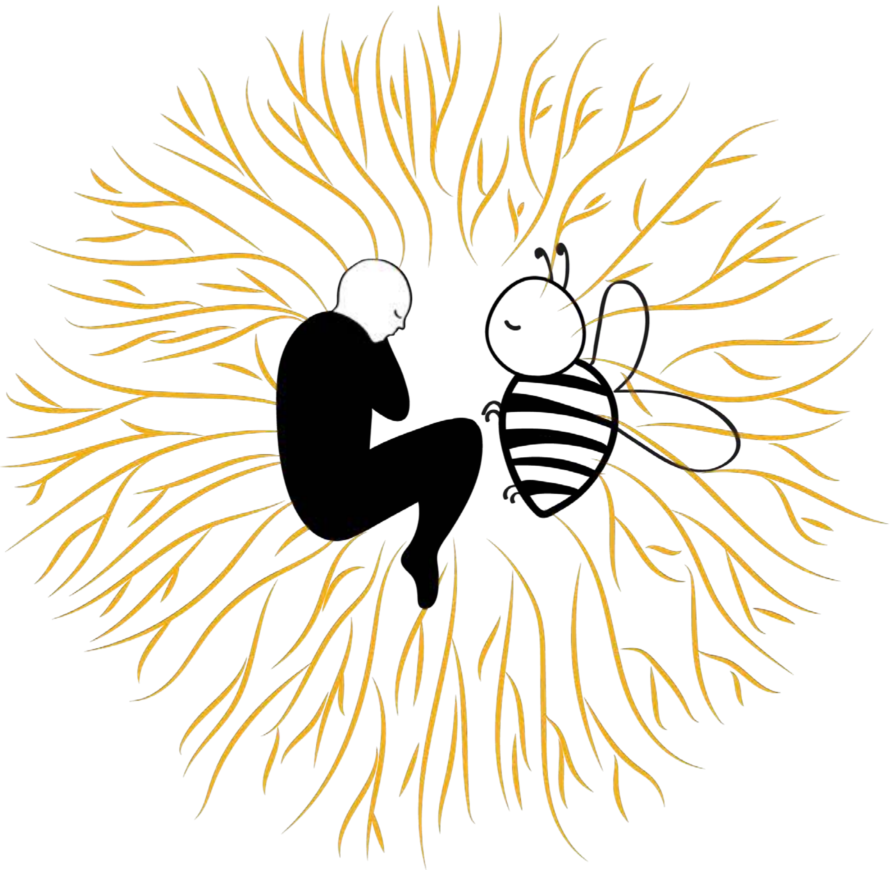

Mycelbiosis

Living in synergy with other species

CHALMERS
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Mycelbiosis

Living in synergy with other species

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Master's Thesis in
Architecture and Planning Beyond Sustainability
& Architecture and Urban Design
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Abstract

In the current era of Anthropocene humans have been exploiting the planet at an unprecedented scale often caused by extraction, production, and manufacturing of building materials. Human habitats compared to their non-human counterparts, are entwined with nature contributing to ecosystem services.

This sets the curiosity to explore areas of bio fabrication to create human habitats that are no longer intruders to nature but works in synergy. The use of bio-based materials possibly enhances the symbiotic relationship among species to promote both environmentally friendly and sustainable innovation.

Research and findings show a potential use of mycelium to produce bio-composite building materials. Fungal lignocellulosic material shows inherent property obtained from the cellulose substrate and mycelium making it a suitable bio-composite material with high insulative, tensile and compression properties (Goidea, Floudas, & Andréen, 2020). On the other hand, mycelium is also used to feed bees to develop resistance to diseases especially colony collapse disorder, where many bee populations disappeared (The Editors of Fungi Perfecti, 2020). Bees provide vital ecosystem service to regulate and maintain world food security through effective pollination in turn preserving the biodiversity of plant species. But due to various human driven factors including use of pesticides, urbanisation and climate change their population is in danger.

Mycelium forms an integral part of the thesis exploration to stitch the gap between the humans and bees for their symbiotic co-existence. A monolithic mycelium wall is grown by maintaining the fungi in alive state using growth as an element of design propagation. The life cycle of the wall forms a closed loop circular system by providing shelter and food throughout the year and finally goes back to soil as compost offering vital ecosystem services.

Using biomimicry and computational design tools, desired structure has been achieved to test the technique of casting mycelium composite in 3D printed moulds. Experiments have been conducted to understand the qualities of mycelium composite by merging different cellulose-based substrates to explore material properties that influence the habitation of the two species to expand its architectural application and usability in creating a monolithic living mycelium composite wall to celebrate mycelium as a key to symbiosis.

Keywords: mycelium; symbiosis; bee; human; monolithic wall.

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Acknowledgement

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And, of course special thanks to our dear families and friends on the one hand Balashanmugam & Umarani, and on the other hand Ghazaleh, Nadereh, Vafa & Baran for all their supported and love shared with no expectancy.

Student Background

"I am a student of MSc. Architecture and Planning Beyond Sustainability program. I did my Bachelors in Architecture (2012-2017) in India and started working immediately after graduation for a year. I soon stepped forward and worked on freelance projects before travelling to Sweden for my master's program. As an architect, I wish to break the approach of human dominant design but consider humans as one of the several species on earth. With this moto my design thoughts are oriented towards an inclusive design for all. I envision the future Architecture would drive humans to get connected with nature and the environment creating a safe habitable space for all."

Aswini Balashanmugam

"I am a student of MSc. Architecture and Urban Design program. Having obtained my BSc Architectural Engineer in 2010 at Iran University of Science & Technology, started working and developing my toolbox and joined to Iran Construction Engineering Organization as an Architect. After a couple of years established my company and started teaching BIM and Architectural Visualisation and following that basic courses of architecture in some institutes and universities in Iran. Since 2019 within resolution of deeper learning of sustainable architecture, I have studied my second cycle degree at Chalmers University of Technology. This thesis is my strong desire toward working in the realms of architecture, environment, and biomimicry by tackling bio-based material through computational design. I wish all human and other species could live in symbiotic relationship eventually."

Aran Mardoukhi

Thesis Questions

To what extent can a pure mycelium composite structure be maintained in alive state to benefit both bees and humans for mutual symbiosis?

Is it possible to add new aesthetic and functional qualities of buildings with the use of mycelium composite? To what degree are the surface qualities explored by the use of mycelium composite?

How does the life-cycle of growth and natural degradation of the bio composite material influence the habitat of the bees and humans?

Aim

The aim of the thesis is to propose a living wall structure with mycelium composite to establish a symbiotic relationship between bees and humans to expand the use of human habitable spaces. How a monolithic living structure made of mycelium could influence the co-existence of humans and bees to redefine the purpose of human built environment to reconnect with nature is explored. This is intended to add new architectural qualities with respect to structural durability, comfort environment, surface finishes and texture of mycelium composite exploring different substrates, for habitation of both the species. The structure is designed to function both as a source of food and shelter for the species in co-existence. Using different methods of fabrication of casting and 3D printing technique as an optimized design solution for the structure is evolved. A small detail of the mock-up of the design is fabricated to the actual scale with several samples of the iterated prototypes showcasing different architectural qualities is produced. While the structure is used as an element to demonstrate the concept and findings, the actual application of the design detail is intended to be adaptable to any human habitable space.

Delimitation

The thesis does not focus on testing the mechanical properties of all the different substrates but consider the substrate for the main load bearing structure based on theoretical reference due to the time constrains. The health and safety of the inhabitants in the mycelium composite structure is not analysed but rather it is an initiation to explore the possible application of mycelium composite to establish symbiosis between architecture and the environment by creating a co-existing space for humans and bees. The use of different strains of mycelium is not to test how the strain influence the properties of mycelium composite but to create a diversity in the fruiting body.

Methodology

The thesis had a strong focus on both the material and design aspect of mycelium composite materials, making it both interesting and challenging to work. We took both material research of mycelium-based materials and design for co-existence structure as point of departure of this thesis process in parallel. Based on the theoretical reference an initial hypothesis was made to initiate the design process which was revised based on our experimental findings. Data during whole process was documented with digital media, like photo and video and illustrations (Digital Drawing).

We started with the inquiry to test how the substrates and mould influence the quality of mycelium composite. Mycelium materials got stiffer when their feeding substrate is harder to digest (Muhammad et al., 2017). Considering this differential in properties based on the substrates, our investigation in obtaining different qualities of mycelium composite was put forth. Different architectural qualities of surface finishes, texture, softness and porosity of the material was derived with different experiments. This was tested using various substrates including straw, jute, saw dust, paper, wood chips and coffee grounds. We tried to use different strains to obtain a diversity in the mushroom fruiting body and not to assess the quality of mycelium growth.

Using a biomimicry perspective, we extracted the functional systems in nature to achieve the structural geometry of the mycelium composite wall. Considering the benefits mycelium posed to humans and bees, different spatial qualities for the habitation of both were designed. With the help of computational design the design and fabrication of the prototype were tested and iterated based on the results from the material research periodically. The fabrication process of the prototype was explored through the technique of 3D printed moulds to apply the mycelium composite appropriately. Both the inert and living state of mycelium composite were considered to maximise the scope of the mycelium composite both in the interior and exterior structures. Different experiments were designed and tested to achieve optimized function, material efficiency, life cycle and environmental qualities to enhance the ecosystem services contributed by the monolithic mycelium composite wall.

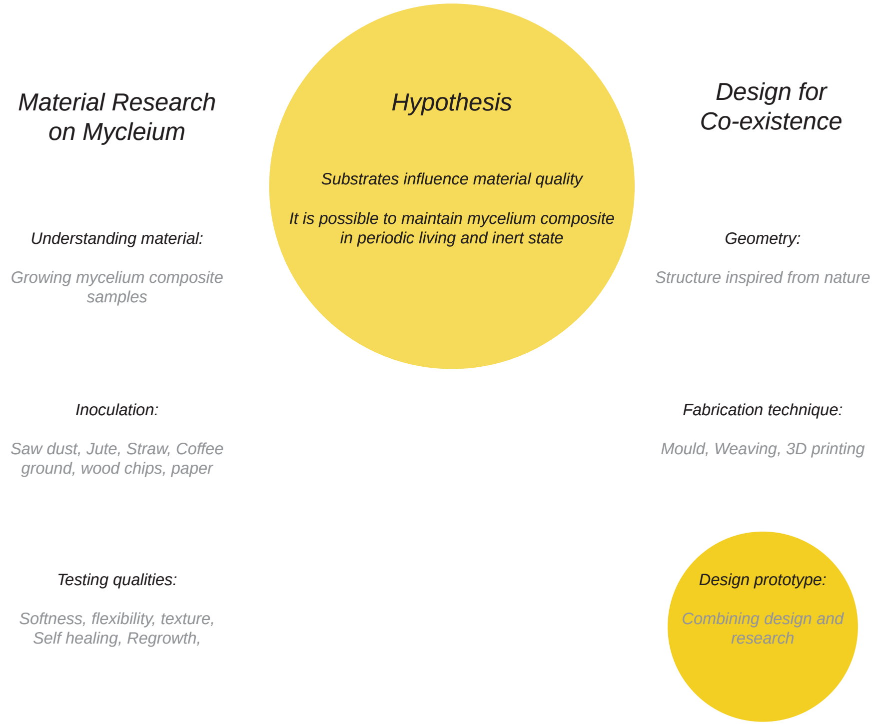


Figure 1: Methodology stages

Background

Introduction

Nature functions as a closed loop circular system from grow to decay, created by the symbiotic relationship between the environment and the species. This contributes to vital ecosystem services within the natural systems creating a perfect balance, as a continuous cycle of growth and decay among the various lifeforms for their survival. But this balance is disrupted in recent years by us, the human beings under the name of civilization and development for a comfortable and luxurious lifestyle. Polluted and contaminated with non-degradable materials produced by extraction, processing and discharge led to an ecological crisis at an unprecedented scale. This breaks the loop of growth-decay cycle, creating undesirable living conditions for not just humans but all life on earth. Based on the study where life on earth is quantified in terms of biomass, human beings account for only 0.01% of the collective biomass on earth, yet we dominate and are responsible for the current issues of global warming, climate change and much more (Ritchie, 2019). How could we change this trend and step back to a life to live in synergy with other species on earth? The annual global emission report shows that about 39% of the total annual carbon dioxide emissions comes from construction and building operations (The Editors of Architecture 2030, 2018). Materials and materiality form the base for such exploitation, and it is time to investigate on alternatives to counter act the damages already created by us. This questions the role of Architects to alter this trend to create a synergy between Architecture and the environment through research and exploration in bio fabrication.

In this thesis, the relation between architecture and the environment and how they influence each other based on the use of bio material is in focus. The essence of our world view addresses how architecture deals with the natural environment. In our vantage point, there is no hierarchy between the two. But so far, when natural habitats provide significant ecosystem services, human habitats have been dominating the environment pushing towards the era of Anthropocene. But recent research in architecture within the field of sustainability and biomimicry provide hopes for reversing this trend by drawing inspiration from the nature and its systems.

When it comes to biomimicry, we study nature on how to solve built environment problems (Pawlyn, 2016). This comes true by emulating functional solution within million-year evolution historic background of nature. Being inspired by nature, we tackle the issue, which probably is more sustainable than inventing new methods both at macro and micro scale. For instance, regarding biological structure, studying bamboo which can reach 40 meter in height, demonstrates how such a long hollow tubular structure does not fail through collapsing in toward central axis, due to interrupting smooth tubular growth with regular nodes (Pawlyn, 2016). Furthermore, with respect to bioTRIZ, the demonstration that of the synthesis (thesis and antithesis) found in biology most commonly involves modifications to structure. For instance, when it comes to manipulation of energy in a building, this method is used to apply an insulation layer on a concrete roof that blocks most of the sunlight while it funnels the long-wave radiation employing reflectors towards transparent apertures. This led to decrease in temperature of the roof by 13 degree below ambient (Pawlyn, 2016).

This principle with the help of computational design tools aids greatly in recreating natures system in human built environment which are one with nature. The process of simulating the nature's function through computation and digital fabrication resolves complex issues in the built environment.

In the current pandemic of COVID-19, where we spend most of our times indoors it evokes a feeling of being surrounded by dead inorganic walls made of concrete, steel, etc. raise a question on the very existence of these structures. Can it hold a strong reason of existence than just sheltering human beings? How would the material and its composition alter the function and lifestyle of the people living? Can architecture create a close-knitted inclusive design not only among humans but also for other species? The thesis evolves under this context to investigate what ecosystem service architecture provide within its surrounding environment to host and celebrate all life forms. This sets a compelling measure to rethink materiality and fabrication to live in synergy with nature.

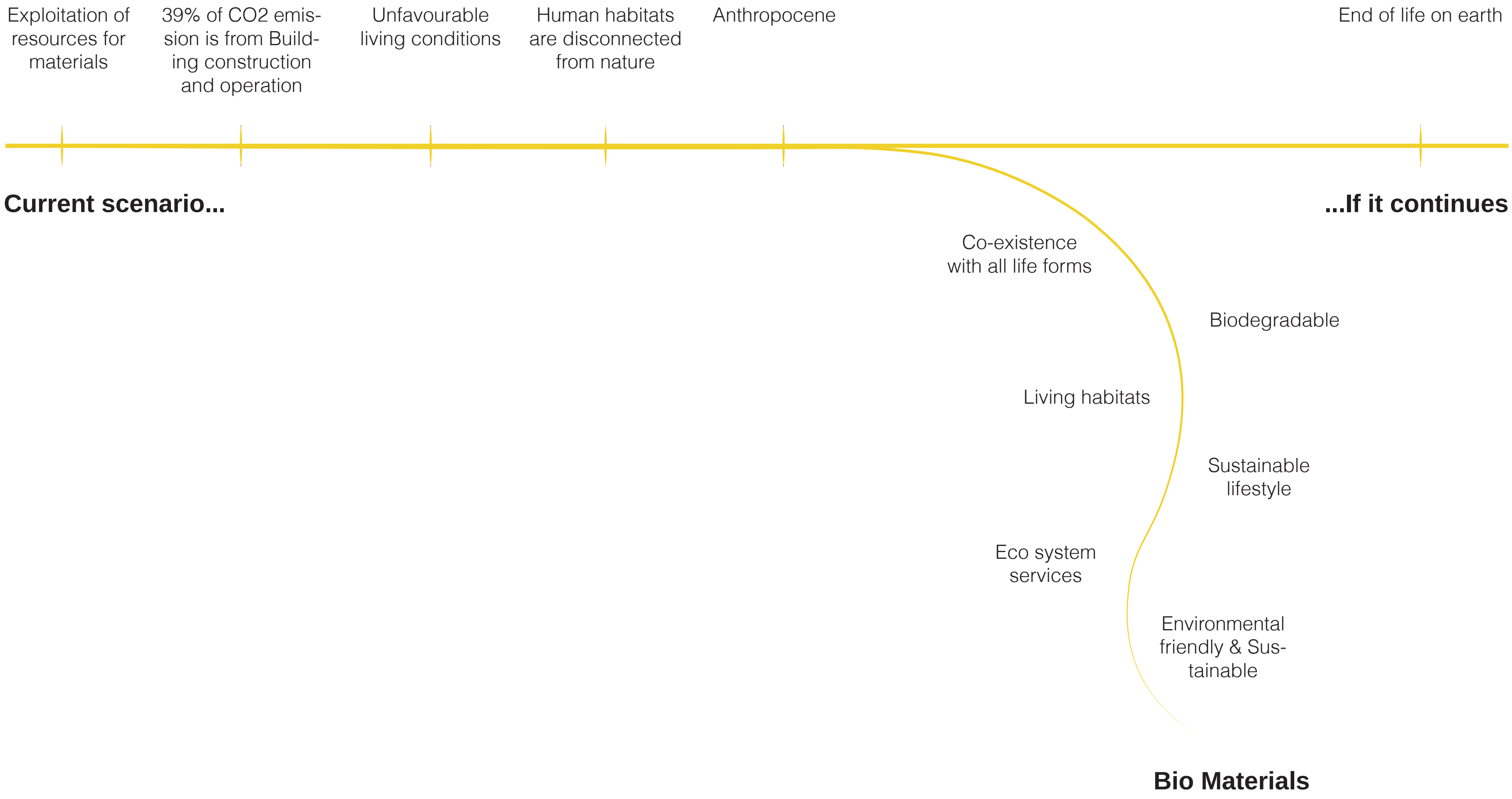


Figure 2: Why bio-based material?

Symbiosis

Nature exhibits the symbol of coexistence by mutual dependency on each other. Several species live in symbiosis contributing to vital ecosystem services to provide and receive benefits from each other. Pierre Lahaye in his publication under the title “Symbiosis and Architecture” in the journal Leading Architecture and Design says,

“Symbiosis is an interaction between two different organisms living in close physical association, usually to the advantage of both”.

Trees for instance is a habitat for several species. It also depends on the micro-organisms and fungi for exchange of nutrients for it survival. While it is so true that this is a continuous uninterrupted phenomenon happening in nature, the buildings do nothing more than destruction to this continuous balanced interaction in the ecosystem. This strong mutual connection is what differentiate human built structure from those created by nature mainly due to the materials used to build those structures. This creates a mental barrier that excludes human habitats from considering part of nature.

As mentioned by The National Wildlife Federation, ecosystem service is used to describe all the benefits that the wildlife or the ecosystem provides to human beings. While we look at ways nature could offer us, it’s time to focus on services that human actions and habitats provide to the wildlife and ecosystem.

Recent works in Architecture have been focused on constructing buildings with eco-friendly materials such as earth, wood bamboo, etc. that are non-toxic to the environment to mitigate the damages and create a close interaction with the environment. But the focus on commissioning services to add value and resource to the environment by Architecture has been of limited scope. This sets demand for exploring how these materials set grounds for a symbiotic relationship between architecture and the environment as a holistic approach to provide services to not only humans but a wider species.

Food is essential for the survival of all life forms on earth. Pollinators plays a significant role to regulate and maintain the diversity of food crops. About one third of the food we consume across the world depends of pollination of insects, of which bees account for about 80 percent of pollination worldwide (The Editors of Greenpeace, 2021). Humans have been responsible for the loss of habitats and population decline for several species including bees. The Swedish government in the budget bill of 2020, allotted around 70 million SEK per year between 2020-2022 to initiate measures that benefit the pollinating insects, considering their population decline. As we directly depend on bees to maintain the global food security both through effective pollination and production of honey in case of honey bees, it becomes our soul responsibility to alleviate the damage in order to receive a mutual benefit from each other and also enrich the ecosystem values. This interdependency would possibly reduce the hierarchy and rather create a more balanced and inclusive space for all.

According to the research of Paul Stamets, the founder of Fungi Perfecti proved that bees exhibit immunity boost upon drinking the mycelium extract of different mushrooms. On the other hand, humans depend on mushrooms both as a food source and as a mycelium composites for architectural applications. This strong dependency of both humans and bees on mushroom mycelium opens scope for investigating opportunities for mycelium structures as an integral part to establish a mutual symbiosis in creating a habitable space for both species to live in synergy.

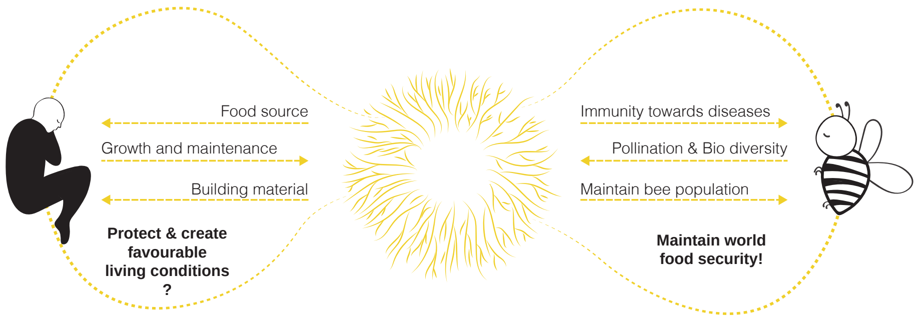


Figure 3: Human, bee, and mycelium symbiosis

Mycelium

Mycelium is the vegetative part of the mushroom that is made of long, branching white filamentous mass called hyphae. The hyphae are made of chitin, a structural polymer of the cell wall. The enzymes secreted by the hyphae break down organic polymers upon which the carbon-based materials are decomposed. Mycelium (plural mycelia) plays a significant role in the process of reproduction and decomposition to bring the nutrients back to the soil (Anderson, 2020). Based on the type of decomposers involved they are classified as white rot and brown rot fungi. The white rot fungi digests both cellulose and lignin and leave behind thread like white residual cellulose while the brown rot fungi decompose only cellulose and leaves behind cuboid residual lignin (Blanchette, 2018). Mycelium looks like a ball of cotton in the naked eye but at a microscopic scale it looks like a network of branching thread like structure. The mushrooms are the fruiting body of fungi which grows and dies, but the mycelium remains alive under the soil surface and gets activated under favourable environment condition including temperature, humidity, nutrients etc. The mycelium spreads the hyphal network in a circular manner to reach the nutrients, which at times grows even up to a kilometre (Anderson, 2020).

The ability of mycelium to digest carbon rich dense cellulose substrates is applied in the production of mycelium composite materials. The dense network of hyphae is what gives strength to these materials acting as a natural binder. The production of the mycelium composite materials follows a simple 5 step process (refer to the graph); Collecting mycelium strain, Sterilization of substrate, Inoculation, Moulding and Cultivation and Drying/Heating (Ghazvinian, Farrokhsiar, Vieira, Pecchia, & Gursoy, 2019).

The mycelium composite materials are obtained by stopping the colonization process of mycelium over the organic substrates by drying or heating. Drying keeps the mycelium inactive and can regrow when favourable environmental conditions are established. During heating the mycelium is killed and the growth is stopped permanently. (Ghazvinian, et. al, 2019) Thus, drying facilitates the ability of mycelium to self-heal and regenerate and expanding the opportunities for scaling up living architecture.

Several factors influence the properties of mycelium composite which include, the fungal strain, substrates and nutrient source, environmental conditions (temperature and humidity) and fabrication technique. In general, the mycelium composites are good in both thermal and acoustic insulation. They are safe and fire-resistant posing as a suitable material for architecture and interior application. (Ghazvinian, et. al, 2019). This fibrous composite material exhibits hydrophobic property with water contact angle higher than 120 degree. (Anderson, 2020). Several precedent researches prove that mycelium composites are relatively light weight compared to plastics. While it is true that they have low tensile strength, it is good in compression. (Ghazvinian, et. al, 2019). The composite material gets stiffer on feeding upon hard substrates (Anderson, 2020).

