, *5*, 2139–2145. [CrossRef]
14. Haneef, M.; Ceseracciu, L.; Canale, C.; Bayer, I.S.; Heredia-Guerrero, J.A.; Athanassiou, A. Advanced Materials From Fungal Mycelium: Fabrication and Tuning of Physical Properties. *Sci. Rep.* **2017**, *7*, 41292. [CrossRef] [PubMed]
15. Jones, M.P.; Lawrie, A.C.; Huynh, T.T.; Morrison, P.D.; Mautner, A.; Bismarck, A.; John, S. Agricultural By-Product Suitability for the Production of Chitinous Composites and Nanofibers Utilising Trametes Versicolor and Polyporus Brumalis Mycelial Growth. *Process Biochem.* **2019**, *80*, 95–102. [CrossRef]
16. Attias, N.; Danai, O.; Tarazi, E.; Pereman, I.; Grobman, Y.J. Implementing Bio-Design Tools to Develop Mycelium-Based Products. *Des. J.* **2019**, *22*, 1647–1657. [CrossRef]
17. Jones, M.; Mautner, A.; Luenco, S.; Bismarck, A.; John, S. Engineered Mycelium Composite Construction Materials from Fungal Biorefineries: A Critical Review. *Mater. Des.* **2020**, *187*, 108397. [CrossRef]
18. Ghazvinian, A.; Farrokhsiar, P.; Vieira, F.; Pecchia, J.; Gursoy, B. Mycelium-Based Bio-Composites For Architecture: Assessing the Effects of Cultivation Factors on Compressive Strength. *Blucher Des. Proc.* **2019**, *7*, 505–514. [CrossRef]

19. Siwulski, M.; Drzewiecka, K.; Sobieralski, K.; Chong, Y. Comparison of Growth and Enzymatic Activity of Mycelium and Yielding of Pleurotus Ostreatus (Fr.) Kumm. on Different Substrates. *Acta Sci. Pol. Hortorum Cultus* **2010**, *9*, 45–50.
20. Appels, F.V.W.; Dijksterhuis, J.; Lukasiewicz, C.E.; Jansen, K.M.B.; Wösten, H.A.B.; Krijgsheld, P. Hydrophobin Gene Deletion and Environmental Growth Conditions Impact Mechanical Properties of Mycelium by Affecting the Density of the Material. *Sci. Rep.* **2018**, *8*, 4703. [CrossRef] [PubMed]
21. Lelivelt, R.J.J.; Lindner, G.; Teuffel, P.; Lamers, H. The Production Process and Compressive Strength of Mycelium-Based Materials. In Proceedings of the First International Conference on Bio-based Building Materials, Clermont-Ferrand, France, 22–25 June 2015; pp. 1–6.
22. Jiang, L.; Walczyk, D.; McIntyre, G.; Bucinell, R.; Tudryn, G. Manufacturing of Biocomposite Sandwich Structures Using Mycelium-Bound Cores and Preforms. *J. Manuf. Process.* **2017**, *28*, 50–59. [CrossRef]
23. Karana, E.; Blauwhoff, D.; Hultink, E.-J.; Camere, S. When the Material Grows: A Case Study on Designing (with) Mycelium-Based Materials. *Int. J. Des.* **2018**, *12*, 119–136.
24. Kırdök, O.; Akyol Altun, D.; Dahy, H.; Strobel, L.; Hameş Tuna, E.E.; Köktürk, G.; Andiç Çakır, Ö.; Tokuç, A.; Özkaban, F.; Şendemir, A. Chapter 17–Design Studies and Applications of Mycelium Biocomposites in Architecture. In *Biomimicry for Materials, Design and Habitats*; Eggermont, M., Shyam, V., Hepp, A.F., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 489–527, ISBN 978-0-12-821053-6.
25. Arup HyFi Reinvents the Brick. Available online: https://www.arup.com/en/news-and-events/hyfi-reinvents-the-brick (accessed on 7 March 2020).
26. Heisel, F.; Lee, J.; Schlesier, K.; Rippmann, M.; Saeidi, N.; Javadian, A.; Nugroho, A.R.; Mele, T.V.; Block, P.; Hebel, D.E. Design, Cultivation and Application of Load-Bearing Mycelium Components: The MycoTree at the 2017 Seoul Biennale of Architecture and Urbanism. *IJSED* **2017**, *6*, 296–303. [CrossRef]
27. Carlo Ratti Associati The Circular Garden. Available online: https://carloratti.com/project/the-circular-garden/ (accessed on 7 March 2020).
28. Modular Lakeside Pavilion at Vietnamese Tea Farm Made from 2000 Wooden Crosses. Available online: https://www.dezeen.com/2019/01/16/nkpa-dang-partners-modular-pavilion-tea-farm-vietnam/ (accessed on 19 April 2022).
29. Hudert, M.; Scholte-Wassink, J.; Kotnik, T. Interlocking Particle Structures: Design and Fabrication of a Medium Scale Demonstrator. In Proceedings of the IASS Symposium 2018 Conference: Creativity in Structural Design, Boston, MA, USA, 16–20 July 2018.
30. Grown.bio Grow-Kit HEMP Substrate. Available online: https://www.grown.bio/product/giy-packaging-kit/ (accessed on 21 September 2022).
31. Sakhaei, A.H.; Kaijima, S.; Xuereb Conti, Z.; Dunn, M. Integrating User-Defined Elements for Topologically Interlocking Joints and Application in Large Scale Structural Analysis. In Proceedings of the IASS Annual Symposium 2016 Conference: Spatial Structures in the 21st Century–Computational Methods, Tokyo, Japan, 26–30 September 2016; pp. 1–10.
32. Arifin, Y.H.; Yusuf, Y. Mycelium Fibers as New Resource for Environmental Sustainability. *Procedia Eng.* **2013**, *53*, 504–508. [CrossRef]
33. Sippach, T.; Dahy, H.; Uhlig, K.; Grisin, B.; Carosella, S.; Middendorf, P. Structural Optimization through Biomimetic-Inspired Material-Specific Application of Plant-Based Natural Fiber-Reinforced Polymer Composites (NFRP) for Future Sustainable Lightweight Architecture. *Polymers* **2020**, *12*, 3048. [CrossRef] [PubMed]
34. Piker, D. Kangaroo: Form Finding with Computational Physics. *Archit. Des.* **2013**, *83*, 136–137. [CrossRef]
35. Allner, L.; Kroehnert, D.; Rossi, A.; Tam, M. Natural Form(s): Case Study of a Spatial Framework Composed of Naturally Grown Forked Branches. In Proceedings of the IASS Annual Symposium 2019 Conference–Structural Membranes, Form and Force, Barcelona, Spain, 7–10 October 2019; pp. 1–7.