Several qualities of porosity, hardness, softness, texture can be altered based on the type, size, fibre orientation and properties of the substrates the mycelium feeds on. It is easy to grow and shape. This cost-effective biodegradable mycelium composite material sets wide scope of exploration on growth and fabrication for suitable applications. (The Editors of Ecovative Design, 2021).

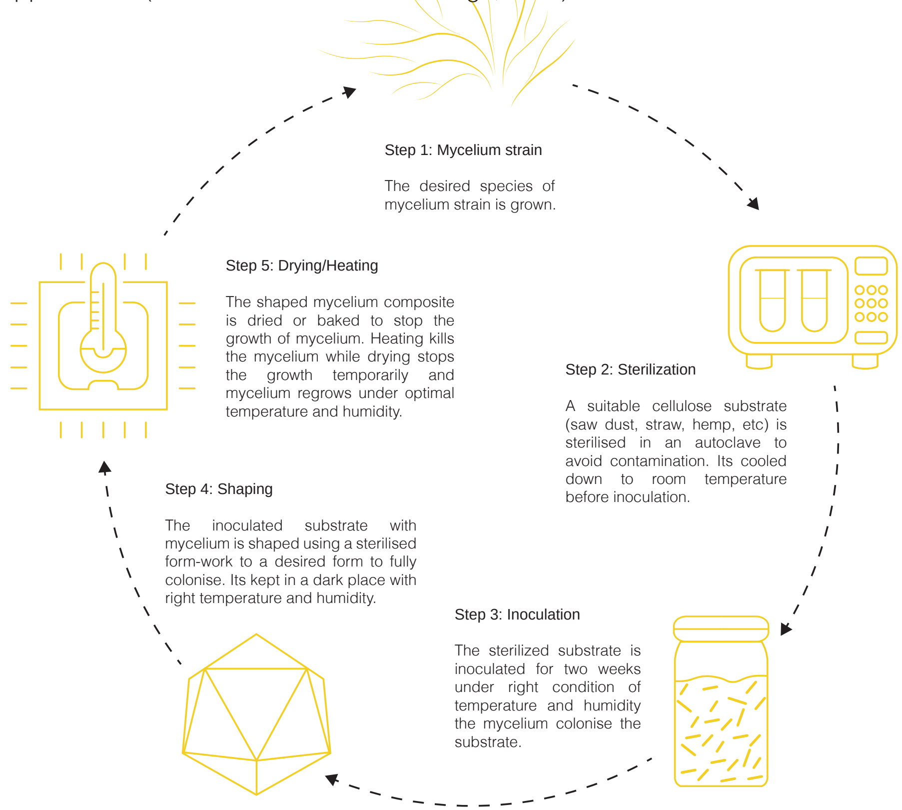


Figure 4: Mycelium composite fabrication process

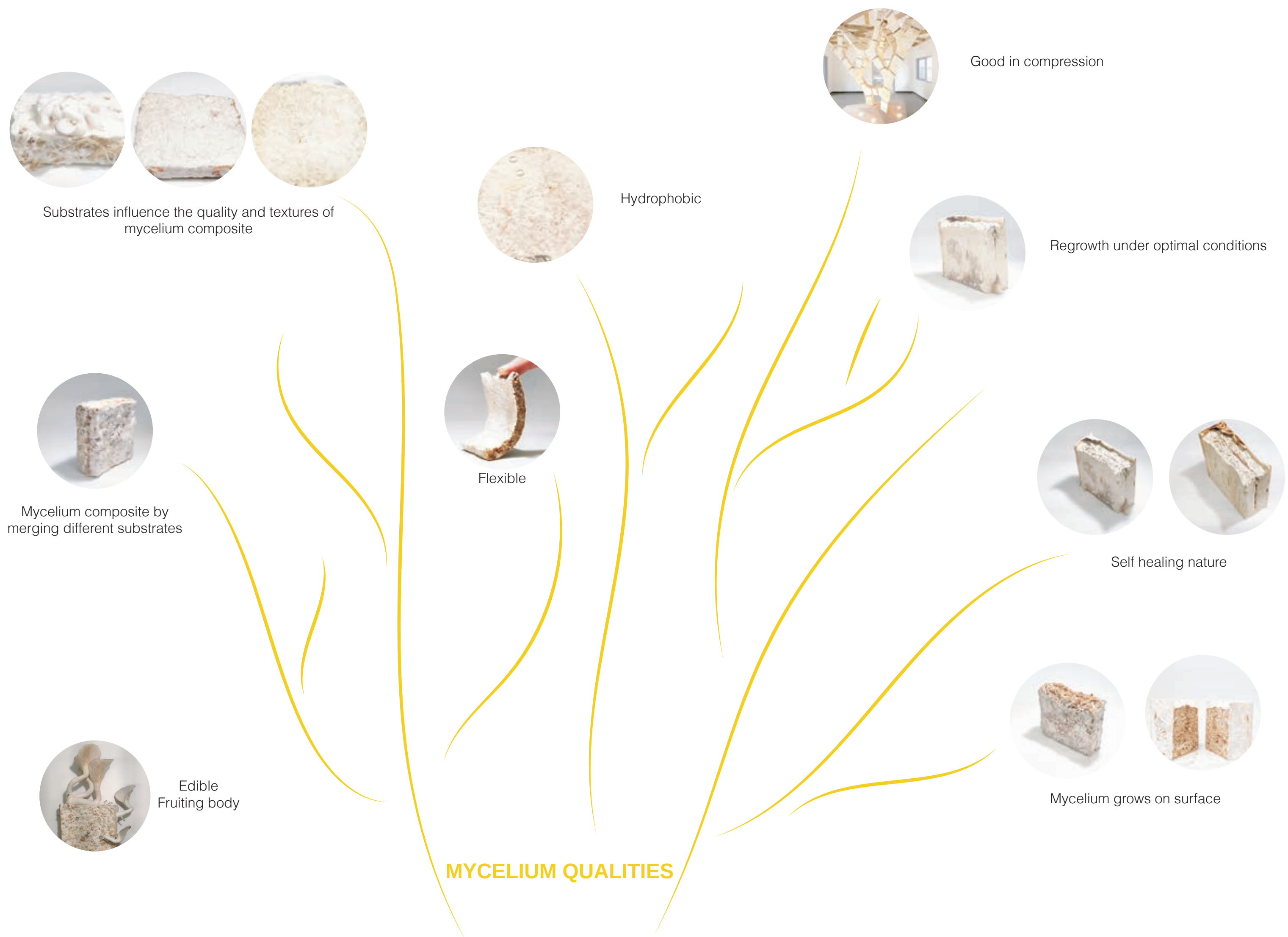


Figure 5: Mycelium qualities and experiments

Bees

Bees are the primary pollinators of plants and play a significant role in maintaining world food security. There are about 30,000 species of bees in the world of which most of them are solitary bees (The Editors of Animal Corner, 2020). They live independently in underground tunnels or in the cracks on the trees. Compared to the other bees that live in colonies like bumble bees and honey bees, solitary bees live alone. They have high pollination rate. A single solitary bee is capable of providing pollination as much as 120 honey bees (Romare, 2014). Every single solitary bee is a female and each female is capable of producing 20 to 30 offspring. These solitary bees are harmless making them safe around kids and pets. As they do not produce honey, they have nothing to protect and do not usually sting unless disturbed (The Editors of Space10, 2021). This makes solitary bees more promising both in enhancing pollination and also creating close interaction with humans. This generates the interest in investigating on the ways to create habitats for solitary bees to enhance humans for a mutual benefit compared to other bees for instance honey bees which are dangerous.

Bees in general occupy man-made habitats which are rich with flowers, like the agricultural lands due to their close proximity to rich source of food, flight distance and nesting sites. But due to urbanization and change in agricultural practice, their loss of habitats is one of a major cause for their decline in population. More than one third (98 species) among the 274 species of bees in Sweden are red listed, stating the need for immediate attention to protect them (The Editors of Chalmers, 2016). This sets several initiatives by different organizations and individuals to protect the bees by creating several nesting units and food source. Bee hotels are introduced in several nesting grounds to attract bees of different species.

Bees are attracted to bright colours of blue, violet, white- and yellow-coloured flowers and also many bee hotels exhibit the colours to attract the bees. A constant source of food is necessary around the bee hotels to ensure they inhabit these human-made tunnels (Fog, 2019a). Some species require access to raw materials like mud, leaves, straw to seal their nest after laying eggs like Mason bees and leaf cutter bees for instance (Fog, 2019b). The design of the nesting tunnel for bees plays a significant role in attracting a diverse range of bee species. The size of the diameter of the hole and the depth of the tunnel determines which species gets attracted to nest inside. The bees choose the cavities based on their body size to ensure there is no space for the parasites to enter the brood cells. The tunnels are usually 15 to 20 cm deep with diameter less than 1 cm. The depth of the tunnel increases with the size of the diameter of the holes (MacIvor, 2017). It is important to have the nesting tunnels covered on rear end to protect the larvae from falling over (Fog, 2019b). The design and construction of these bee hotels plays a significant role to host the varied species. The surface of the tunnel should not be rough as that would damage the wings of the bees. Creating damp free spaces with overhang to protect from rain, wind and accessibility to cleaning the nesting cavities is essential to avoid moulds. The bee house is located above the vegetation line to increase the visibility and also facing the south east direction to orient towards sunlight (MacIvor, 2017). As important as these influencing factors are, building materials with which these habitats are made reflect on the life and well-being of these species.

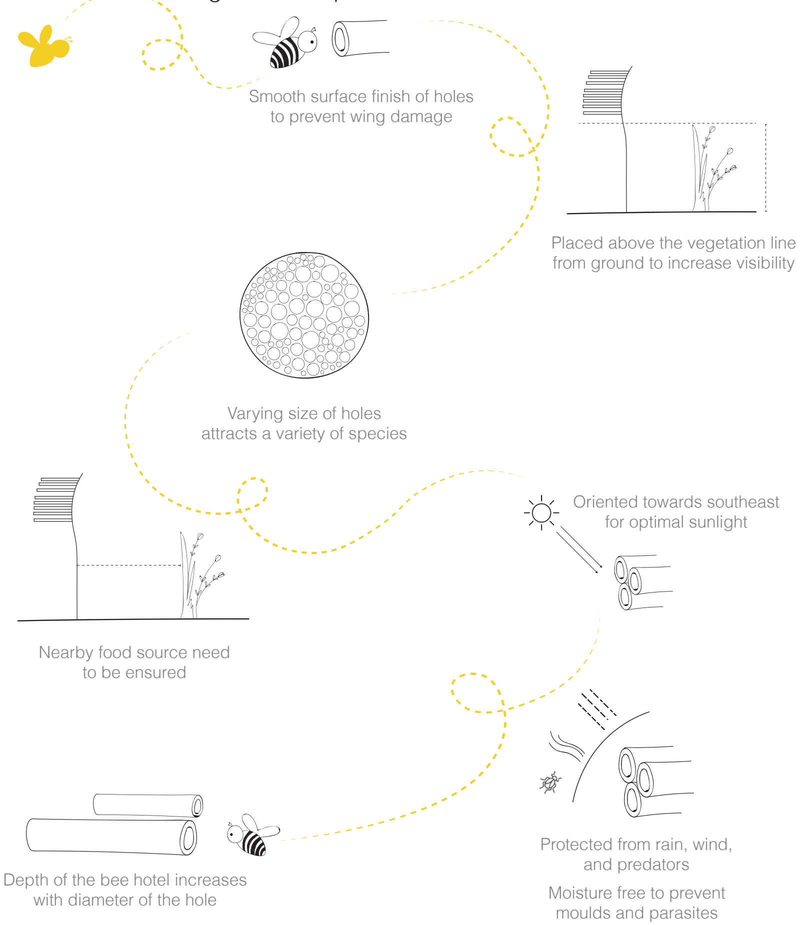
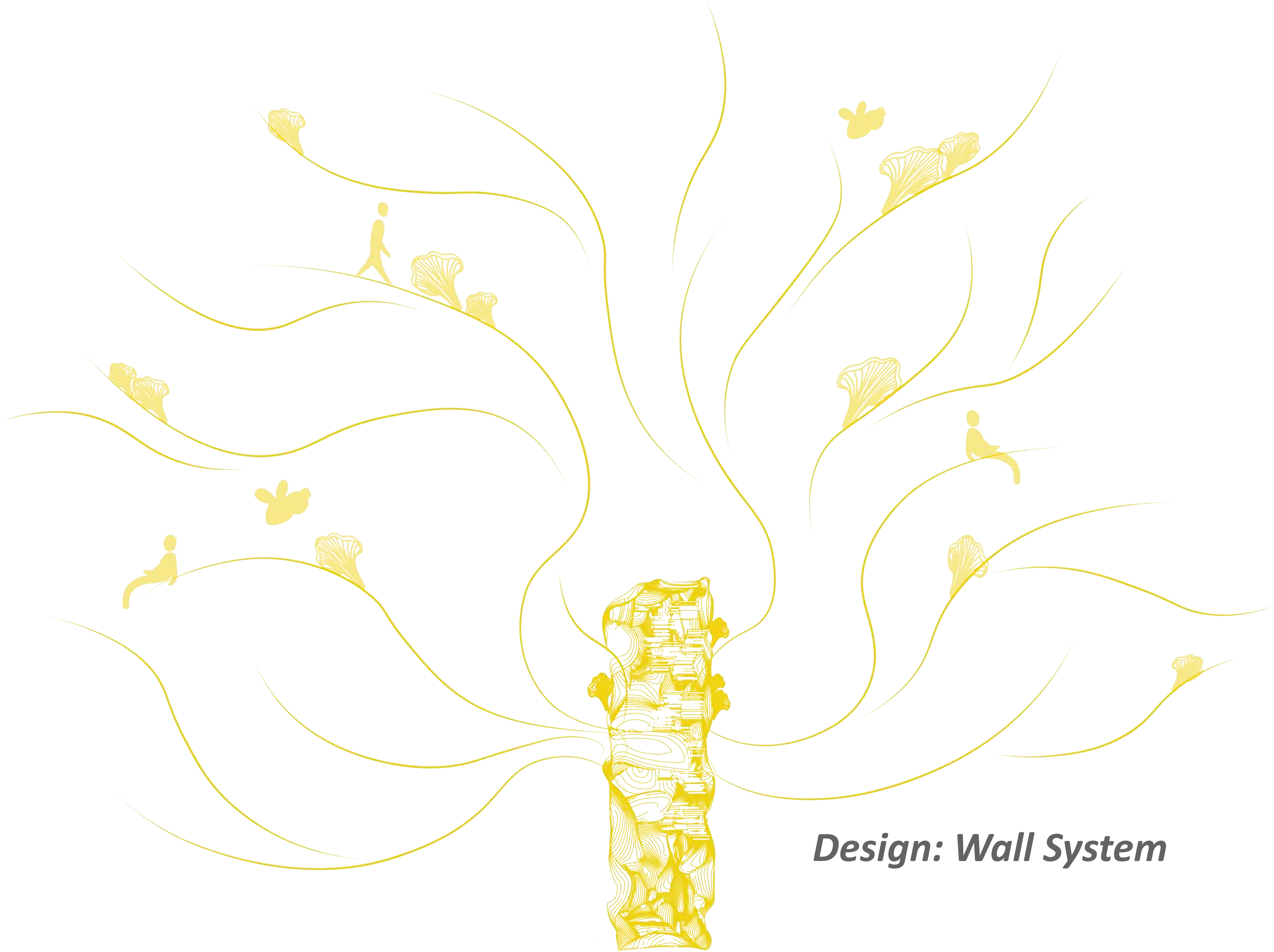


Figure 6: Bee habitat Qualities

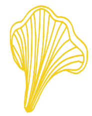


Design: Wall System

Manifesto

Keep the mycelium alive from planting to fruiting stage

Circular design by optimised life cycle process.
Permanent structure with annual renewal.

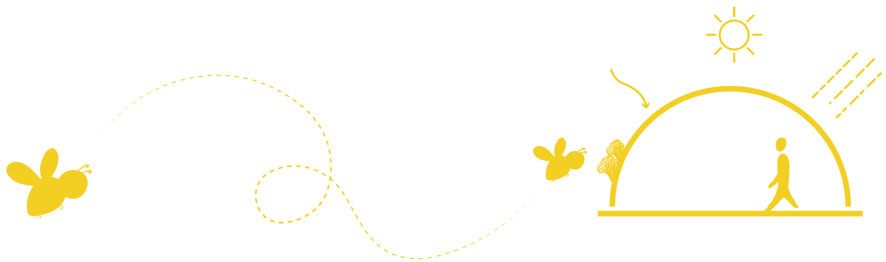


Diverse strain of mushrooms

Well-being of the bees and humans.

Platform to showcase design for co-existence

To show all lifeforms are interdependent.
Significance of bee in human livelihood.
To counteract the era of Anthropocene.



Self-sustained structure

Provide food sources and shelter for bees and humans.
Habitat offering effective ecosystem services.

Solitary bees

Create awareness about the importance of bees in urban environment.
Increase the population of bees.

Focus on system design

Techniques of growing and fabrication of mycelium composite.
Celebrate the wide application of mycelium in Architecture.

Have a seasonal feeding and harvesting phases

Follow the process of growth (Autumn) and decay (spring) as a natural system.

Figure 7: Manifesto of design

Context

The C-hive project of Team Sweden for Solar Decathlon Europe competition 2021 forms the base to propagate the design system. The context of the house prototype is used to construct the monolithic mycelium composite wall to spatially orient the habitable spaces for humans and the bees considering their respective qualities for creating a comfortable habitat. The L shaped corner with window along the dining area is chosen to idealize the wall to enhance the opening that connects the interior and the exterior. Though the system focusses on the wall design, the elements of floor and roof are conceptualized to expand the possibility of application of mycelium composite to other building components explaining the versatility of the material in architectural applications.

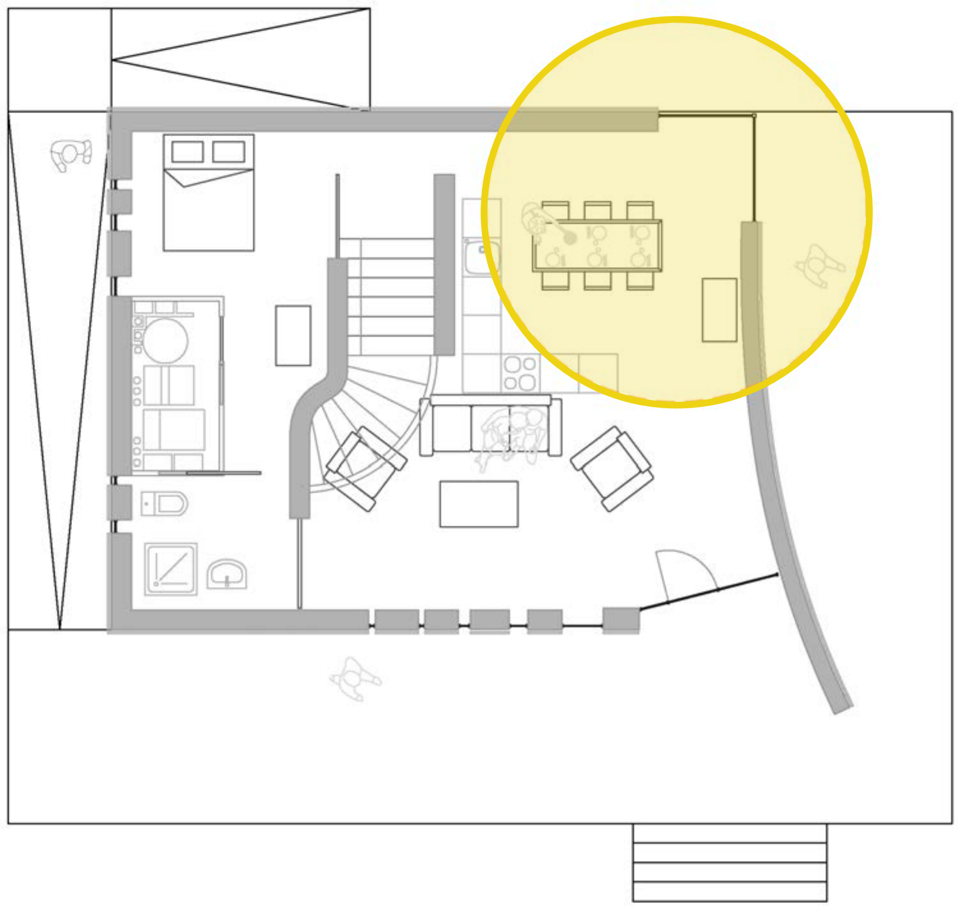


Figure 8: Existing plan of C-Hive Project - Scale 1 : 50

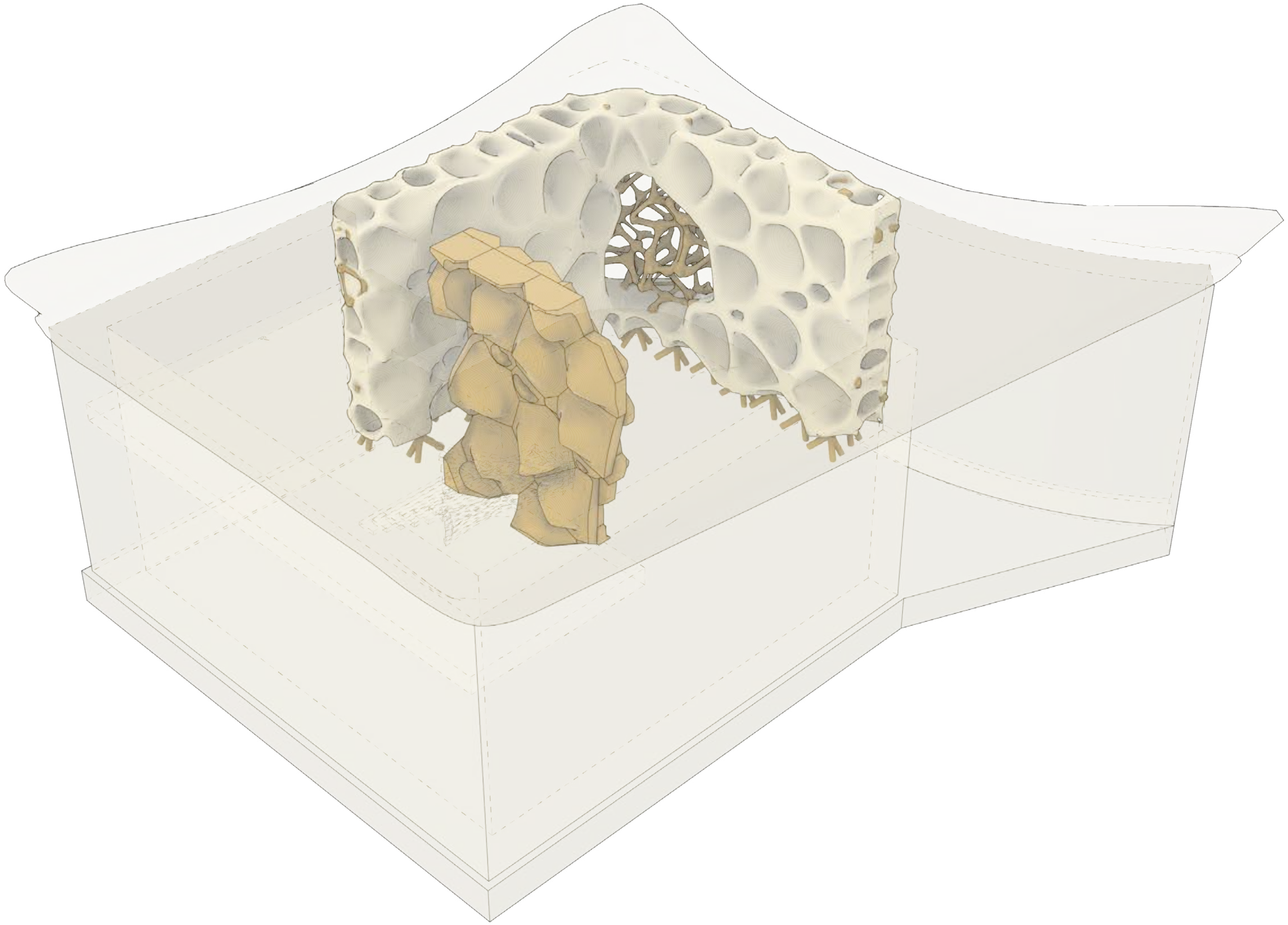


Figure 9: Positioning of the wall in C-Hive project - Perspective

Concept

A monolithic mycelium wall is conceptualised using growth as an element of design propagation. The life cycle of the wall forms a closed loop circular system by providing shelter and food(mushrooms) throughout the year and finally goes back to soil as compost towards the end of its lifespan offering vital ecosystem services.

The process of growth and decay of any life-form on earth is contextualized to the human habitats. The design follows the natural transition of the seasonal changes and the activities to thrive alongside the other living matter. The four seasons of summer, fall, winter and spring is utilized to grow, maintain and harvest in the different growth phases of mycelium. This in turn is associated with the species like humans and bees that depend on this living material as a source of food and shelter creating a mutual symbiosis. Mycelium needs optimized temperature and humidity to grow and maintain in dormant stage. During summer the fully grown mycelium with mushroom fruiting body is consumed by both humans and bees. The structure is regrown in the end of summer with temperature favourable for the mycelium to grow. The growth is stagnant during late autumn and winter as the mycelium remains in hibernation below 5 degrees. The growth is propagated again during summer and the cycle continues as long as it is maintained by humans and bees. Initial inoculation of mycelium with flowering seeds suitable for the bees goes back to the soil during the renewal of the wall. This increases the biodiversity of the species which also helps the bees to navigate to the living wall.

Considering the fact that mycelium composite poses different properties based on the qualities of the cellulose substrate it digests a mix of several substrates is used in a single monolithic structure to bring in variation in the structural and finish quality suitable for the habitation of the species. A 3D printed central hollow is used to supply oxygen to maximise the growth of mycelium composite in the core.

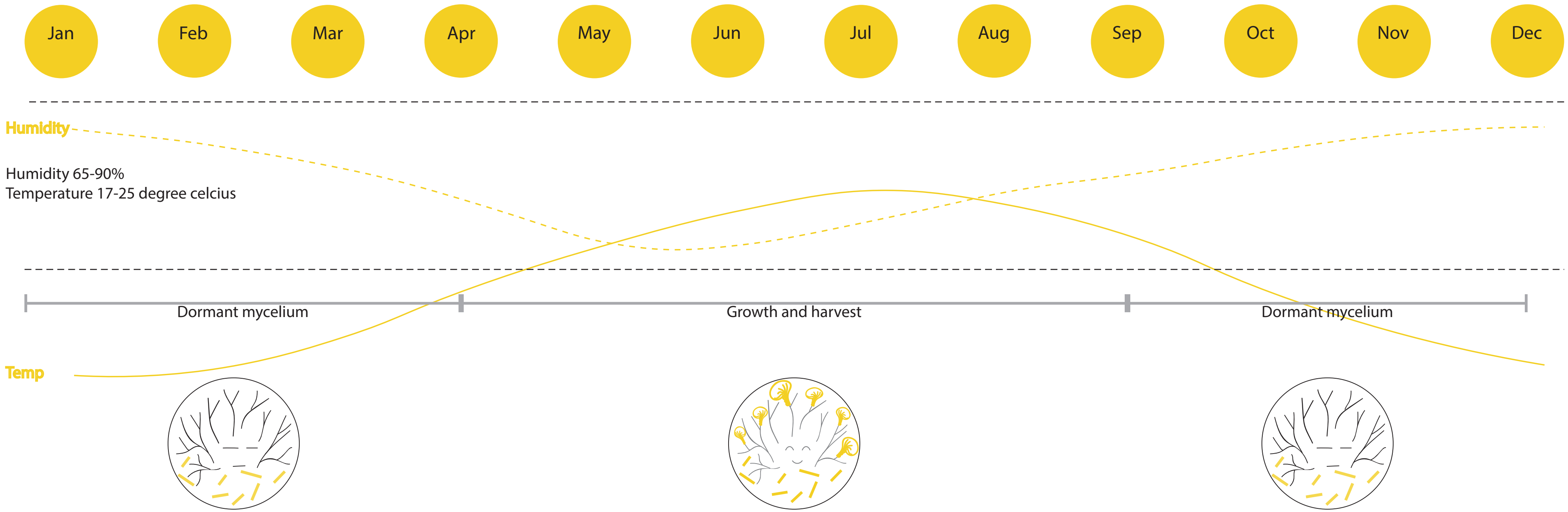
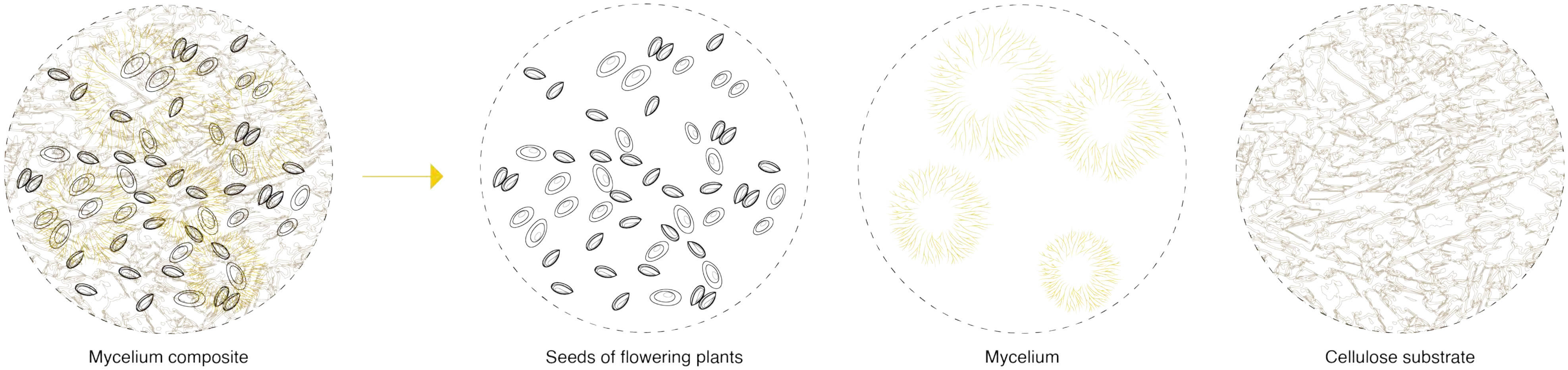


Figure 10: Climate analysis of Sweden



The initial inoculation process is done on seeds of flowering plants preferred by the bees and the saw dust and wood chips substrates are then inoculated with these seeds to produce the mycelium composite mixture suitable to grow the monolithic mycelium wall.

Figure 11: Mycelium composite mixture

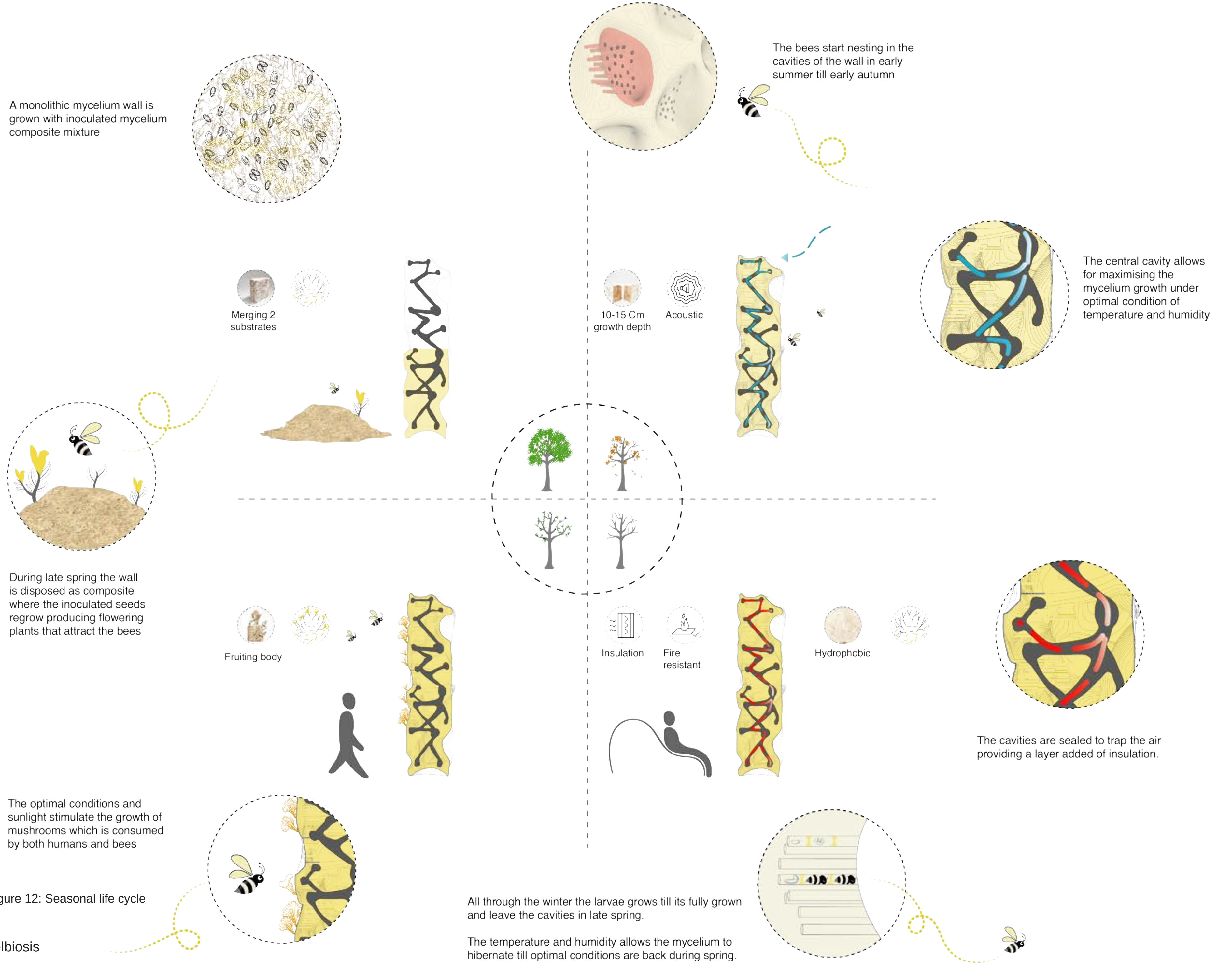


Figure 12: Seasonal life cycle

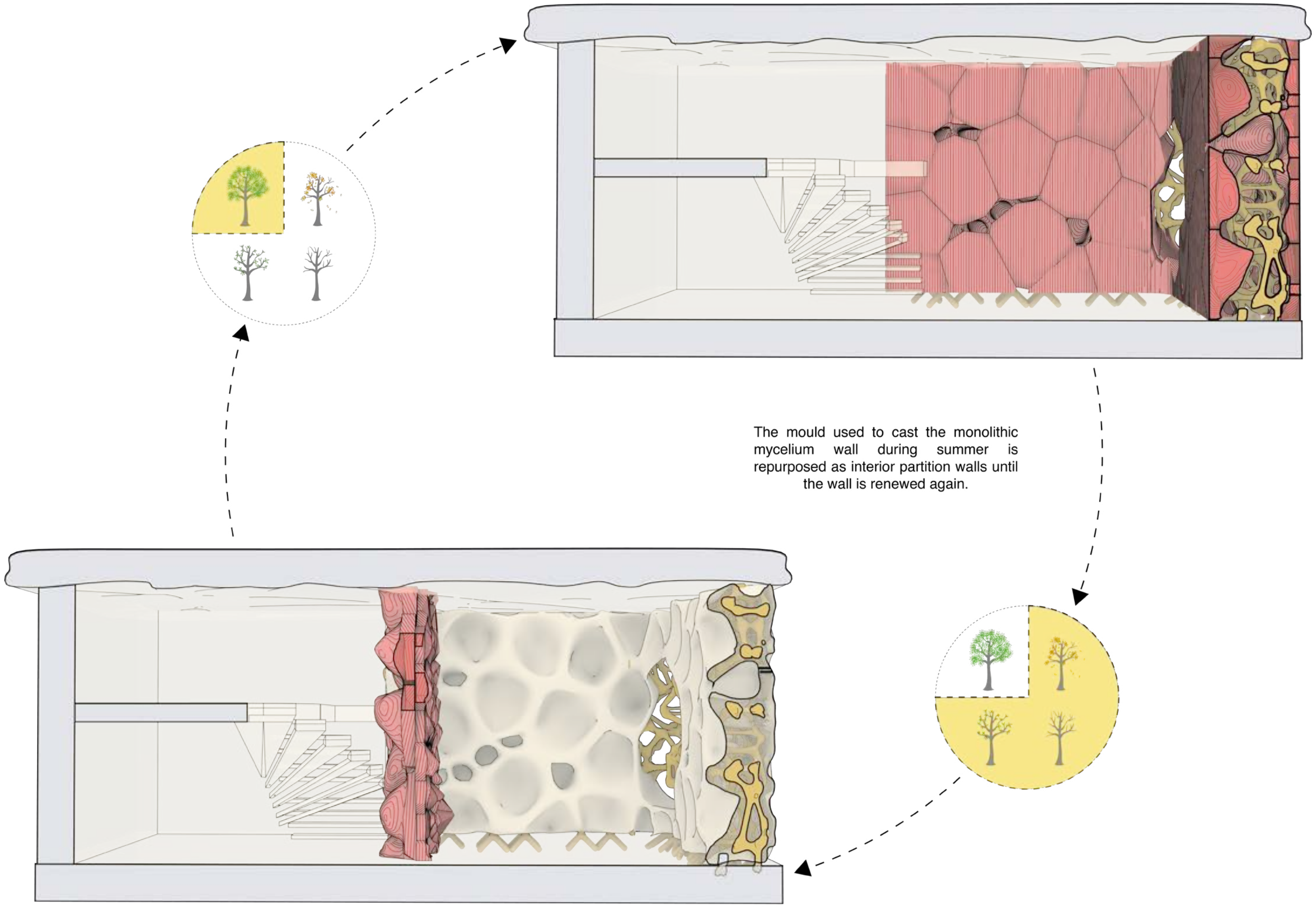
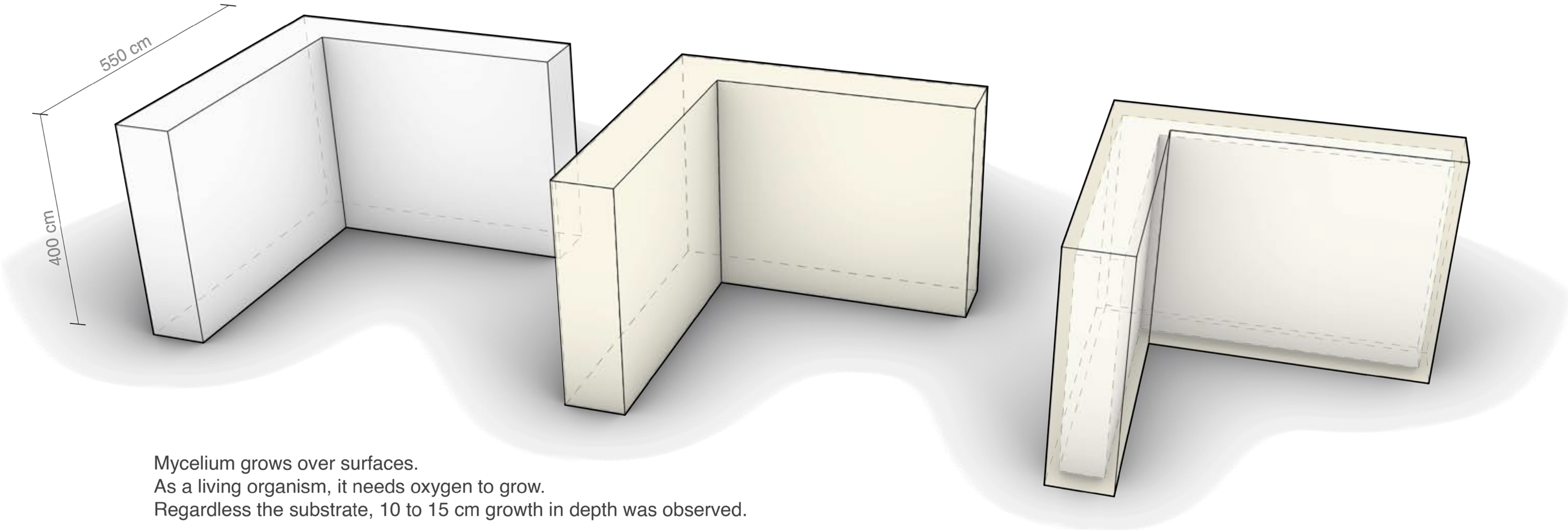


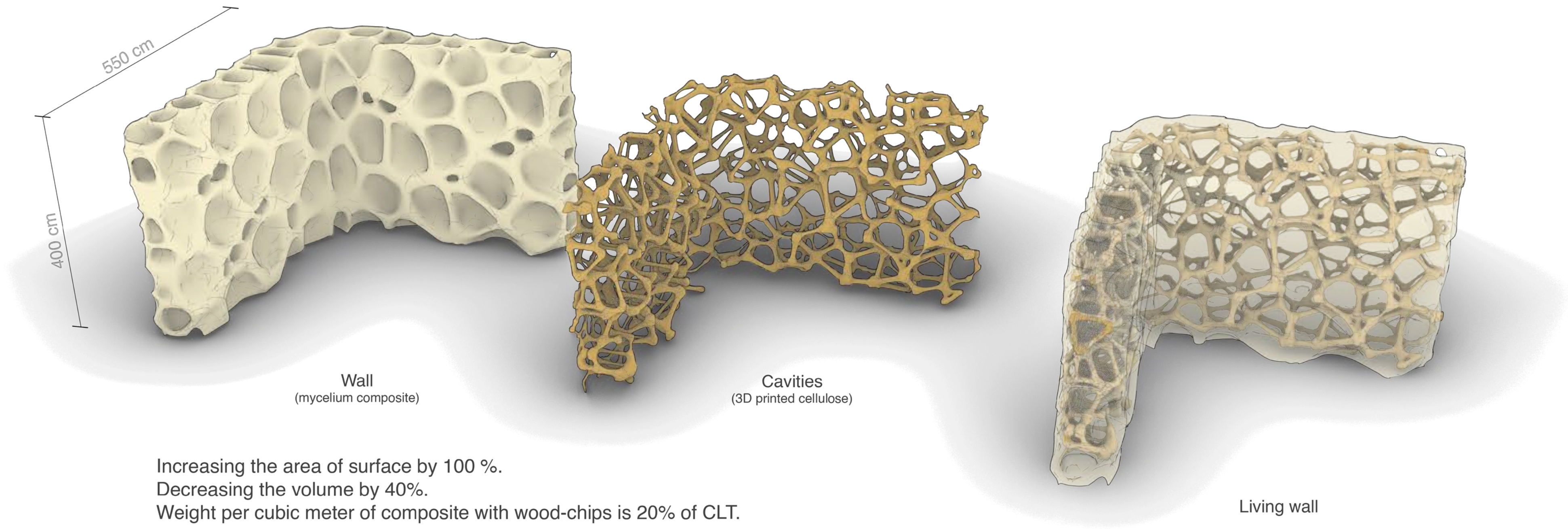
Figure 13: Repurpose of the moulds

Computational Design



Mycelium grows over surfaces.
As a living organism, it needs oxygen to grow.
Regardless the substrate, 10 to 15 cm growth in depth was observed.

Figure 14: Growing mycelium composite as a conventional structure



Increasing the area of surface by 100 %.
Decreasing the volume by 40%.
Weight per cubic meter of composite with wood-chips is 20% of CLT.

Figure 15: Computational designed components

Plan

Figure 16: New plan layout of C-Hive project - Scale 1 : 50

Section

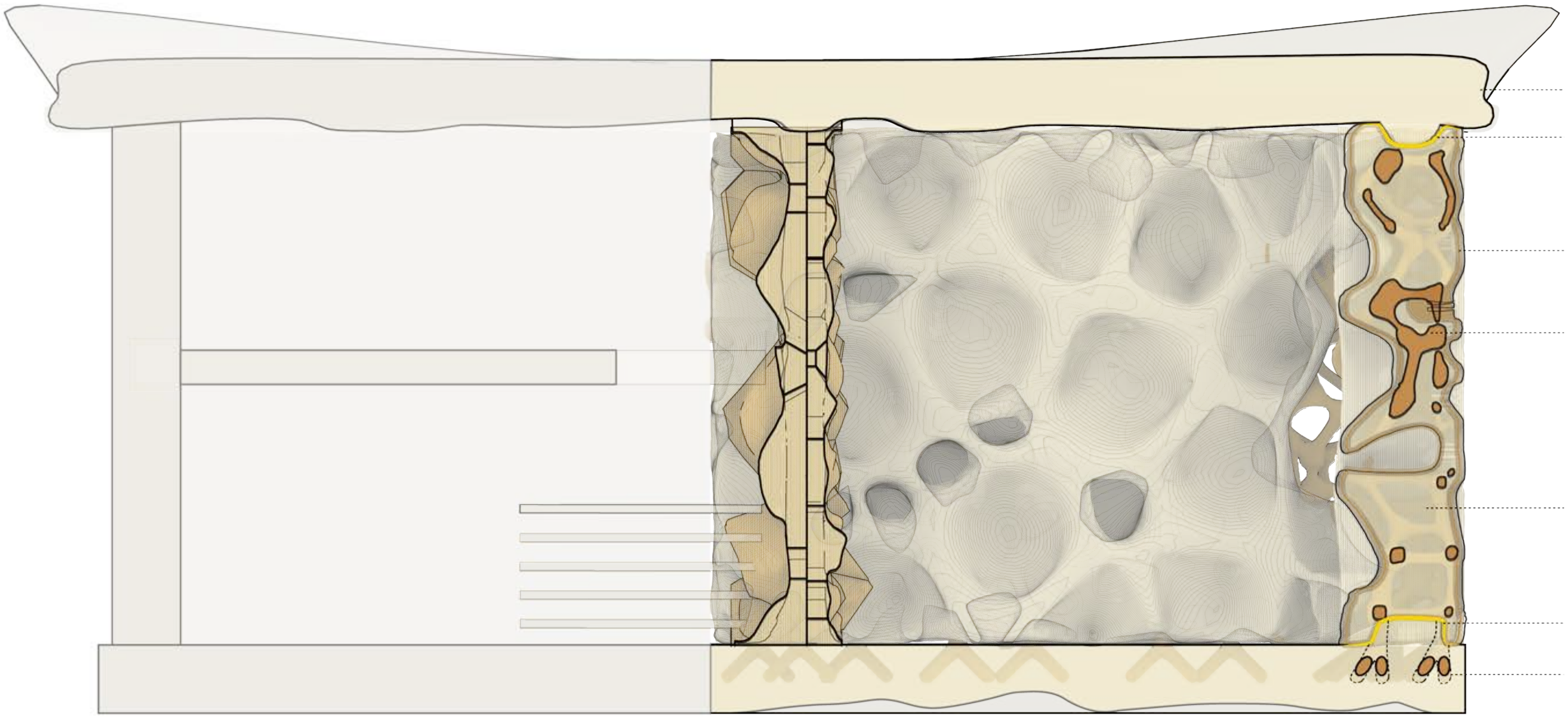


Figure 17: New section of C-Hive project - Scale 1 : 50

Interior Perspective

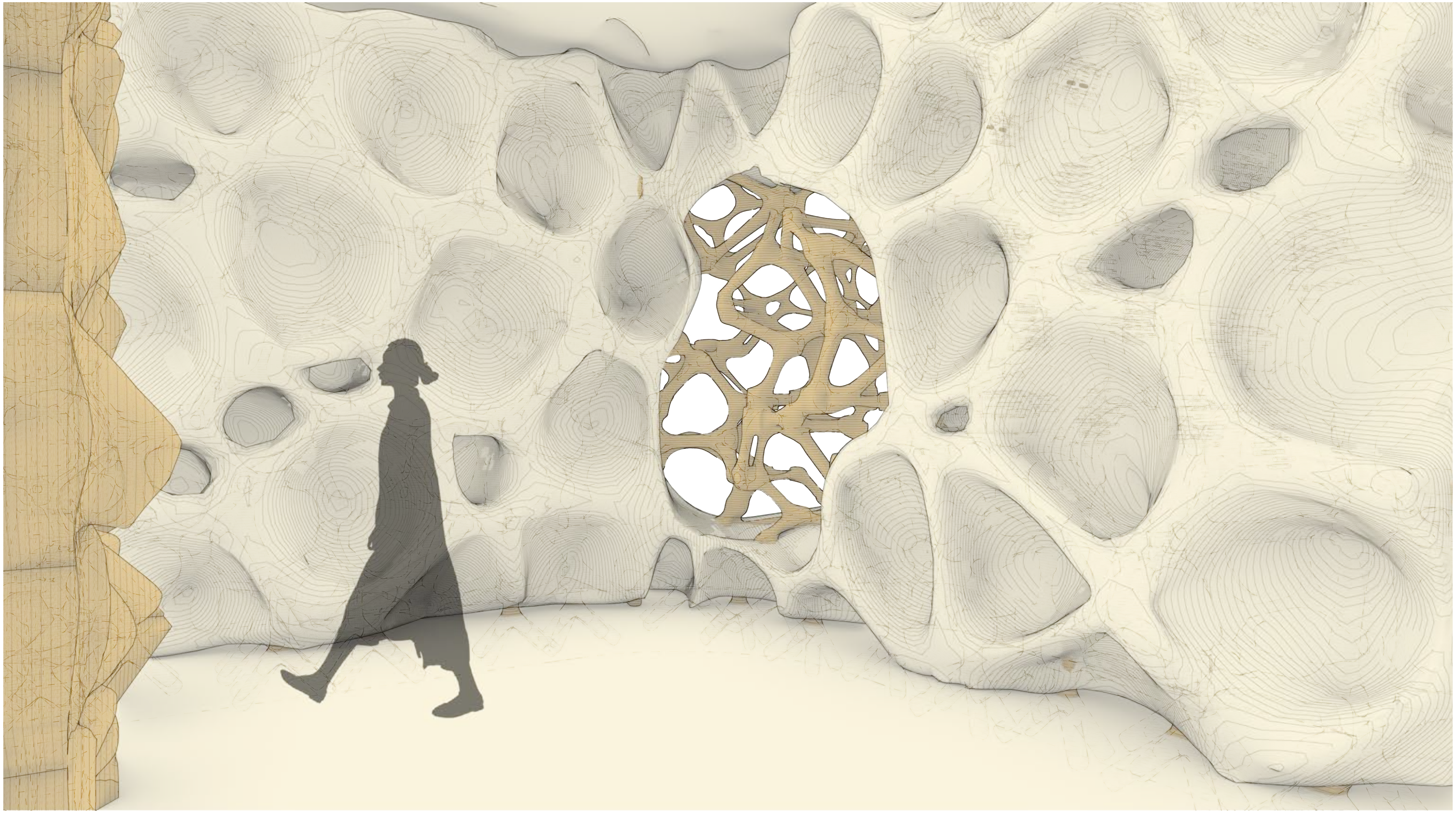


Figure 18: Interior Perspective with the corner alcove

Interior West Elevation

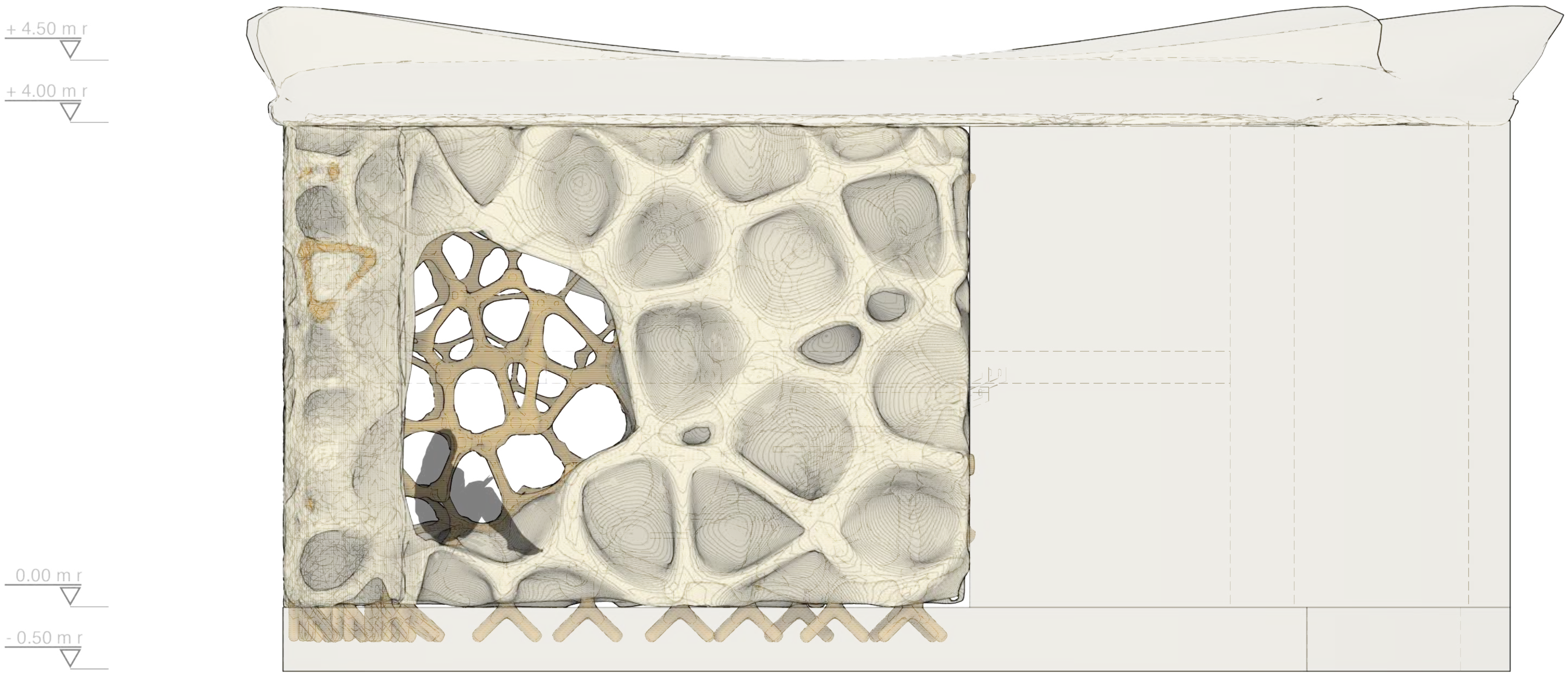


Figure 19: Interior west elevation - 1 : 50

Exterior Perspective

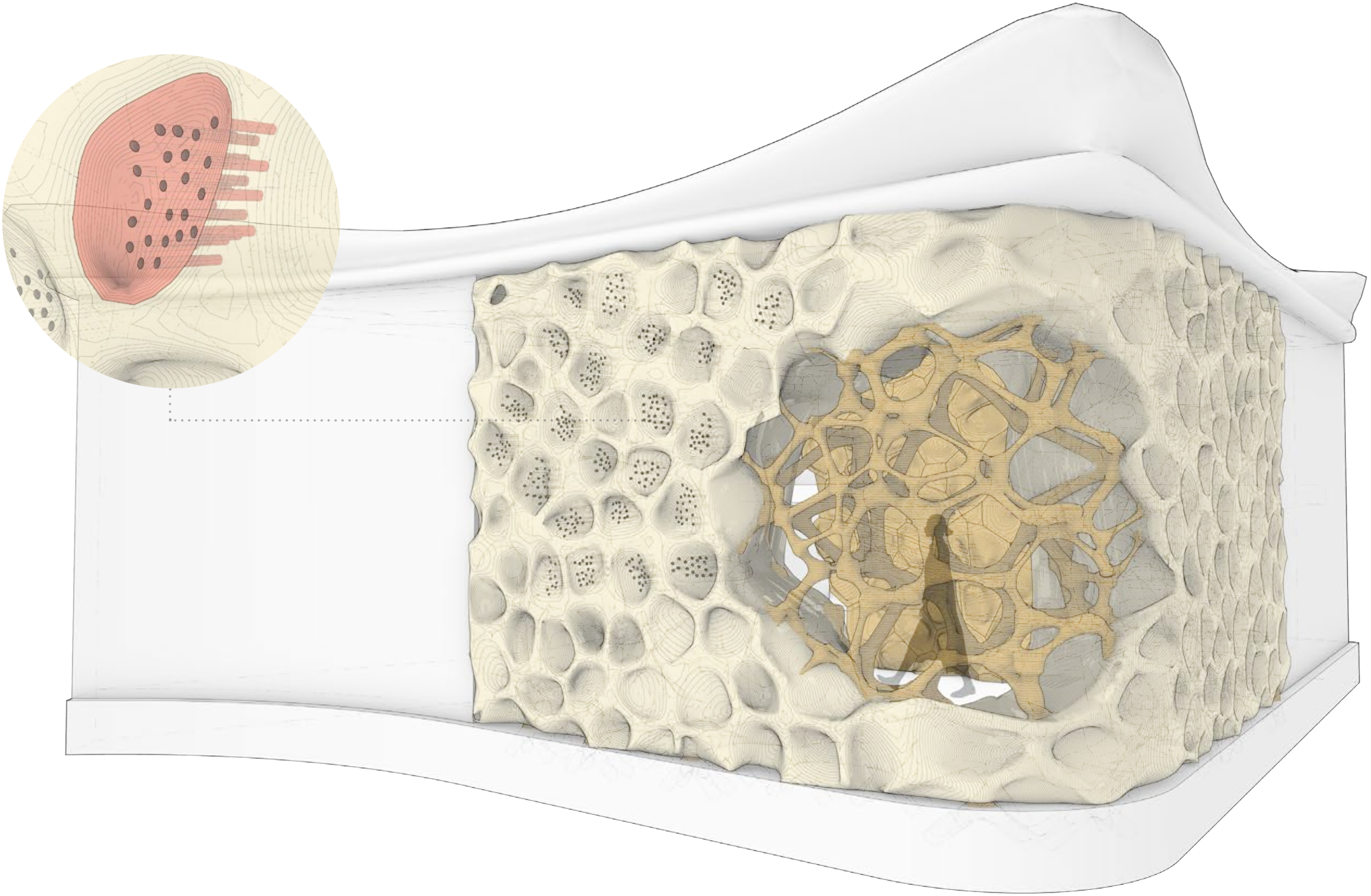


Figure 20: Exterior Perspective with the bee houses

Exterior East Elevation

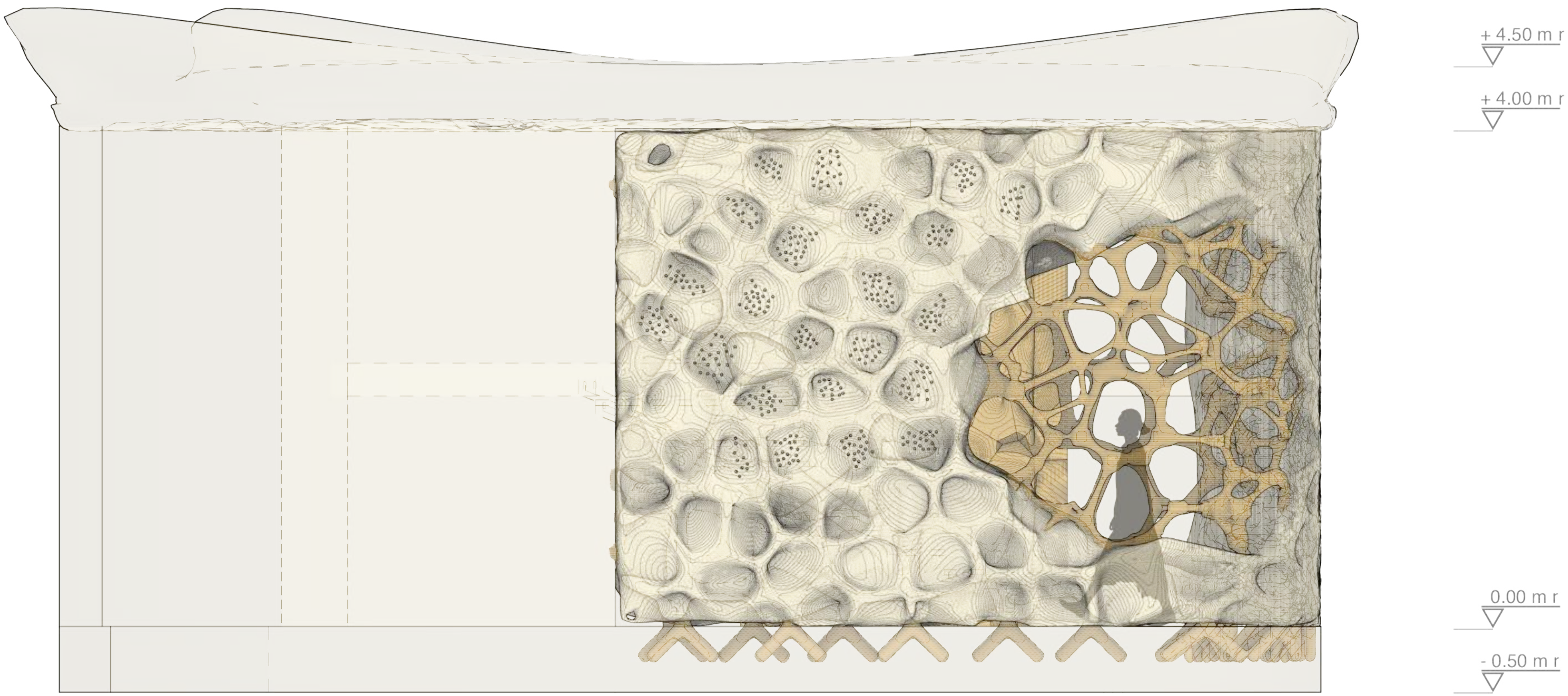


Figure 21: Exterior east elevation - Scale 1 : 50

Assembling

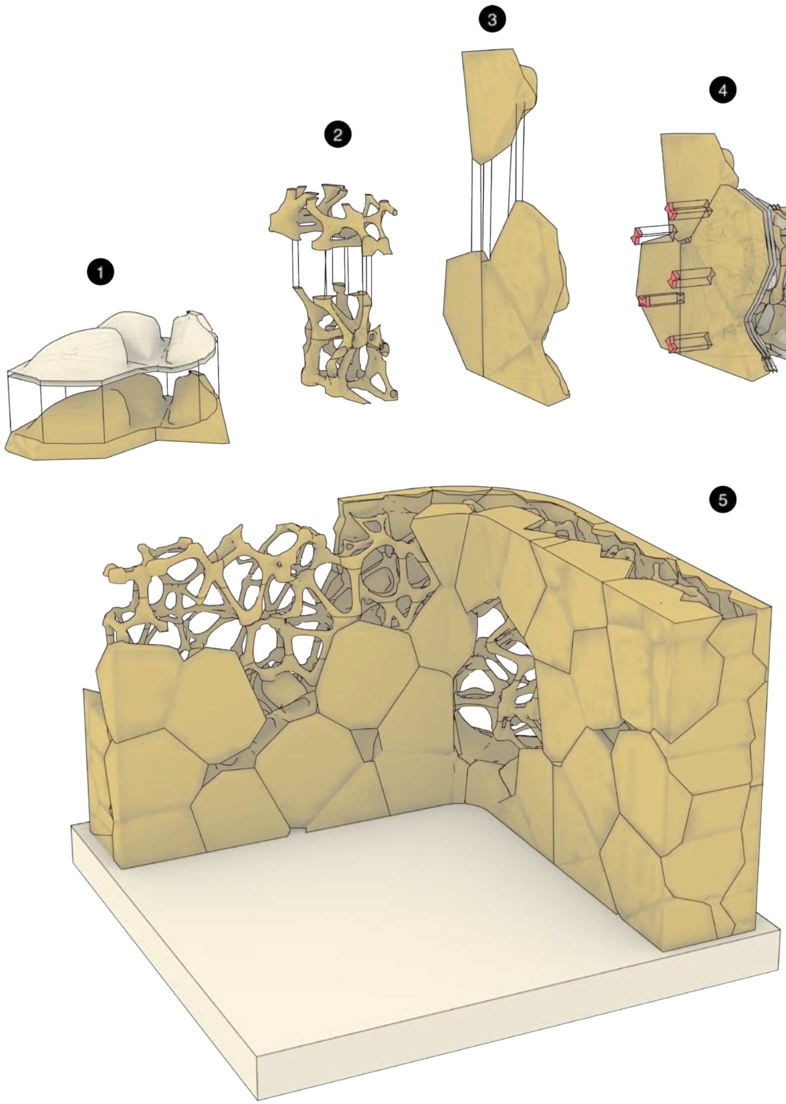


Figure 22: Process of the Assembly

1. A 5-10 cm layer of mycelium composite with saw dust substrate is applied over the 3D printed cellulose moulds

2. The central 3D printed cellulose cavities are assembled by stacking one above the other. The surface of the cavity is porous allowing a breathing surface for mycelium to grow in the inner surface.

3. After 7-10 days when the first layer of mycelium composite with saw dust substrate is stable, the 3D printed cellulose mould is flipped vertically. The moulds are assemble by stacking system.

4. The moulds are connected using the butterfly joint with the cavities place in-between the exterior and interior moulds.

5. The assembled structure is constantly filled with mycelium composite with wood chips substrates providing strength and stability to the monolithic mycelium wall.

Design: Design proposal

Concept Sketch

The design for co-existence focuses on creating habitable spaces for both bees and humans. Considering the humans needs the elements of openings, furniture and surface finishes are considered. On the other hand the exterior envelope consisting of the roof, wall and the surrounding environment is utilised to design the habitats of bees. The design enhances the qualities of interaction and shared spaces between the species using mycelium as that creates a natural circular loop year-round. The design is conceptual showing the spatial qualities required for co-existence that are derived based on our experimental findings.

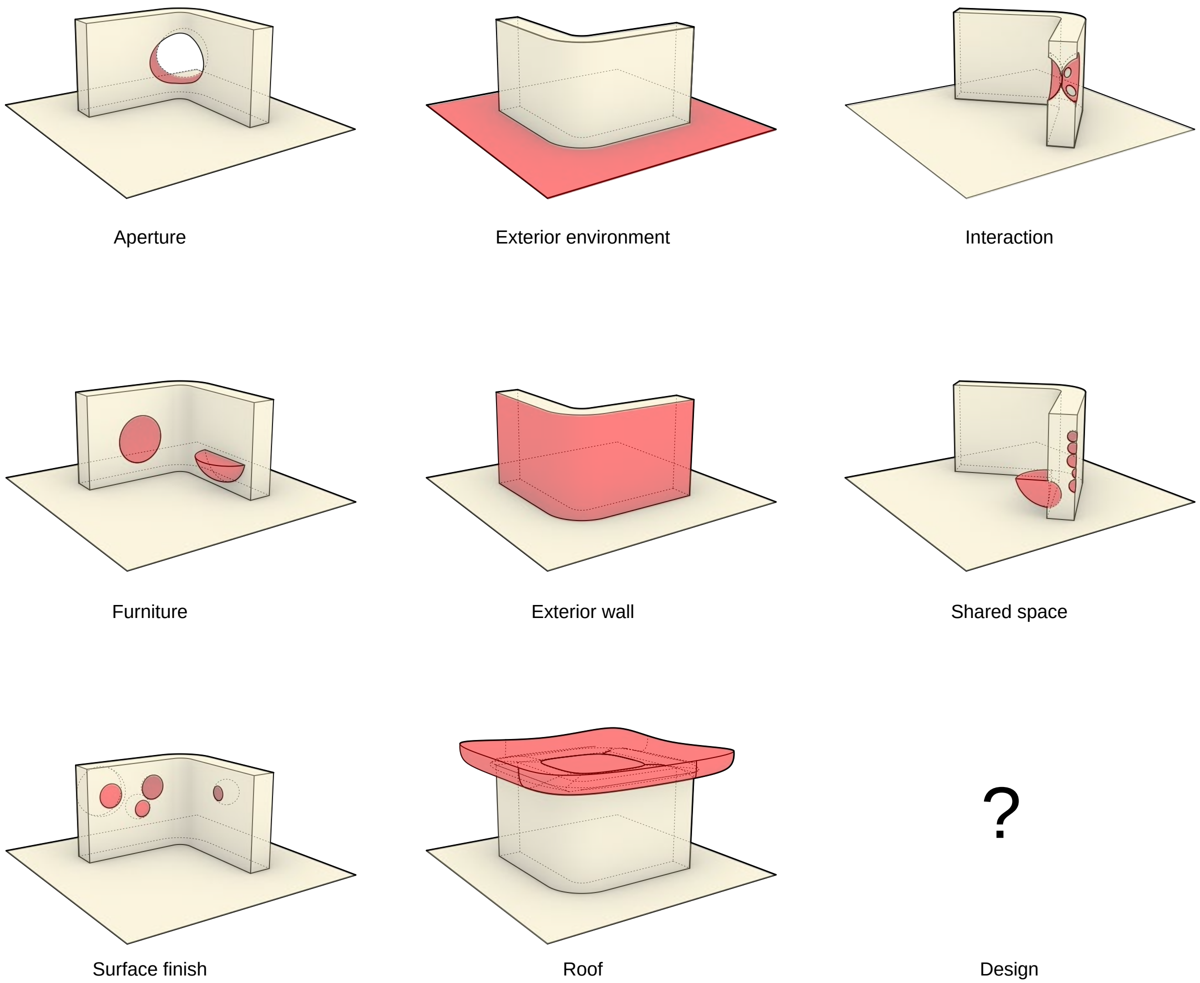
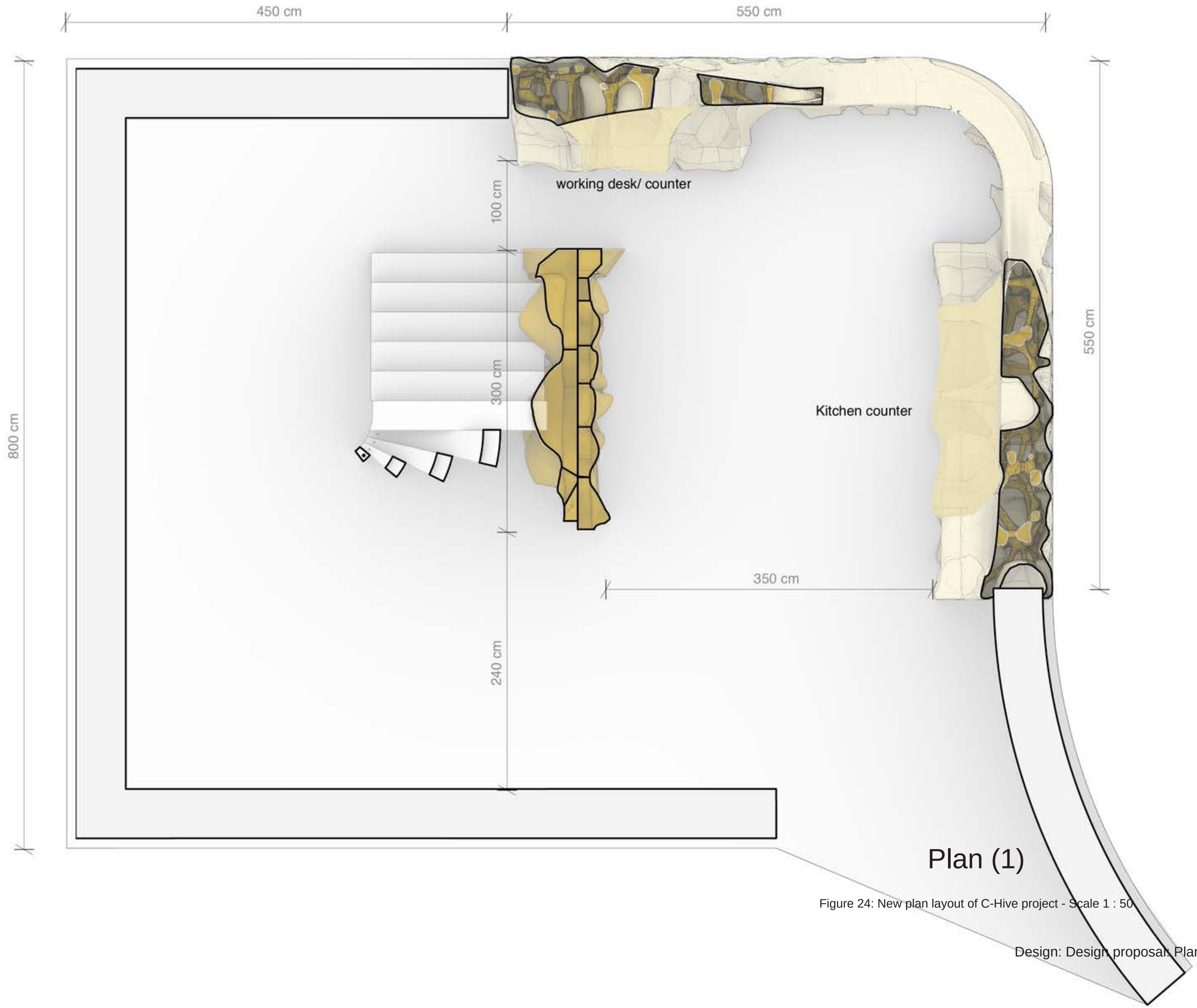


Figure 23: Architecture merits



Plan (1)

Figure 24: New plan layout of C-Hive project - Scale 1 : 50

Section (1)

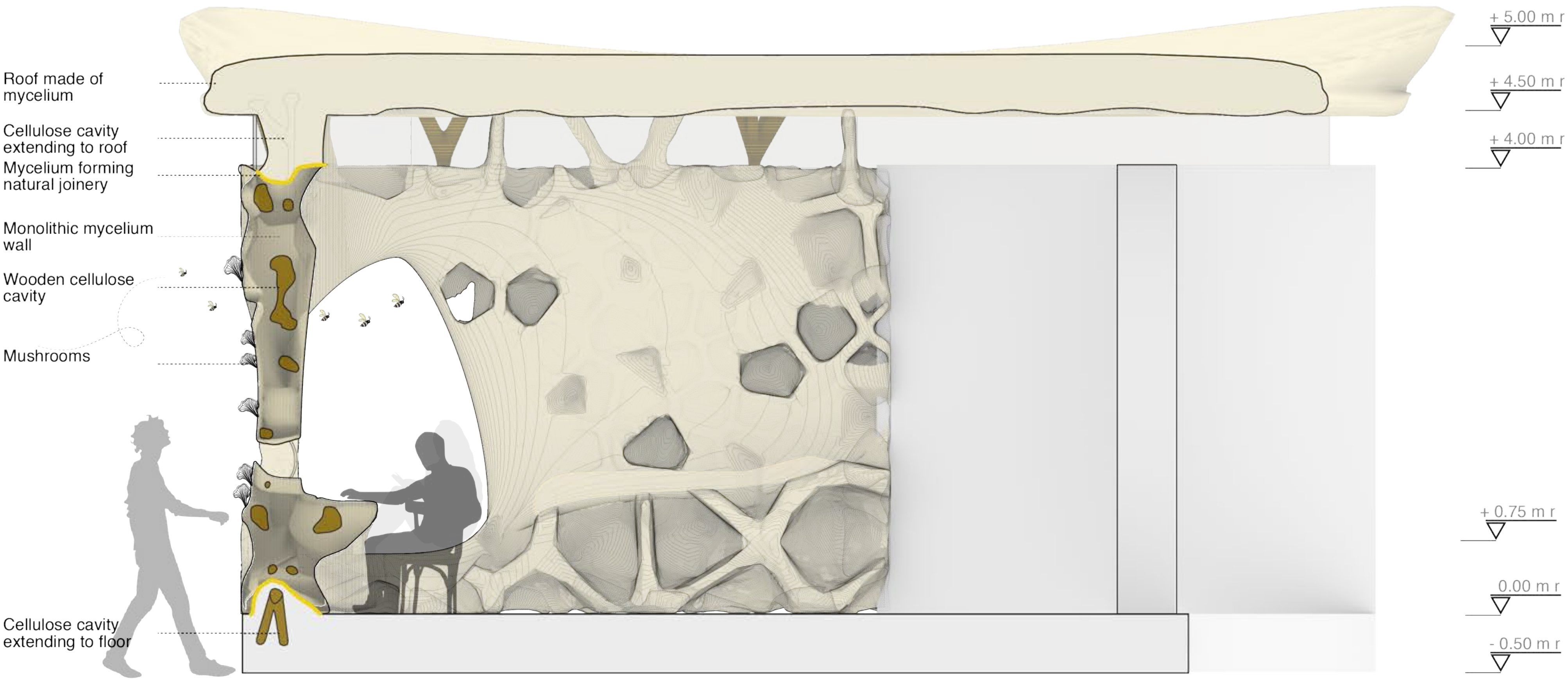


Figure 25: New section (1) of C-Hive project - Scale 1 : 50

Exterior Perspective (1)

Figure 26: Exterior perspective (1) with the bee houses

Exterior East Elevation (1)

Figure 27: Exterior east elevation (1) - Scale 1 : 50

Exterior North Elevation (1)

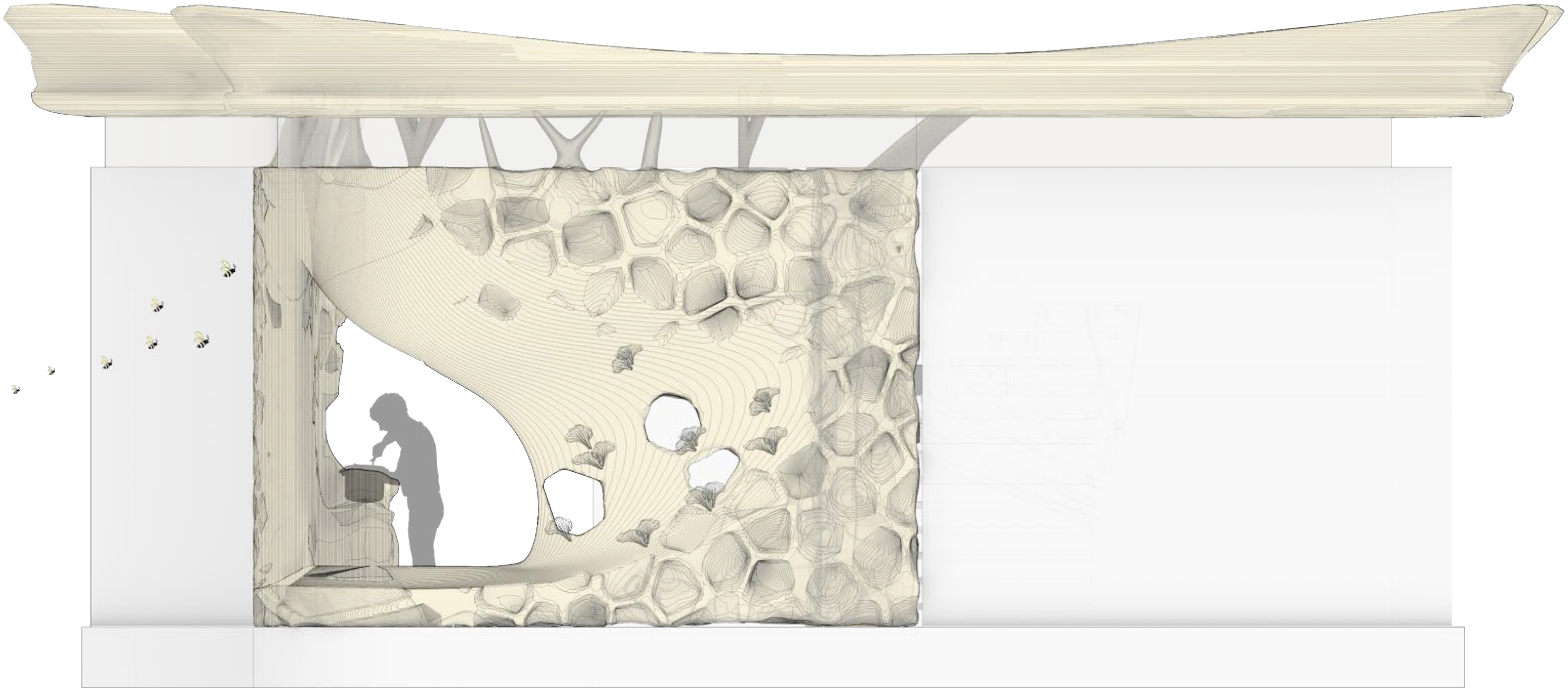


Figure 28: Exterior north elevation (1) - Scale 1 : 50

Interior Perspective (2)

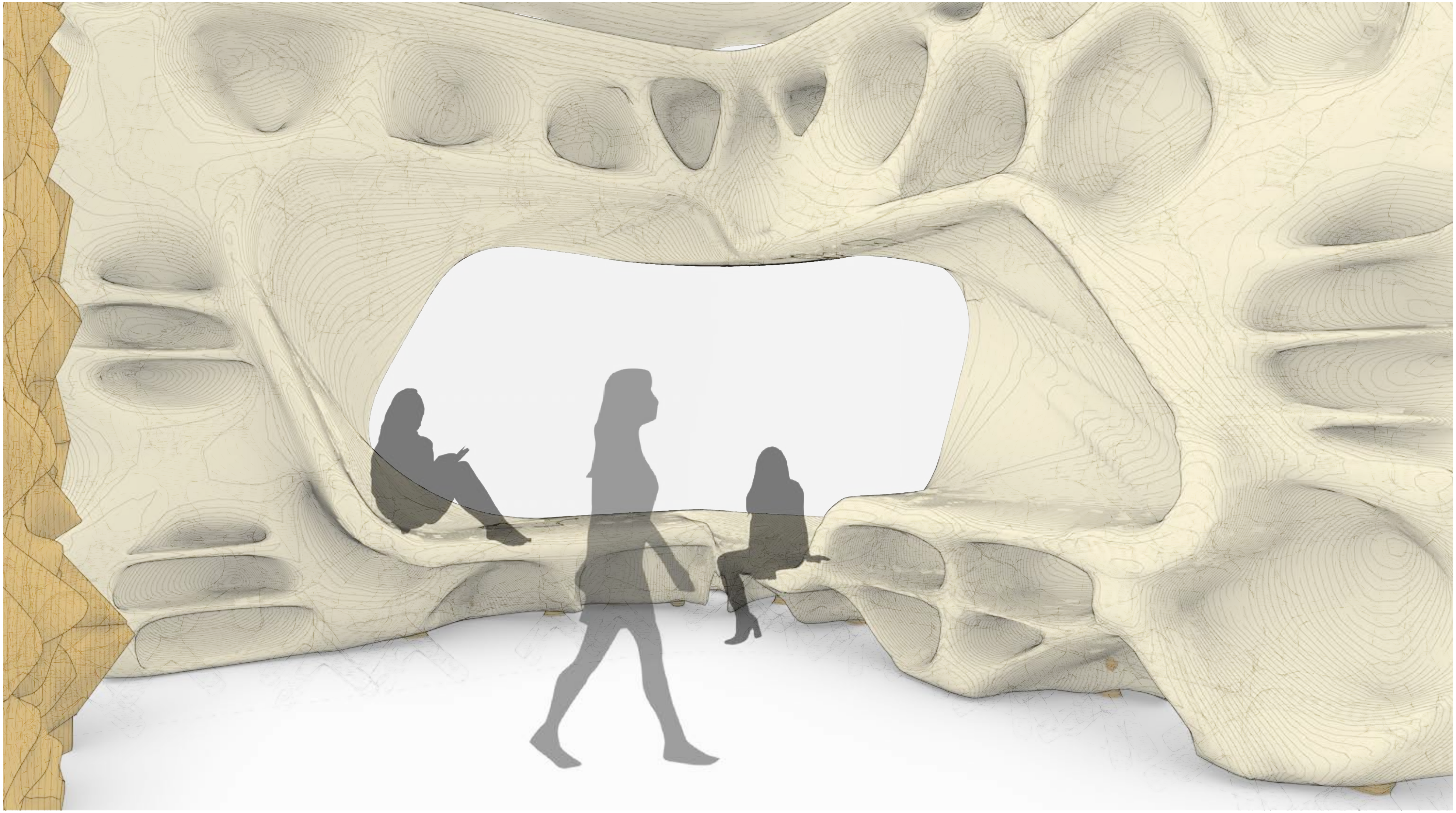


Figure 29: Interior Perspective (2) with the corner alcove

Interior West Elevation (2)

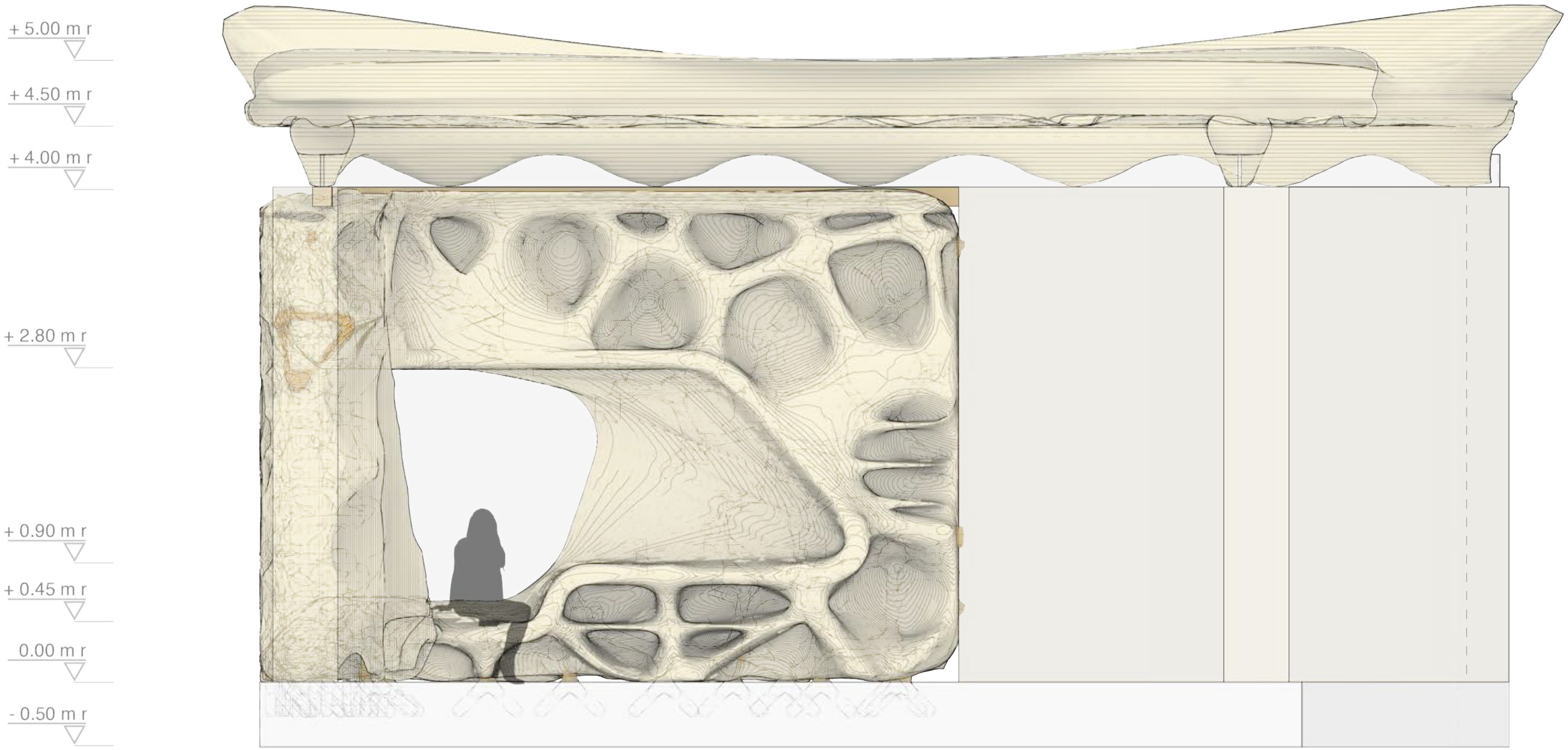


Figure 30: Interior west elevation (2) - 1 : 50

Exterior Perspective (2)

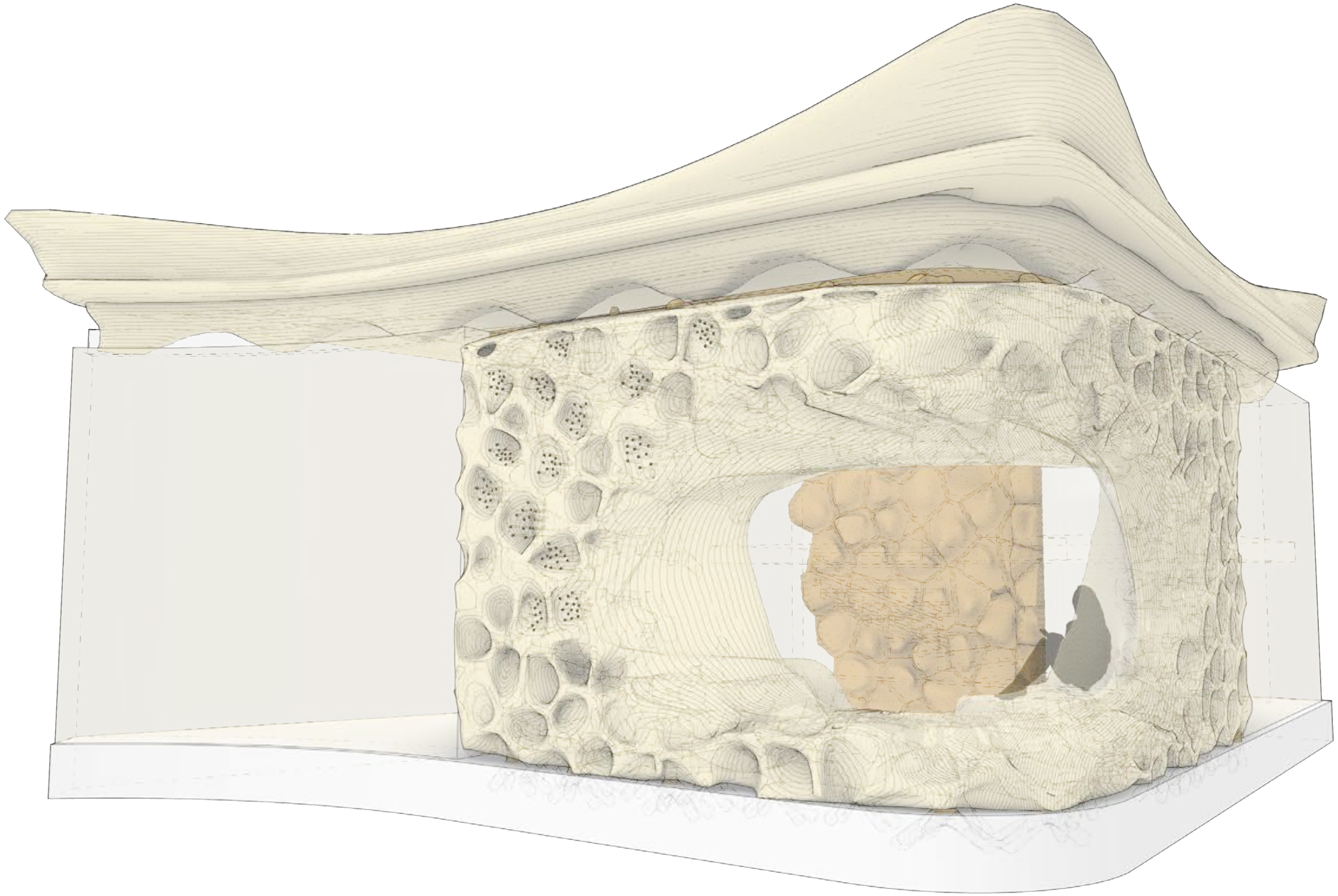


Figure 31: Exterior Perspective (2) with the bee houses

Exterior East Elevation (2)

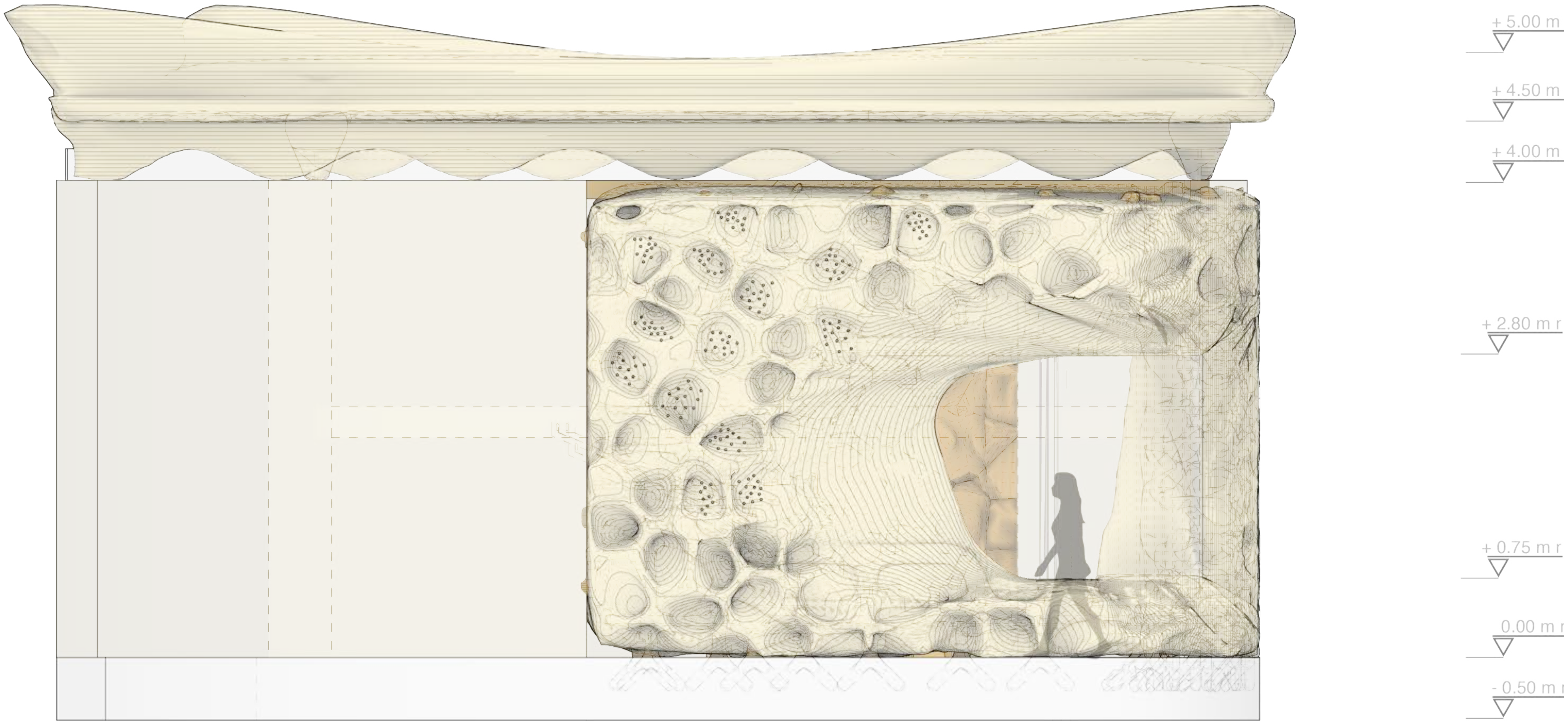


Figure 32: Exterior east elevation (2) - Scale 1 : 50

Prototyping

The Living Wall

Figure 33: The Living Wall prototype - Scale 1 : 10

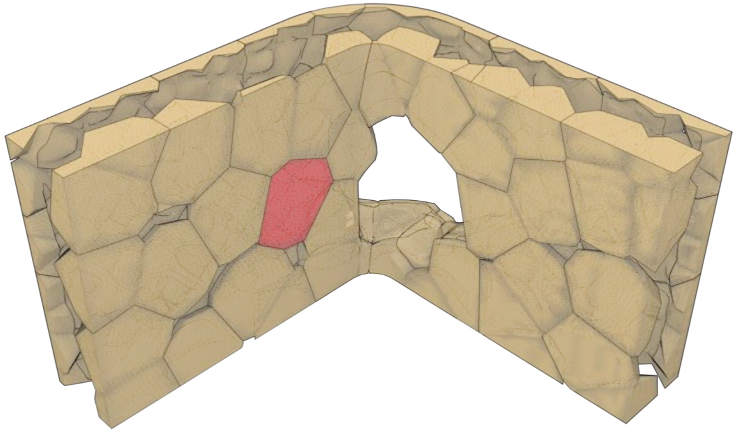


Figure 34: 3D model of assembled moulds - Scale 1 : 10 (50x50x40 cm)

Figure 35: 3D model of a mould sample for 3D printing in scale of 1 : 10 (15x15x5 cm)

Figure 36: 46 pieces of 3D printed moulds with light wooden PLA - Scale 1 : 10

Figure 37: Assembled moulds - Scale 1 : 10 (50x50x40 cm)

Figure 38: Assembled interior moulds - Scale 1 : 10

Figure 39: Assembled interior moulds - Scale 1 : 10

Figure 40: Assembled exterior moulds - Scale 1 : 10

Figure 41: Assembled exterior moulds - Scale 1 : 10

Figure 42: Assembled moulds without alcove surfaces - Scale 1 : 10

Figure 43: Casting the prototype - Composite: Oyster fungi inoculated into straw and corn seed

For testing fabrication and manufacturing technique of the Living Wall system whole L-corner was made at scale of 1 : 10. Two sets of exterior and interior, in addition to alcove surface moulds were 3D printed with light wooden PLA. In order to facilitate the process in small scale, based on the maximum print size of the Creality 3D Ender-3 V2 printer (220x220x250 mm) some panels were merged into one piece and joints were eliminated. After assembling pieces ,it was filled with oyster mycelium inoculated into straw and corn seed and it grew for two weeks. Since thickness of prototype was less than 10 cm, cavities was not functional so they were eliminated as well.

The Chunk of Living Wall

Figure 44: The chunk of Living Wall prototype - Scale 1 : 2

Figure 45: The chunk of Living Wall prototype - Scale 1 : 2

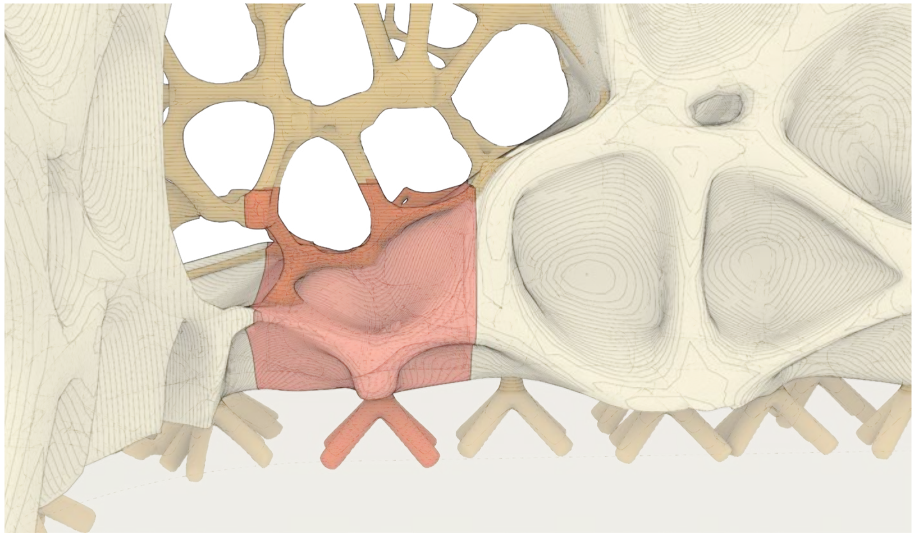


Figure 46: Position of chunk prototype - Scale 1 : 2

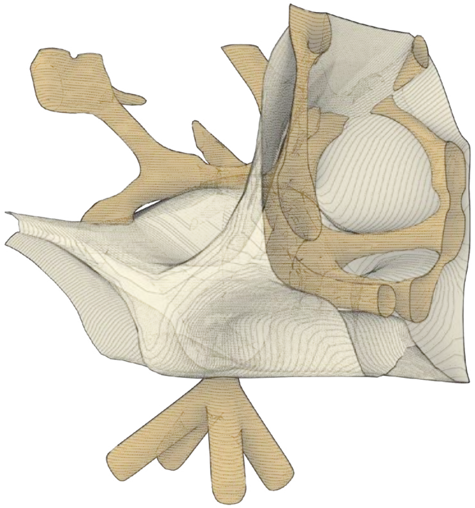


Figure 47: 3D model of prototype - Scale 1 : 2 (50x50x70 cm)

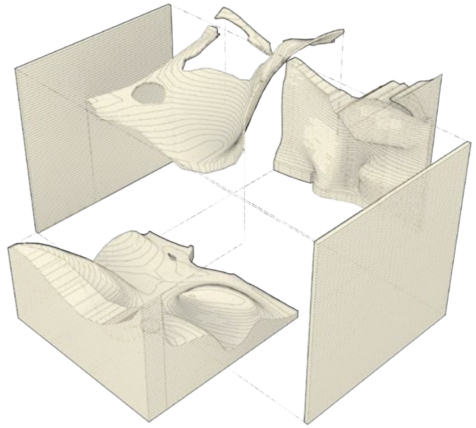


Figure 48: 3D model of moulds for CNC - Scale of 1 : 2 (50x50x50 cm)

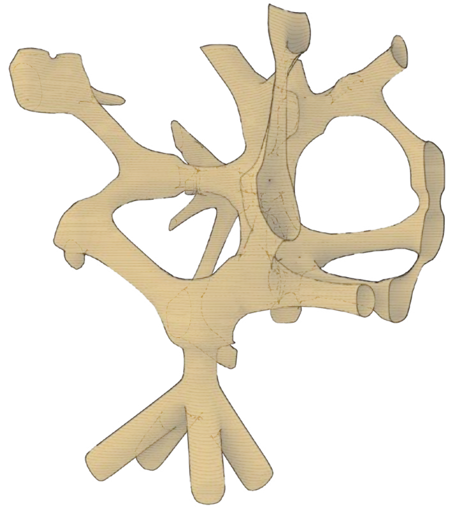


Figure 49: 3D model of cavity for 3D printing - Scale 1 : 2 (50x50x70 cm)

Figure 50: 25 pieces of 3D printed cavity element with light wooden PLA - Scale 1 : 2

Figure 52: CNC EPS moulds - Scale 1 : 2

Figure 51: Assembled cavity element - Scale 1 : 2

Figure 53: Assembled moulds - Scale 1 : 2

For testing the function of the Living Wall system, a chunk of the all was made at scale of 1 : 2. In this prototype cavities were chopped into printable size by Creality 3D Ender-3 V2 printer (220x220x250 mm) and were glued later. To mimic semi-porous surface of cellulose 3D printed in big scale, small holes with 1 inch threshold were drilled on the cavities. To facilitate the process, instead of the 3D printing moulds, CNC EPS was made for casting. It was filled with oyster mycelium inoculated into two different substrates; one for the core and another one for the finish surfaces and it grew for two weeks.

The Bee House

Figure 54: Bee House prototype - Scale 1 : 2

Figure 55: Bee House prototype - Scale 1 : 2

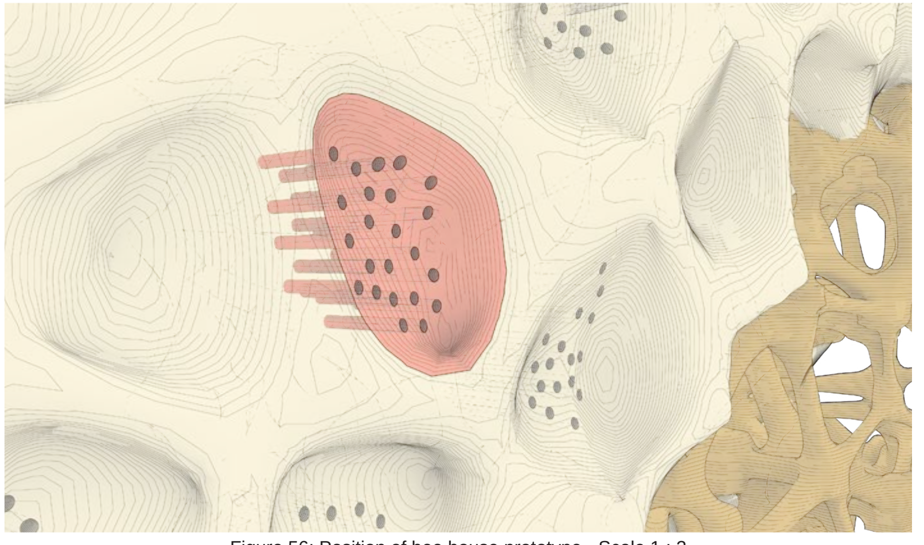


Figure 56: Position of bee house prototype - Scale 1 : 2


Figure 58: Casting the prototype - Composite: Oyster fungi inoculated into straw and corn seed

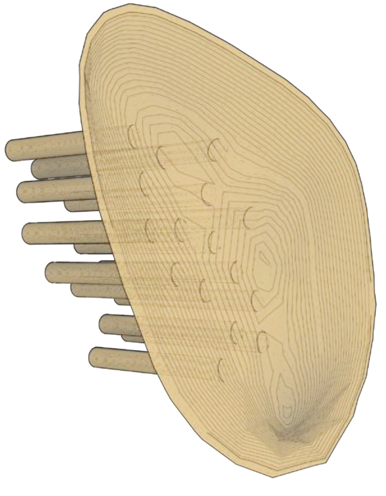


Figure 57: 3D model of bee house mould for 3D printing in scale of 1 : 2 (20x20x20 cm)


Figure 59: 3D printed mould with light wooden PLA - Scale 1 : 2

For testing the fabrication and manufacturing technique of the Bee House, one panel was made at scale of 1 : 2. This scale was chosen based on the maximum print size of Creality 3D Ender-3 V2 printer (220x220x250 mm). Mould was filled with oyster mycelium inoculated into straw and corn seed and it grew for two weeks.

Precedent study

Mycelium

Figure 60: Mycelium chair (Pallister, 2014)

Figure 61: 3D print iterative testing of Mycelium chair (Pallister, 2014)

Although there is a long way to introduce a concrete method(s) and form(s) of mycelium-based material to apply massively in the building industry and architecture, it is almost two decades, plenty of prototypes represents diverse functions and capacity of this bio-based material. Here, we focused on a couple of latter exemplars representing various characteristics of mycelium composite, to study recent discourse and projects. Nowadays, automated machines can involve in design, fabrication, and assembly of a building. Additive manufacturing, also known as 3D-printing, helps architects and designers to get aid of computer to prototype their design concepts. While 3D-printing process varies widely, it is usually done by adding a new layer of material to previous printed layer, in three dimensions. Designer Eric Klarenbeek in collaboration with scientists at the University of Wageningen, had developed a new approach to print mycelium-based materials.

“Our main purpose was to bring together the machine and nature to create a new material that could be used to make any product.” Said Eric Klarenbeek (Pallister, 2014)

His fully 3D-printed prototype called “mycelium chair” was shown at Dutch Design Week 2013, in Eindhoven. This lightweight chair was compounded from a thin coating layer and an infill scaffold which could support a person’s weight, as long as mycelium composite would grow enough (Pallister, 2014). Coating layer was produced from bioplastic - a common biodegradable material produced from agricultural by-product - widely used in FDM 3D printers. The skin was filled with internal support structure of a paste which was a mixture of water and powdered straw with injected mycelium. Once mushrooms sprouted, structure was dried out to halt growth of mycelium (Pallister, 2014).

Mycelium chair is a prototype by a computational design approach in order to fashion a mycelium composite into the complex form, while functionally speaking, it also worked properly. There are some other points to consider; firstly, whole structure was eventually inert. It means, although a living organism used at early stage, but final product was not alive; Mycelium only used as an organic glue for joining particles of straw for a certain period, and mushrooms were a very temporary ornament. Secondly, despite using two separated exterior surface and internal support, the complex external framework gradually entwined with the internal scaffold of mycelium composite. Technically, it was not possible to remove the framework without any damage. In other words, framework was a single-use and structure is a single unit.

Regarding this stunning mycelium chair, it came to our mind that what if a single mycelium-based material could be printed and fabricated without internal support,


Figure 62: Pulp Faction (Protomycokion) (The Editors of Green Product Award, 2021)


Figure 63: Pulp Faction (Protomycokion) (The Editors of Green Product Award, 2021)

meanwhile structure would be kept alive?

A research team made of David Andreen collaborating with Ana Goidea, and Dimitrios Floudas at Lund University, conducted a survey on fungal-lignocellulosic composites, and developed the design and fabrication process of 3D printing with a single mycelium-based material, called “Pulp Faction”. At the departure point, it was already known that the properties of the material directly relate to what extend mycelium spreads out within the composite; and mycelium only covers surfaces due to a need of oxygen for growth (Goidea, Floudas, & Andréen, 2020). As a matter of fact, solidity in terms of form, limits the qualities of the composite. Pulp faction tried to achieve maximum coverage of mycelium; hence, additive manufacturing technique applied to increase surface area within a certain volume (Goidea, Floudas, & Andréen, 2020).

“Biomimicry – design inspired by the way functional challenges have been solved in biology – is one of the best sources of solutions that will allow us to create a positive future and make the shift from the industrial age to the ecological age of humankind.” Said Michael Pawlyn (Pawlyn, 2016)

Additive manufacturing of a composite material, by employing computer and machines, sounds very industrial strategy; nevertheless, according to Pulp Faction, the idea was inspired by symbiotic coexisting of Macrotermitinae - a genus of termite - with a fungus of the genus Termitomyces; the termites bring the collected dried twigs, grasses, etc., back to the mound; in the appropriate micro-climate of the mound, the fungus can survive and process the collected plant-based material to supply food source for the both fungus and termites. In addition, geometry of the fungal comb also plays important role for thriving of the system; this unique geometry, not only facilitates access of termite to manipulate the structure, but also assists with air flow to provide oxygen within all comb surfaces, by chimney effect. (Goidea, Floudas, & Andréen, 2020).

Substrate in the Pulp Faction research was tailored to meet dual need; material within living organism required an appropriate condition for growth; besides, it had to be stable enough to print and stand alone without subsidiary support. Hence, the recipe of the substrate inoculated with mycelium consisted of mixture of water with fine wood-chips, mashed paper - as a food source for fungus - and kaolin clay to make pulp more stable during the process (Goidea, Floudas, & Andréen, 2020).

Furthermore, concerning the geometry, the algorithm used for fabrication was designed to ensure that structure had noticeable vertical continuity which eased air flow for mycelium growth; in addition, every layer shaped by merging all single

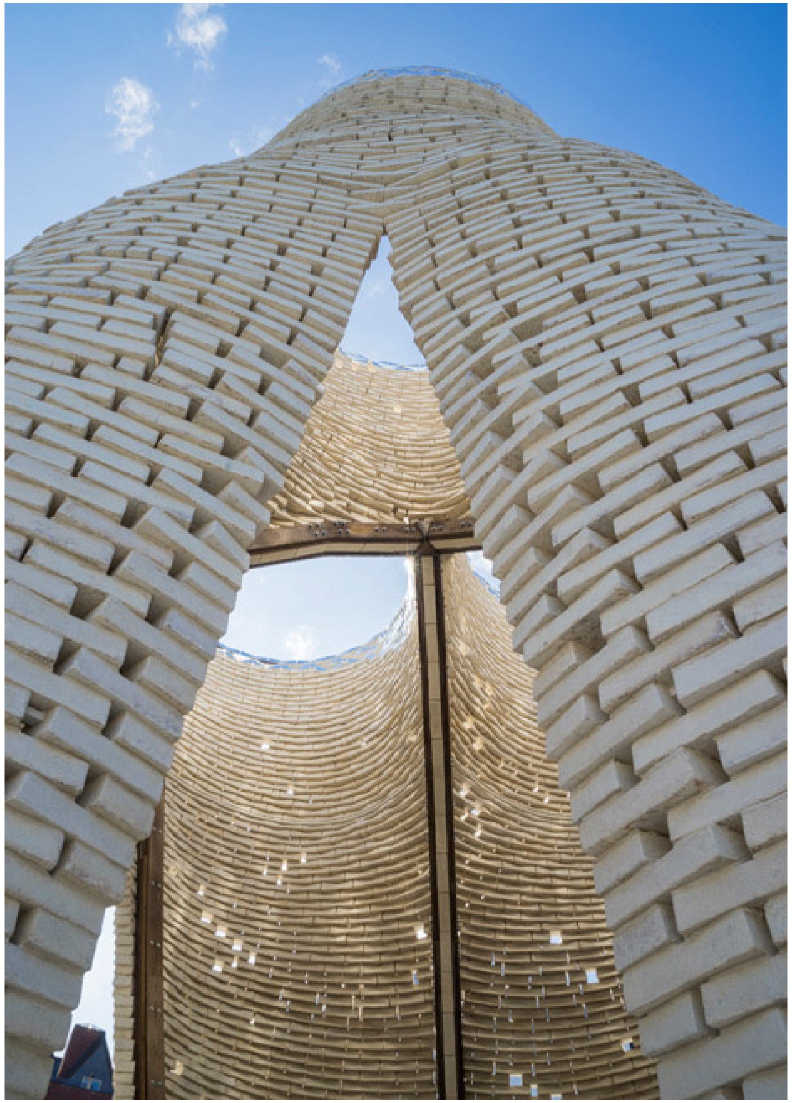


Figure 64: Hy-Fi (Frearson, 2014)

curvature into double curvatures in order to enhance stability of structure; while the thickness of walls kept 4 mm as the efficient depth for fungus growth (Goidea, Floudas, & Andréen, 2020).

The column - final prototype of Pulp Faction research - is a computational design approach to apply stand-alone mycelium composites for creating complex form within a proper functional purpose; however, it had got some delimitation which is also important to investigate. The first and foremost issue is how to scale up the structure, within the certain defined protocols, worked in small scale at laboratory; for instance, it is an inquiry yet if walls in a mock-up - 3D printed surfaces - within optimal thickness of 4 mm could work properly as a column or other building elements. In addition, although colour aspect of the final product in Pulp Faction, was not at scope of research, using a fungus from genus brown rot resulted in bright orange prototype; nevertheless, mycelium composites are usually dominant white if cultivated fungus is a white-rot one. Finally, similar to Mycelium Chair, the final product was inert; otherwise, structure would start to decay later on.

Beyond what discussed and the valuable achievements by Pulp Faction research, we realised that working with mycelium-based materials needs meticulous care, since mycelium fungi in their early stage of life cycle are highly delicate; this delicacy is correlated to low rate of growth in comparison to other species at same or close taxonomies, like moulds, which due to higher rate of growth take over and eliminate all food source sooner than mycelium. As a matter of fact, It solves straightforwardly by working in sterile condition to plunge risk of contamination; however, situation is getting worse when it comes to 3D printing mycelium composites; and, even it is the worst in the realm of building industry and massive production. Therefore, we asked ourselves what if mycelium composites could work properly as a material within enough stability and durability to build a structure, beyond a furniture or other small scale conceptual prototype by an insensitive process?

Casting is a way to manufacture a material within various geometries and sizes; it is done either by employing a disposable mould(s), or multi-use ones. Building industry is rich in materials, like, adobe, clay, concrete, etc., accomplished by casting technique. Therefore, mycelium composites could also be manufactured within applicable small-scale bricks under every certain strict condition; then, they might be fabricated to erect a bigger scale structure. “The Living” studio in New York, tackled mycelium composite, by casting a bio-brick material, to design and construct a tower, called “Hy-Fi”, at MoMA PS1 gallery pavilion in New York.

“Hy-Fi offers shade, colour, light, views, and a futuristic experience that is refreshing,

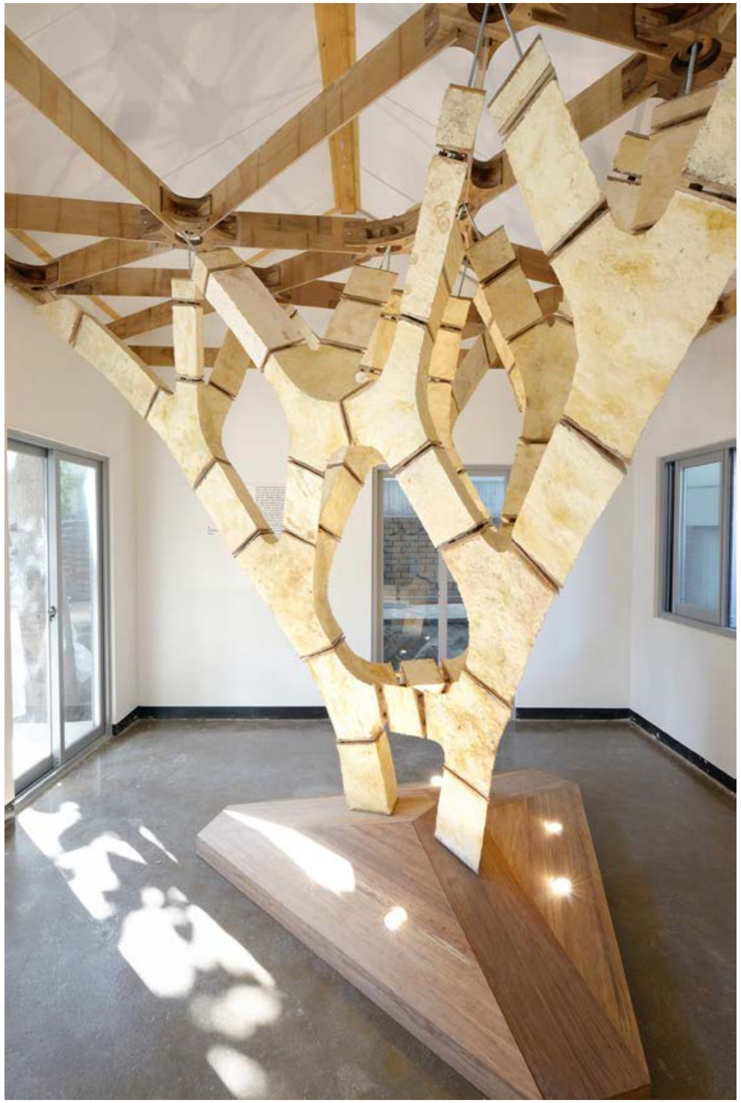


Figure 65: MycoTree (Frearson, 2017)

thought-provoking, and full of wonder and optimism, ..., designed to create a pleasant micro-climate throughout the summer." Said the gallery. (Frearson, 2014)

The project had proposed a temporary structure which was totally built from biodegradable materials - won the annual "Young Architects Program" competition. The bricks were mycelium composites made of corn stalks as the main substrate and mycelium as organic growing glue; and they were coated with thin layer of particular refracting-material to promote light bounces inside of the structure. In addition, some gaps in brick bond assisted in stack effect for natural ventilation. (Frearson, 2014).

As far as material was concerned, Hy-Fi and Mycelium Chair had shared a same idea, but within two alternative manufacturing and fabrication approaches; a thin layer subsidiary material coated the rest infill mycelium composite. Furthermore, deliberate gaps took place by playing with brick bond; therefore, credit of the porous pattern could not be given to material itself, but the design. However, main challenge was the final geometry picked for manufacturing process; Accordingly, what if geometry of the composites could be actively engaged with the qualities were looked for in the design? - In this case qualities could be the porosity and assisting with natural ventilation.

Different studies explored, proved, and showed some properties of mycelium-based materials; for instance, they easily get shaped in any forms. In addition to inherent qualities of mycelium composites, some qualities can also be promoted within the well-though given form; take self-supporting for example. Architect Dirk Hebel and engineer Philippe Block associating their team, conducted a research to promote and test constructional properties - compression tolerance - of mycelium composite by employing appropriate designed geometries; a prototype of this structural framework called "MycoTree" shown at Seoul Biennial of Architecture and Urbanism, in Seoul.

"In order to show the potential of new alternative materials, particularly weak materials like mycelium, we need to get the geometry right. Then we can demonstrate something that can actually be very stable, through its form, rather than through the strength of the material." Said Philippe Block (Frearson, 2017)

It was argued that mycelium composites could properly provide a structure of two-storey building, as long as they were formed within an appropriate geometry; in other words, structural components designed for taking only compression load, could be entirely made of mycelium composite. (Frearson, 2017)

"In nature, materials are expensive, and shape is cheap." Said professor Julian Vincent (Pawlyn, 2016)


Figure 66: Exterior of Growing Pavilion (Pownall, 2019)


Figure 67: Interior of Growing Pavilion (Pownall, 2019)

The system was inspired by bamboo; a plant which thanks to regular nodes at ends of each tuber segment, can reach as tall as a towering tree. Likewise, every block - having been manufactured by casting with moulds - was joined with end-plates and metal dowels. Material study itself was beyond the scope of this research; the substrate used for the composite consisted of sawdust and sugar-cane as a food source for mycelium (Frearson, 2017).

This instalment was a high-end digital fabrication approach to make a structural framework provided by mycelium-based materials. With respect to MycoTree, mycelium still used as an organic glue and living organism became inert, like Hy-Fi; but, in comparison, MycoTree was only a structural prototype and Hy-Fi was only a skin; so, what if mycelium composite could provide entire elements of a structure consisting framework and skin simultaneously?

In realm of bio-based materials, we are dealing with living or once-living organisms. Regarding mycelium-based composites, material itself is biodegradable; keeping mycelium growing, even material starts to decay far sooner, and mushrooms sprout. Therefore, mycelium-based materials are naturally suitable for temporary structure, within all low environmental footprint benefits. By the way, uncertain lifespan of a structure could be the biggest challenge if it was entirely provided from mycelium composites. Pascal Leboucq in collaboration with Erik Klarenbeek - designer of Mycelium Chair - designed a temporary pavilion made entirely from bio-based materials; curtain wall system was employed to form the cylindrical pavilion.

"The idea of the Growing Pavilion started from the mushrooms, but it became bigger. Everything is built from plants and trees or agricultural waste, ..., mycelium is very organic and natural. This combination of the two was magic for me." Said Pascal Leboucq (Pownall, 2019).

The structure called "Growing Pavilion", was constructed, and shown at Dutch Design Week 2019, in Eindhoven. Two rows of panels provided from mycelium composites were supported on a timber structural framework. Thanks to curtain wall system, panels could be disassembled, in case of a need to be reassembled. In addition, it is argued that those light waterproof panels promoted the thermal and acoustic insulation while the pavilion used for live concert performance. Furthermore, mushrooms were collected daily from panels to be served for purchase (Pownall, 2019).

Growing Pavilion was a fully functional structure while the mycelium composites were kept alive; nevertheless, those panels were non-structural elements, and the rest of the structure were made of other bio-based materials. By the way, this project only targeted humans as users, and the mushrooms only used as food source. But what if a structure provided from alive mycelium composite could also contextualise a symbiotic coexisting between human and other species?

Bees

Figure 68: The Birds and Bees Installation (Harrison et al., 2016)

Figure 69: A panel of The Birds and Bees Installation (Harrison et al., 2016)

The era of Anthropocene brings in several alternative thoughts among architects and experts in other fields to design spaces for the co-existence of different species with humans. This shows how post-human architecture is expanded over years considering a balance for all species to thrive in synergy.

The project “the Birds and Bees” designed by Harrison Atelier Architects for the Socrates park in New York was an open educational pavilion with co-existing space for the local species especially the endangered species of birds and solitary bees with humans. While usually the bird houses resemble human habitats, it is often attracted by the predators as a good place to perch which pose risk to the birds inhabiting. The flat roofs also have poor drainage of the water from the cavities which attracts bacteria and fungi. Considering these issues of conventional habitats designed for other species, this pavilion was designed as a wall system that functions as the habitat for species (Harrison et al., 2016). The system of the wall panels integrated with habitable cavities eliminate the need for roof in each dwelling. The roof of the wall system was supported by polycarbonate sheet for rainwater catchment system with conduits channelizing the water through the wall. The exterior wall comprised of 2 by 2 feet precast concrete wall panels with different size of holes to nest cavity dwelling birds and solitary bees and the interior face was made of waterproof plastic sheets that functions as a surface for projection for classes and performance (Harrison, Harrison, Ullman, Javed, & Gillen, 2016). The panels were carefully designed with different size of apertures to attract different species and deter predators. Apertures with size of 1 inch attracted house wrens, while 1 1/8 inch house Black capped chickadees and 1 1/4 inch Red Breasted Nuthatch and Tufted Titmouse. On the other hand, the pavilion also attracted several species of solitary bees. There are around 4,000 species of solitary bees in North America. They do not produce honey and thus do not have stings. This makes them friendly, enabling it to live close to humans. Thus, the nesting holes for solitary bees that do not bore their own holes but nest the existing cracks and hollows are designed with diameter ranging between 1/4 to 3/8 inch. It is also essential to have their favourite plants that they feed on in close proximity to attract the desired species. This pavilion brought in a mutual usable space for both humans and other species enhancing their co-existence (Harrison et al., 2016).

“Architecture should address multiple species, enabling their existences and their co-existences with humans.” Said Harrison Atelier (Harrison, Harrison, Ullman, Javed, & Gillen, 2016)

Considering the importance of bees for pollination, the Harrison Atelier architects designed the “Pollinators Pavilion” to both monitor and provide habitat for various bee species. In the Stone House Farm in New York’s Hudson Valley, the Pollinators

Figure 70: Pollinators Pavilion (Harrison, Harrison, Chen, Kang, & Rappaport, 2019)

Figure 71: Close-up of Pollinators Pavilion panels (Harrison, Harrison, Chen, Kang, & Rappaport, 2019)

Pavilion housed several species of solitary bees which contributed to 70% pollination of the non-agricultural environment in America (Harrison, Harrison, Chen, Kang, & Rappaport, 2019). The design of the pavilion was evolved from the compound eye structure of the bees with precast concrete panelling system that consists of hundreds of nesting tubes for the solitary bees. There were about 300 concrete panels that nests around 2000 solitary bees. The structure of each panel with the pointed form was designed efficiently creating a suitable microclimate for the bees that act as rain shield and to hold the solar powered monitoring unit developed with the support of Microsoft's AI for Earth grants with the integration of machine learning interface; it helped in automatic identification of species that enter the nesting tunnel. The movement of the bees entering the nesting tunnel triggered the motion sensor to photograph the insects. This information was fed through the microprocessors to the database which through machine learning system identified the species without causing any harm (The Editors of Harrison Atelier, 2021).

The "Bee MycHotels" project by Kart Ayres from the Central community college at Nebraska focussed on constructing bee hotels from mycelium. While it is important to create habitable spaces of species that are vital to pollination this project focussed on sustainable material as an alternative to conventional materials which is not environmental-friendly. With the research background from Paul Stamets, mushroom mycelium boosts the bee's immune system which helps in fighting several diseases caused by bacteria and viruses, this project was developed to redesign the traditional bee hotels with mycelium (Editors of Central Community College, 2020). This is an ongoing project where the inquiry of testing the cavity tunnels are being made with mycelium but preferably in the inert state. Since the mycelium grows and might cover the cavities, she proposes to bake the cavities of bee hotel, while the external envelop is kept alive for the bees to feed on (The Editors of Central Community College, 2020). Breaking the traditional construction of the bee hotels which mainly focuses of solitary bees Econooc was an innovative design that focussed on the issue of declining bee population in Ireland. It was estimated that about one third of the bee population in Ireland would be extinct by 2030. To solve this issue of declining native Irish black bee population Niamh Damery from the University of Limerick, designed a conservation beehive made of mycelium and other natural and recycled materials which have minimal impact on the environment. The design also won the 2020 James Dyson award. Econooc mimicked the form of the tree hollow, which is a perfect shape to inhabit the bee colony. The design of Econooc had three segments, where each segment was assembled with smaller units made of mycelium composite from agricultural bi-product. The overlap between each segment was held together laterally with a ring made from composite made of corn starch, bamboo and a bio

Figure 72: Bee MycHotels (Editors of Central Community College, 2020)

degradable resin. The landing pad for the bees - also provided ventilation for the hive - had a small hole where the user could watch the happenings inside the hive. This was made of recycled plastic which provided varied colours and makes each hive distinct. The hive was assembled and attached to the trees. The assembly kit also came with a calendar to educate the user about the activities happening in the hive based on different seasons. The lower part of the calendar was made of recycled paper with seeds of wild flowers along with the instructions to plant them in corresponding locations from the hive. This project was not only intended to protect bees but educated the user about the importance of bees and protecting biodiversity (Damery, 2021).

Experiments

Introduction

Figure 73: Homemade laminar for experiment setup

Figure 74: Basic tools and equipment for homemade laminar

In a small room allocated for our experiment in the studio space, we created a confined sterile space using a wooden framework covered with plastic sheets with small openings for ventilation. We used coffee filter to cover the openings to purify the air to a certain extent. All the samples for inoculation was carried out with in this enclosed sterile space to avoid contamination. All the substrates used in the experiments are sterilised before inoculation. Due to the lack of access to autoclave and lab equipments, the substrates were sterilised at home. The substrates were individually sealed in a clean plastic cover by removing all the air as much as possible and boiled in a vessel of water for about 2 to 3 hours.

Before starting each experiment we sanitized our hands every time we entered the room and sterilised all the surfaces using 85% alcohol spray. All the necessary precautions were taken to eliminate moulds. After the experiments,the samples were wrapped with clean plastic warp and a couple of holes were made using a wooden skew to provide required oxygen for the mycelium composite to grow. A humidifier was used to increase the humidity of the room. Both the temperature and humidity of the room was monitored and was maintained at 22 degree Celsius and 42 percent respectively.

The following terms are used to describe different growth pattern of mycelium composite in the experiments;

Infill: The mycelium composite is filled inside a defined mould made with different cellulose based substrate.

Over growth: The mycelium composite is allowed to grow over or above the cellulose based structure.

Mixed: This is a mixed pulp in the form of a paste with or without the mycelium. This allows for mycelium growth both as an infill and overgrowth, which is tested by extruding the pulp to a desired form using 3D printing technology.

Basic tools and equipment for homemade laminar:

- Air filter
- Temperature and humidity meter
- Humidifier
- Cultivation bags

Figure 75: Single-use moulds made of mashed paper

Figure 76: Lion's mane composite with fruiting body

Experiment 1

AIM
To test how the thickness of mashed paper mould impact the properties and qualities of mycelium composite.

MANUFACTURING TECHNIQUE: Casting with single-use mould made of mashed paper with thickness of 2mm, 4 mm, and 8mm.

FUNGAL STRAIN: Lion's mane mushroom

SUBSTRATE: Sawdust and wheat

SAMPLE SIZE: 10x10x4 cm

GROWTH PATTERN: Infill

PROCESS
- Mashed paper mould made from a mixture of soaked paper, fenugreek seeds, and a variation with turmeric for colour was prepared.
- The mould was dried for a week to eliminate water.
- The moulds of different thickness was filled with mycelium composite.
- All samples were kept for 7 days, in almost dark drawer in the room temperature and humidity.

OBSERVATION
- The samples were soggy and contaminated.
- Mushrooms were grown on the open surfaces.
- No penetration through the mashed paper was observed.

CONCLUSION
- The excess dampness of the mashed paper led to contamination of the samples.
- The samples were disposed prior to finish of the experiment due to foul smell and fast spreading contamination.
- Highly sterile environment is required.

COMMENT
Due to lack of time the experiment could not be repeated.

Experiment 2

Figure 77: Oyster composite - The sample with 10 cm thickness cut in half

Figure 78: Left: Flexibility of the sample with 1 cm thickness - Right: Testing hydrophobicity

AIM
To test properties and qualities of different thickness of mycelium composites.

MANUFACTURING TECHNIQUE: Casting with single-use mould made of Balsa wood of 1 mm thickness.

FUNGAL STRAIN: Oyster mushroom

SUBSTRATE: Wood-chips and flour

SAMPLE SIZE: 10x10x1 cm; 10x10x10x2 cm; 10x10x10x4cm; 10x10x8cm.

GROWTH PATTERN: Infill

PROCESS
- The disinfected mould was filled with mycelium kit.
- All samples were kept for 10 days, in almost dark drawer at the room temperature and humidity.
- Sample within 10x10x1 cm was left to dehydrate. Sample within 10x10x2 cm baked for 2 hours in oven at 75 Celsius degree. Subsequently, 3 droplets of water dropped on each and likewise on a plastic plate.
- Sample 10x10x8 cm was cut into half and were wrapped in plastic again to grow for another 10-days.

OBSERVATION
- Mycelium composite was filtrated by mould and it grew over moulds.
- Droplets on both mycelium composites and plastic evaporated without any absorption.
- Average density of samples were almost 0.1 g/cm^3

CONCLUSION
- Balsa worked well as a filter and it was possible to extract pure mycelium.
- The extracted membrane was hydrophobic, which could be applied on the exterior surfaces
- Both baked and dried mycelium composite sample were hydrophobic.
- Sample within 10x10x1 cm was very flexible and resilient.

COMMENT

Experiment 3

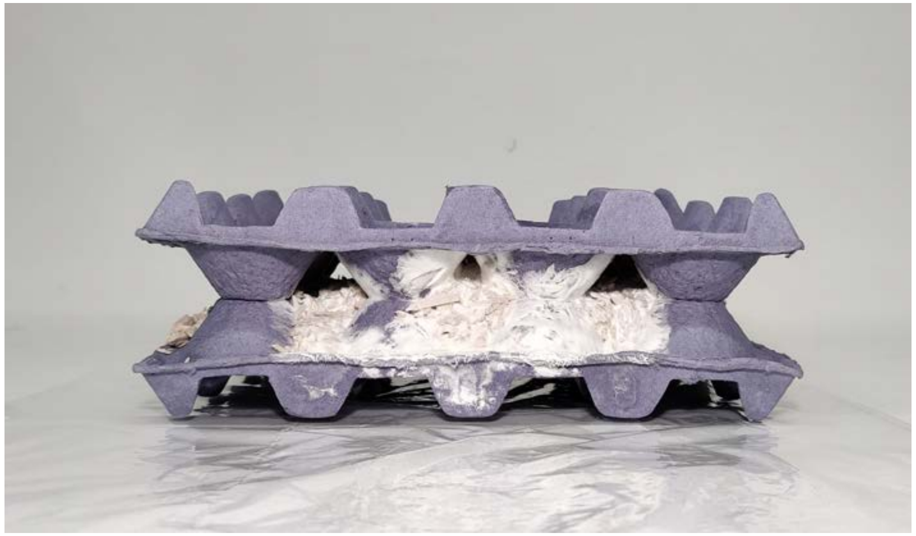


Figure 79: Growing mycelium over the paper pulp (egg tray)

Figure 80: Mycelium was filtered by thin later of paper pulp (egg tray)

AIM
To test if mycelium digests mould made of paper pulp.

MANUFACTURING TECHNIQUE: Casting with single-use mould made of mashed paper

FUNGAL STRAIN: Oyster mushroom

SUBSTRATE: Wood-chips and flour

SAMPLE SIZE: Free form (egg tray)

GROWTH PATTERN: Infill

PROCESS
- The mycelium kit was used as an infill layer between the mashed paper.
- Sample was kept for 10 days, in almost dark space at room temperature and humidity.

OBSERVATION
- Mycelium composite was filtrated by mould and it grew over the moulds.

CONCLUSION
- Mycelium digests mashed paper mould.
- It is possible to extract pure mycelium.

COMMENT

Experiment 4

Figure 81: Inoculating different substrates

Figure 82: Composite samples of:
Top Left: Cut jute - Top Right: Chopped straw - Bottom Left: Saw dust - Bottom Right: Wood-shaving

AIM
To test properties and texture of the substrate; softness; hardness; flexibility; porosity.

MANUFACTURING TECHNIQUE: Casting with single-use mould made of EPS

FUNGAL STRAIN: Oyster mushroom

SUBSTRATE: Cut jute; wood-shaving; short paper; saw dust; coffee ground; chopped straw.

SAMPLE SIZE: 10x10x2 cm

GROWTH PATTERN: Infill

PROCESS
- All the substrates were boiled for 3 hours inside a plastic bag to sterilise.
- The sterilised substrates were inoculated in a grow bag with flour, mycelium and water inside the self made laminar.
- After 14 days of inoculation the substrates were filled in the EPS moulds.
- All successful samples after inoculation were kept for 14 days, in almost dark space at room temperature and humidity.

OBSERVATION
- No mycelium growth was observed in coffee ground
- Short paper and shaved wood substrates were contaminated
- Chopped straw and cut jute substrates were successfully inoculated but mild contamination was observed. Yet the sample had dense mycelium growth.
- Cut Jute sample had soft spongy texture with fruiting body after 21 days. The mild contamination was overtaken by mycelium except in areas where holes were pierced for oxygen.
- Chopped straw sample was soft and light weight with fruiting body after 21 days.
- Saw dust substrate wasn't contaminated and the sample had highly dense mycelium growth on the surface.

CONCLUSION
- Different substrates provide different qualities of the mycelium composite.
- The rich nutrition from flour helped mycelium to overtake the mild contamination observed in cut jute and chopped straw samples.

COMMENT
The flour used for inoculation and for the samples was not sterilised.

Experiment 5


Figure 83: Lion's mane composite applied on weaved frame structure


Figure 84: Lion's mane composite applied on twisted rope of tower structure

AIM
To test the pattern and the tension property of rope.

MANUFACTURING TECHNIQUE: Support structure with rope.
FUNGAL STRAIN: Lion's mane mushroom
SUBSTRATE: Sawdust paste;
SAMPLE SIZE: 20x20 cm; 20x10x10 cm
GROWTH PATTERN: Over grown

PROCESS
- The jute strings are coloured with turmeric and sterilised by boiling for 3 hours in a plastic bag.
- 20x20 cm Plexiglas frame was weaved with random pattern.
- Jute strings were randomly weaved between the two 10x10 Plexiglas plate drilled with holes and twisted into a thick rope of around 1cm to create tension as a tower structure.
- The mycelium paste was applied on both the weaved structures.
- All successful samples were kept for 7 days, in almost dark space at room temperature and humidity.

OBSERVATION
- The mycelium was attached to the rope in the weaved frame structure yet it was brittle.
- The mycelium on the twisted rope of the tower structure was brittle yet keeps the rope in shape.

CONCLUSION
- The mycelium provides compression strength to the tensile jute strings.

COMMENT
The consistency of the mycelium paste might influence the brittleness.

Experiment 6

Figure 85: Oyster composite with 3D printed cavities

Figure 86: Oyster composite with 3D printed cavities

AIM
To test if mycelium digests 3D printed cellulose.

MANUFACTURING TECHNIQUE: Support structure by additive manufacturing
FUNGAL STRAIN: Oyster mushroom
SUBSTRATE: Wood-chips and flour
SAMPLE SIZE: 20x20x20 cm
GROWTH PATTERN: Infill and overgrowth

PROCESS
- One piece of cellulose mould was filled with the mycelium kit as an infill.
- Another piece of the mould was place in a plastic container and filled with mycelium kit externally.
- All samples were kept for 10 days, in almost dark space at room temperature and humidity.
- Samples were left to grow for another 10 days

OBSERVATION
- A mushroom sprouted on the mycelium composite.
- The cellulose mould remained intact.
- The mycelium composite was hardened and held the cellulose mould in place.

CONCLUSION
- 3D printed pieces can be used as void or place holder inside of the mycelium composite.
- 3D printed pieces can be filled by mycelium composite to promote their properties.
- Mycelium hardly digested the 3D printed cellulose mould, and the surfaces were kept free of mycelium.

COMMENT

Experiment 7

Figure 87: The sample with cut surfaces

Figure 88: Cuts were healing and fruit body was sprouting

AIM
To test the property of self healing and regrowth of mycelium composite.

MANUFACTURING TECHNIQUE: Casting with single-use mould made of Balsa wood of 1 mm thickness.

FUNGAL STRAIN: Oyster mushroom.

SUBSTRATE: Wood-chips and flour

SAMPLE SIZE: 10x10x4 cm

GROWTH PATTERN: Infill

PROCESS
- The sample from the Experiment 2 prepared 2 months back which was in inert state outside the sterile condition was used.
- Two cuts were made on the sample.
- The cut sample was placed inside the laminar under optimal temperature(22.5 degree) and humidity (more than 80%).

OBSERVATION
- After 10days the mycelium started to self heal the cuts.
- Mushroom fruiting was observed to grow in the cuts.

CONCLUSION
- Mycelium regrows and self heals under optimal environmental conditions even outside sterile environment.

COMMENT
Additional nutrition and water was not used.

Experiment 8

Figure 89: The merged sample of two different substrates

Figure 90: The merged sample of same substrate

AIM

To test if we can merge mycelium composite with same or different substrates into a monolithic structure.

MANUFACTURING TECHNIQUE: Casting with mould made of EPS

FUNGAL STRAIN: Oyster mushroom; lion's mane.

SUBSTRATE: Sawdust

SAMPLE SIZE: 10x10x2 cm

GROWTH PATTERN: Infill

PROCESS

- The samples of mycelium composite of Oyster mushroom and Lion's mane on saw dust were casted in moulds.
- After 7 days two samples of Lione's manes were placed above each other.
- After 15 days two samples were placed above each other. One with both samples of Lione's mane and the other with Lione's mane and Oyster mushroom.
- Flour was used as a nutrition source between the two layers.

OBSERVATION

- After 10 days from placing the samples above each other, gradual merging of the two sample into one monolithic structure was observed.

CONCLUSION

- Merging of mycelium composite with different substrates and strains is achievable.

COMMENT

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Experiment 9

Figure 91: Oyster composite with mushrooms

Figure 92: Lion's mane composite with mushroom

AIM
To observe the texture of fruiting body and test if we can control their growth pattern.

MANUFACTURING TECHNIQUE: Casting with mould made of EPS
FUNGAL STRAIN: Oyster mushroom; lion's mane.
SUBSTRATE: Sawdust
SAMPLE SIZE: 10x10x4 cm
GROWTH PATTERN: Infill

PROCESS
- The samples of mycelium composite of Oyster mushroom and Lion's mane on saw dust from Experiment 8 were used.
- The samples were kept inside the laminar under optimal temperature (22.5 degree Celsius) and humidity(above 80%).

OBSERVATION
- After 7 days mushroom fruiting was observed.

CONCLUSION
- Under optimal conditions fruiting of mushrooms is achieved.
- It is possible to play with the pattern of mushroom fruiting through using different strains.

COMMENT

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Interview

Interview 1

WITH: David Andreen

CAREER: Senior lecturer at Department of Architecture and Built Environment, Lund University, Sweden

ABOUT: Article of "Pulp Faction; 3d Printed Material Assemblies Through Microbial Biotransformation" (Goidea, Floudas, & Andréen, 2020)

DURATION: 1 hour

COMMENT: This is not direct and intact quotations but a summary regarding what we understood based on the pre knowledge had been acquired before we did the interview. Therefore any misunderstanding by us might be considered.

Figure 93: Protomycokion (The Editors of Green Product Award, 2021)

PREAMBLE

- He did this project as architect, intuitively. Although they got far, preceding the project further, needs a massive research in microbiology.
- Project started by studying termite and how they do architecture and structures, built in clay.
- The interesting point is symbiosis relationship between termite and certain type of fungus while they are not competitive. (Other strains of fungus are competitive can overtake and eat all source of food) Termites make artificial structure from twig, grass, and wood, and then fungus grows through it, next termite eats from fungus.
- Technically termite 3dprint fungus intro geometry, naturally, which it was taken as point of departure for project.
- The original fungus collected from visiting Africa could not survive in laboratory. So, they worked with another stains. To compare them, two different stains, one white and one brown rot, used. (Brown rot type does not eat lignin but white eat both lignin and cellulose.)
- Keeping environment sterile was nightmare. Small scale worked well but scaling them up consisted of a lot of setbacks: biological, mechanical, timetable for growing – if it kept long it started to decompose and material are useless.
- It is important that material is kept free of any other living organ, but of course it is going to get contaminated during 3d printing process again.
- After that, fungus became strong enough to protect themselves so semi-sterile environment would be enough.
- Some types of moulds coexist with fungi which it is huge problem. Because they grow much faster than fungus and overtake the environments. According to their experience it was the biggest headache took placed.

QUESTIONS

Why did you choose these two strains of fungi? Any specific reason? And why not oyster mushroom which is common?

- *Generally, in these types of research, it tends to want mycelium totally to be replaced with substrates. But they tried to enhance the substrate properties, instead.*
- *Wood relies on continues fibres, but it is not printable. Because they are ground to use in nozzle. So, they instead use mycelium as a glue to join the fibres in 3D p mixture.*
- *They found those two strains close to the condition they wanted to work with but almost random choice.*
- *They focused on proving the concept, with more trial and error. Of course, if you want to work on it to make a building it needs very systematic study of different stains and their quality more biological than architectural.*

In your project you have tested with both white rot and brown rot fungi strains, and you have concluded brown rot fungi is better qualities, but is it indigenous?

- *Colour was out of the scope. Growing was stopped in certain stage, so it did not take over the material, although a bright orange colour popped up.*
- *While they followed a lot of protocols, a lot of variations happened. As architect he could not find triggers.*

How did you arrive at the ratio of the mix and what impact does it have on the material property?

- *A lot of trail and error. Desperately tried to get it from nozzle and prevent clogging.*

- *Idea was larger aggregate gave less shrinkage and less cracking, higher strength, mycelium quality. But, turned out extrusion process got harder, water and the solid got separated due to air pressure of piston.*
- *Paper pulp helped to have more paste like mixture. But recycled paper like cardboard, probably works better.*

What was the base strategy to produce mycelium? What is the main source for mycelium?
Staring in petri dish. You can harvest a lot of amount of mycelium by it.
Liquid in contrast to theory did not work well.

You have mentioned 4 mm is the ideal thickness for the fungal structure to achieve maximum growth resulting in the desired strength. Have you tested these? Is it general to all species of fungi or specific to the strains you used?
- *It was our optimal to make wall stable. Thicker wall means less mycelium. And there was a huge problem with thick wall, took long time to be dried which made issue. Many factors played important roles, and we found it as a good balance for all of them.*

Can you elaborate a bit on the incubation process, as you mentioned you had to incubate the pulp both before and after printing?
- *Heating kills the mycelium.*
- *Mixed all substrate once, add mycelium waiting for two weeks, and then mixed once again.*
- *Changing material in middle of process give the mycelium a shock! It is better to have constant condition and environment for growing. Printing itself is a stress moment.*

Besides clay you have mentioned about another thickening agent. Could you specify its source and use? How does that affect the quality of the material?
- *That is an option. You can spray mycelium but should consider how to distribute it to all surfaces (geometrical issue), while the risk of contamination is getting higher, because mycelium is introduced to new unsterilised condition. Potentially more difficulties to deal with contamination.*

What do you think is not resolved yet and what would you like to rework on if you have to repeat this process again?
- *Highly recommend that set serious protocols for 3d printing and sterilising, have a good laboratory, and an exclusive 3d printer for the project and do not share it.*
- *Biology is complex thing! It is not linear process.*

How would you continue your research further? Are you continuing this research at present?

- *They applied for more found but they have not get it yet.*

We wondered if we could visit Lund university and your laboratory?
- *Not possible due to pandemic. If it gets better, of course, you are so welcome to have a visit.*
- *Working with 3D printer is not one day experience. It takes a couple of weeks to just become familiar with process.*

Can you tell us about 3D printing device you used? Any other suggestions?
- *Mentioned in the article in “Fabricate 2020” magazine.*
- *All clay 3D printers work well.*

How long was the process duration for your work?
- *Started in 2017, summer 2018 it finished. Half a year part time and then a year full-time.*

Interview 2

WITH: Anita Ollar

CAREER: Ph.D. Student at Department of Architecture and Civil Engineering, Chalmers University of Technology, Sweden

ABOUT: Master thesis of "Myco; An Investigation Into Growing Building Materials" (Ollár & Horn-Jardemark, 2015)

DURATION: 45 minutes

COMMENT: This is not direct and intact quotations but a summary regarding what we understood based on the pre knowledge had been acquired before we did the interview. Therefore any misunderstanding by us might be considered.

Figure 94: Myco (Ollár & Horn-Jardemark, 2015)

PREAMBLE

- She did her thesis with another partner in one of the Chalmers laboratory at MC2.
- Case studies and visits to Ecovative in the U.S. and Ecofungi in Malmö proved beneficial to understand the inoculation and growth conditions of the mycelium material.
- The thesis process was initiated by buying a 20x20 cm mycelium brick from Ecofungi and to cut a cross section to observe what is happening inside. It was obvious that the mycelium was seen on the surface and the depth had more saw dust. This raises the question of structural property of the material and its application.
- After working with the material, it was easy to shape and there was a lot of flexibility in shaping the mycelium composite with the moulds.

QUESTIONS

You have mentioned about lignin in your thesis that it is good for strength. Did you test that?

- *The use of lignin as mentioned in the thesis booklet was just a theory based on the discussion with one of the biologists at the lab. It was through his input that lignin in wood is a natural glue and to reach a stronger material it is advised to combine with lignin rich materials.*

How much is it important to know what type of mycelium (species/ strain) to buy/use?

- *Oyster strain has high resistance against green mould, so we decided to go with this strain. It was a criterion for to use a strain that was available and easy to use. It was also not an invasive species in Sweden.*
- *If it must be kept alive, it is necessary to be sure it does not mess with the local biodiversity and the ecosystem itself and does not harm the nature.*
- *A few people in London used Reishi. That is also good in fighting green moulds. But the availability of the strain from Ecofungi in Malmö made it easy to choose oyster mushroom.*

Where to buy liquid mycelium? And how do you think it is better/ worse to use?

- *Liquid mycelium was bought from Ecofungi. It was so stable as it requires a highly sterile space. It was also difficult to figure out the right amount of liquid mycelium to be added on the substrates for inoculation. But inoculated grained from Ecofungi works best.*
- *A mixture of the grains with straw, water and some nutrients are packed in a mould and let to grow.*

Do you necessarily need a laboratory environment for the experiments? Or can it be conducted in studio space but in a sterile/clean environment?

- *A sterile space to grow the material is necessary as it is sensitive. Regular green mould can take over easily. The air around should be sterile and contain right amount of moisture and properly ventilated. Also, to stop the process it should be stopped at the right moment with enough mycelium coverage but not too much.*
- *The lab we worked had a ventilation hood to have a safe environment to grow the samples.*
- *Ecovative had a high-tech lab in their factory with growing chambers to maintain the sterile atmosphere.*
- *Trial and error can be made to see the minimal sterility that is required, with little ventilation and maybe using cotton to filter the air could be an option.*

What worked and what failed in your experiments and process. How do you think you could have done it better if any?

- *Everyone whom they tried to co-operate with was very open and helpful in the process.*

- *The biggest struggle was finding the right environment to grow the materials and conduct experiments but the access to laboratory helped greatly.*

How did you take the thesis research further in your current research?

- *Worked as a research assistant at the HSB (Living Lab) on a small project in creating partition panels for providing sound insulation between the kitchen and living spaces.*
- *Also tested some samples in the Acoustical Lab at the Department of ACE at Chalmers. The mycelium composite material from the saw dust and straw was most promising in acoustics.*

Scripts

Rhino & Grasshopper

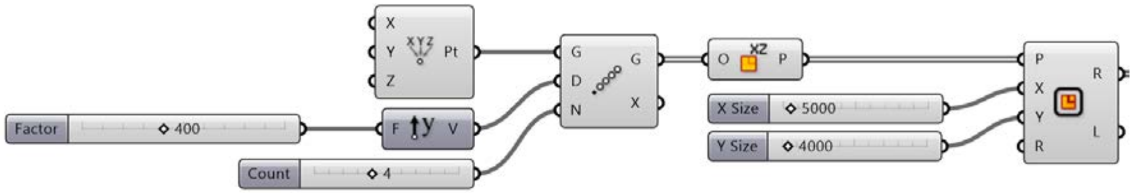

Figure 95: Step 1 - Defining the wall pocket and layers (exterior, core, and interior layers with four surfaces)

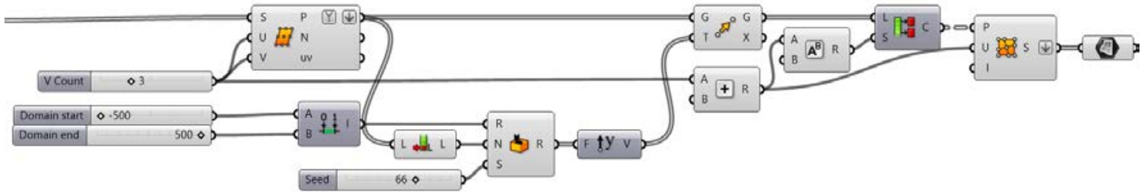

Figure 96: Step 2 - Making distortion on the surfaces

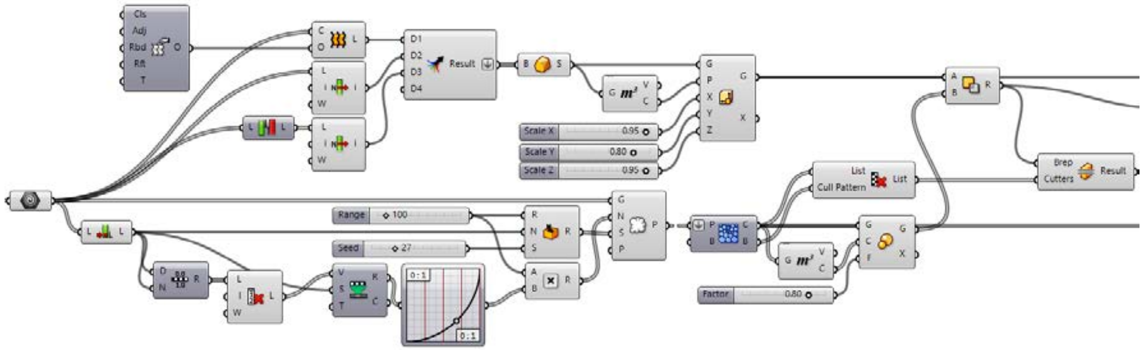

Figure 97: Step 3 - Making the cellular packing and panelling with various sizes of bigger pattern on interior and smaller one on exterior

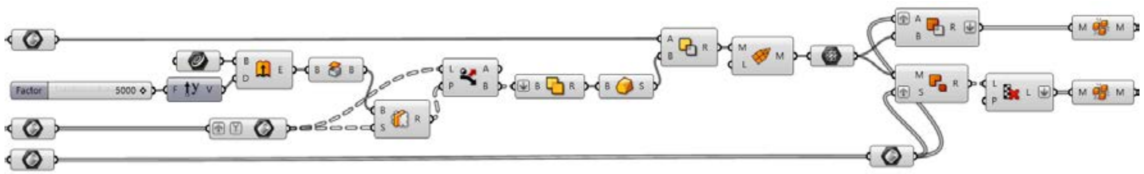

Figure 98: Step 4 - Making fluid wall with an aperture, based on a simple given shape on desire position - Besides making solid and surface moulds


Figure 99: Step 1

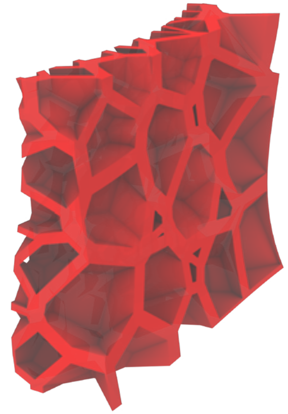
Figure 101: Step 3


Figure 100: Step 2

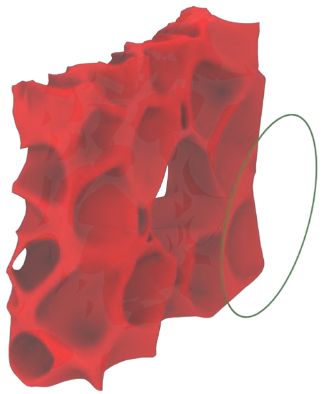
Figure 102: Step 4

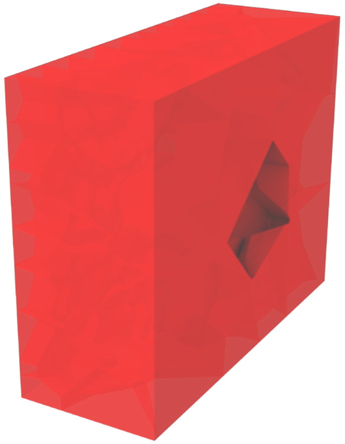

Figure 103: Step 4

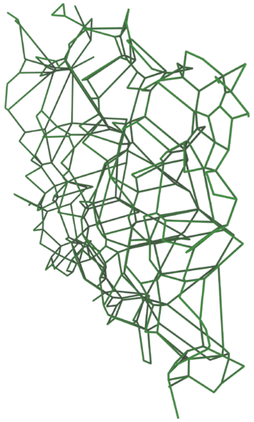

Figure 105: Step 6

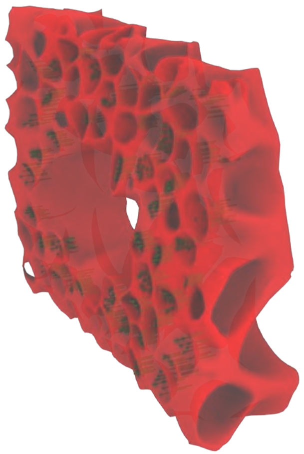

Figure 104: Step 5

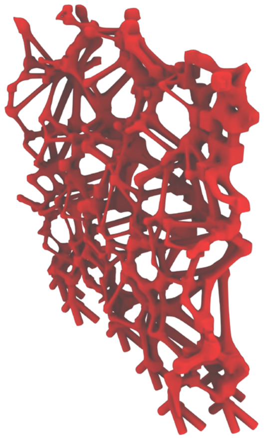

Figure 106: Step 7 & 8

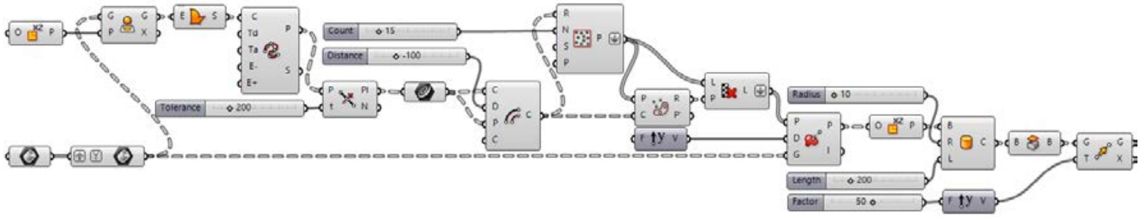

Figure 107 - Step 5 - Making bee houses on selected panels

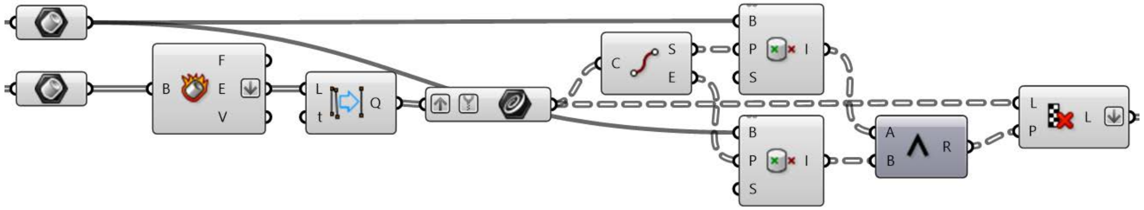

Figure x: Step 108 - Defining cavity elements based on voronoi pattern of the cellular packing

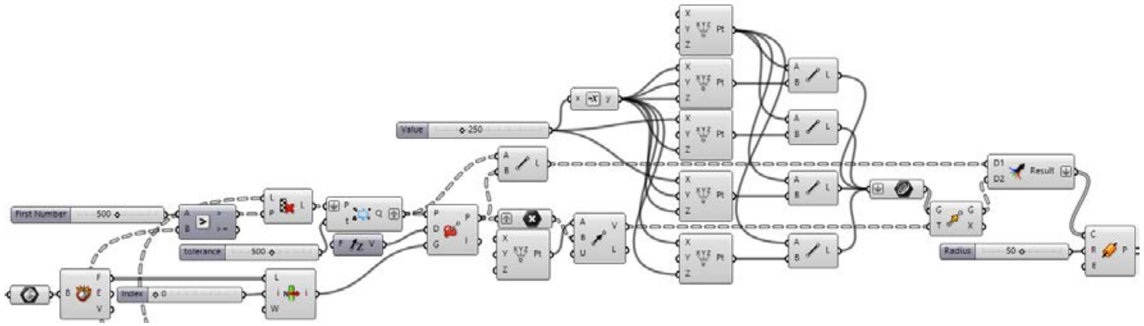

Figure 109: Step 7 - Making the floor joint (extension legs of cavities)

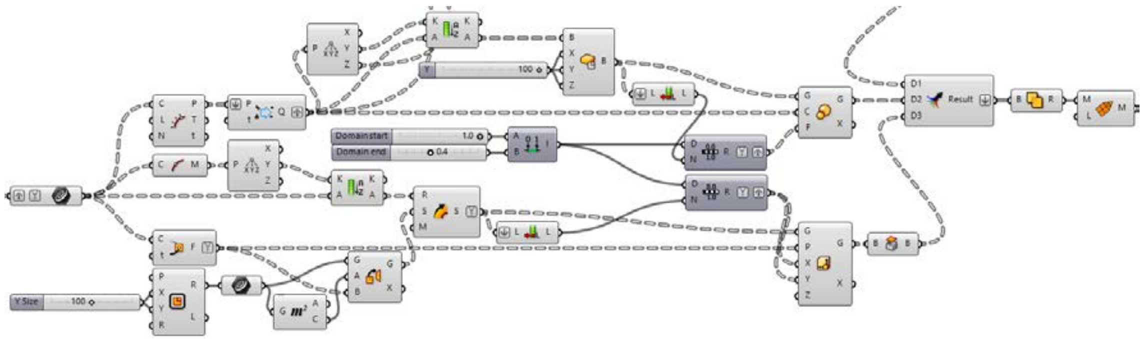

Figure 110: Step 8 - Making cavities with various sizes of thicker and bigger toward interior to thinner and smaller on exterior side

Bibliography

Reference

Anderson, H. (2020). *Mycelium*. MicroscopeMaster. Retrieved February 2nd, 2021, from https://www.microscopemaster.com/mycelium.html

Blanchette, R. A. (2018). Wood Decay: The Action Behind the Polypores. *Fungi Magazine, 11(4),* 10-19. Retrieved February 2nd, 2021, from http://fungimag.com/archives/v11n4_winter_2018-2019.htm

Damery, N. (2021). *ECONOOC*. The James Dyson Foundation. Retrieved February 2nd, 2021, from https://www.jamesdysonaward.org/2020/project/econooc/

Fog, E. (2019a). *Fungi Perfecti mycelium extracts boost bees' immunities*. Save Bee. Retrieved February 14th, 2021 from https://savebees.org/thoughts/fungi-perfecti-mycelium-extracts-boost-bees-immunities/

Fog, E. (2019b). *Offering homes for bees*. Save Bee. Retrieved February 14th, 2021 from https://savebees.org/habitat/homes/

Frearson, A. (2014). Tower of "grown" bio-bricks by The Living opens at MoMA PS1. *Dezeen*. Retrieved February 2nd, 2021, from https://www.dezeen.com/2014/07/01/tower-of-grown-bio-bricks-by-the-living-opens-at-moma-ps1-gallery/

Frearson, A. (2017). Tree-shaped structure shows how mushroom roots could be used to create buildings. *Dezeen*. Retrieved February 2nd, 2021, from https://www.dezeen.com/2017/09/04/mycotree-dirk-hebel-philippe-block-mushroom-mycelium-building-structure-seoul-biennale/

Ghazvinian, A., Farrokhsiar, P., Vieira, F., Pecchia, J., & Gursoy, B. (2019). *Mycelium-Based Bio-Composites For Architecture.* Paper presented at the Architecture in the Age of the 4th Industrial Revolution, Porto, Portugal.

Goidea, A., Floudas, D., & Andréen, D. (2020). Pulp Faction, 3d Printed Material Assemblies Through Microbial Biotransformation. *Fabricate 2020*

Making Resilient Architecture, 42-49. Retrieved January 19th, 2021, from https://www.uclpress.co.uk/products/154646

Harrison, A., Harrison, S., Chen, Y., Kang, D., & Rappaport, B. (2019). *Pollinators Pavilion*. Harrison Atelier. Retrieved February 2nd, 2021, from http://www.harrisonatelier.com/pollinators-pavilion

Harrison, A., Harrison, S., Longoria, D., Gillen, K., Ereskina, V., Beller-Tadiar, L., . . . Kolkau, G. (2016). *The Birds and the Bees Installation*. Harrison Atelier. Retrieved February 2nd, 2021, from http://www.harrisonatelier.com/the-birds-and-the-bees-installation

Harrison, A., Harrison, S., Ullman, S., Javed, A., & Gillen, K. (2016). *The Birds and the Bees*. Harrison Atelier. Retrieved February 2nd, 2021, from http://www.harrisonatelier.com/folly-2016

MacIvor, J. S. (2017). Cavity-nest boxes for solitary bees: a century of design and research. *Apidologie, 48*(3), 311-327. Retrieved from https://doi.org/10.1007/s13592-016-0477-z

Muhammad, H., Ceseracciu, L., Canale, C., Bayer, I. S., Heredia-Guerrero, J. A., & Athanassiou, A. (2017). Advanced Materials From Fungal Mycelium: Fabrication and Tuning of Physical Properties. *Scientific Reports, 7:41292. 10.1038/srep41292*. Retrieved from https://www.researchgate.net/publication/312628939_Advanced_Materials_From_Fungal_Mycelium_Fabrication_and_Tuning_of_Physical_Properties

Ollár, A., & Horn-Jardemark, S. (2015). *Myco - An investigation into growing building materials.* (MSc). Chalmers University of Technology, Gothenburg.

Pallister, J. (2014). 3D-printed mushroom roots "could be used to build houses". *Dezeen*. Retrieved February 2nd, 2021, from https://www.dezeen.com/2014/03/06/movie-eric-klarenbeek-mushroom-roots-fungus-3d-printed-chair/

Pawlyn, M. (2016). *Biomimicry In Architecture* (2nd ed.). Newcastle: RIBA Publishing.

Pownall, A. (2019). Pavilion grown from mycelium acts as pop-up performance space at Dutch Design Week. *Dezeen*. Retrieved February 2nd, 2021, from https://www.dezeen.com/2019/10/29/growing-pavilion-mycelium-dutch-design-week/

Ritchie, H. (2019). *Humans make up just 0.01% of Earth's life – what's the rest?* Our World In Data. Retrieved February 2nd, 2021 from https://ourworldindata.org/life-on-earth

Romare, P. (2014). *All bees are needed – including wild bees*. Lund University. Retrieved February 14th, 2021 from https://www.researchmagazine.lu.se/2014/10/16/all-bees-are-needed-including-wild-bees/

The Editors of Animal Corner. (2020). *Solitary Bees*. Animal Corner. Retrieved February 2nd, 2021, from https://animalcorner.org/animals/solitary-bees/

The Editors of Architecture 2030. (2018). *New Buildings: Embodied Carbon*. Architecture 2030. Retrieved February 2nd, 2021 from https://architecture2030.org/new-buildings-embodied/

The Editors of Central Community College. (2020a). *Bee Mycohotels Presentation*. Central Community College. Retrieved February 2nd, 2021, from https://www.youtube.com/watch?v=zs1CM5vulZI

The Editors of Central Community College. (2020b). *Fungi Fascination*. Central Community College. Retrieved February 2nd, 2021, from https://www.cccneb.edu/alumni-foundation/alumni/community-connection/fall-2020-community-connection/fungi-fascination/

The Editors of Chalmers. (2016). *How many bee species do we have in Sweden and can they live in cities?* Chalmers University of Technology. Retrieved February 14th, 2021 from https://www.chalmers.se/en/departments/ace/research/Urban%20Design%20and%20Planning/Pop_Up_Park_BEE_CONNECTED/Pages/How-many-bee-species-do-we-have-in-Sweden-and-can-they-live-in-cities.aspx

The Editors of Ecovative Design. (2021). *Our Foundry*. ecovativedesign. Retrieved February 2nd, 2021, from https://ecovativedesign.com/ourfoundry

The Editors of Encyclopaedia Britannica. (2017). Pavilion. In *Encyclopedia Britannica*. Retrieved February 15th, 2021, from https://www.britannica.com/art/pavilion-architecture

The Editors of European Parliament. (2019). *What's behind the decline in bees and other pollinators?* European Parliament. Retrieved February 2nd, 2021 from https://www.europarl.europa.eu/news/en/headlines/society/20191129STO67758/what-s-behind-the-decline-in-bees-and-other-pollinators-infographic

The Editors of Fungi Perfecti. (2020). *Give bees a chance with innovative mushroom mycelium solutions*. Fungi Perfecti. Retrieved February 2nd, 2021, from https://fungi.com/pages/bees

The Editors of Green Product Award. (2021). *Protomycokion*. Retrieved February 2nd, 2021, from https://www.gp-award.com/index.php/en/produkte/protomycokion

The Editors of greenpeace. (2021). *Save the Bees*. greenpeace. Retrieved February 2nd, 2021, from https://www.greenpeace.org/usa/sustainable-agriculture/save-the-bees/#:~:text=Honey%20bees%20%E2%80%94%20wild%20and%20domestic,300%20million%20flowers%20each%20day.&text=Seventy%20out%20of%20the%20top,nutrition%20%E2%80%94%20are%20pollinated%20by%20bees

The Editors of Harrison Atelier. (2021). *Pollinators Pavilion*. Harrison Atelier. Retrieved February 2nd, 2021, from https://www.pollinatorspavilion.com/

The Editors of Space10. (2021). *About Bee Home*. Space10. Retrieved February 14th, 2021 from https://www.beehome.design/about/

The Editors of WorldData.info. (2019). *The climate in Sweden*. WorldData.info. Retrieved February 2nd, 2021 from https://www.worlddata.info/europe/sweden/climate.php

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