myco

an investigation into
growing building materials

thesis booklet

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Inoculated oat grains

abstract

The following thesis examines the mass production of materials and building systems which are created through artificial chemical processes. There is a growing need and interest to replace these harmful materials, therefore the thesis investigates the benefits of using biological processes to produce alternative materials.

The thesis focuses particularly on methods of reproducing naturally occurring mycelium, or the vegetative part of fungi, with the aim of producing building materials. Several conclusions were drawn based on the work of individual researchers and designers who have all explored how the binding properties of mycelium to fiber can produce various biocomposites. In addition, these case studies illustrate the need for new tools and knowledge which arise from attempts to bridge the fields of biological science and building technology.

The previous applications of the mycelium material open up a discussion of how the inherent qualities of a biomaterial can better serve the building industry. The production of material samples parallel to conceptual design studies is conducted with the aim to examine the material characteristics of mycelium both as a living and inert bonding agent. More specifically, the research explores how mycelium responds to different types of substrate-mixes which, when combined, can potentially produce a multi-layered material with several properties grown for site-specific environmental conditions. This is reflected upon throughout the thesis in the presentation of hands-on experiments which are contextualized in architectural illustrations.

abstrakt

Följande examensprojekt undersöker hur material och byggnadssystem massproduceras genom artificiella kemiska processer. Utifrån ett växande behov och intresse för alternativ som kan ersätta kemiskt skadliga material, ämnar detta examensprojekt att studera hur ekologiska processer kan användas för att utveckla organiska material.

Projektet fokuserar särskilt på metoder som kan reproducera naturligt förekommande mycel, eller den vegetativa delen hos fungus, med syfte på att producera byggmaterial. Flera slutsatser har dragits baserat på tidigare studier av forskare och formgivare som på olika sätt har utforskat hur de bindande egenskaperna av mycel till fibrer kan generera olika biokompositer. Dessa fallstudier visar också på ett behov av nya verktyg och kunskap som uppstår när områden som biologisk vetenskap och byggnadsteknik sammanfaller.

Vidare diskuteras frågan om hur naturliga material bör användas baserat på dess egenskaper, med referens till de tidigare presenterade tillämpningarna av mycel-baserade material. Genom produktionen av materiella prover parallellt med konceptuella designsketcher undersöks dessutom olika fysiska egenskaper av mycel både i dess levande och inerta form. Mer specifikt testas mycel gentemot ett antal olika substrat-blandningar som, i kombination, potentiellt kan producera ett material med flera enskilda skikten och egenskaper framtaget för specifika miljöer. Denna hypotes tas upp vid flera tillfällen projektet igenom, bland annat i enskilda laboratorieförsök samt i kontextualiserade arkitektoniska skisser.

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introduction

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personal note

Architecture is a product of its time and place. It grows out of the current technological and social conditions, closely monitoring the steps and changes of culture. Avant-garde art and architecture can thus be seen as a response, or a reaction, to the existing patterns of society - as the front-line of human philosophy and exploration. For this reason it is more seriously considered as a source of inspiration and guidance in times of pressure, when innovative ideas are being developed and tested. Yet, in representing ideas ahead of their time, the radical often remains in theory, to be revived and criticized by following generations. It is when these projects are materialized and placed in the human context, that society at large is physically and socially confronted by these ideas, and forced to respond to them.

introduction

New approaches to environmentally responsive architecture explore how the properties of living systems can create more efficient construction materials. This new wave of research challenges embedded cultural notions of nature and architecture by suggesting that our current mode of production is tied to an industrial paradigm, which is too focused on the end product rather than the processes which go into making it. Moreover, rather than concerning ourselves with replications of the form and function of sophisticated natural systems, these systems should be viewed as a technology in themselves.[1]

Although advances in applied technologies and automated information systems have soared in recent decades, the materials which are used to construct these systems remain comparatively antiquated: We continue to process material with a top-down approach, whereby available technology is used to create a desired material performance. This currently requires huge amounts of energy and toxic chemicals, which results largely in dead products with no further use beyond their intended and often brief life span.[2] In contrast, the technology of nature deals with matter which is active and has the potential to self-organize, transform waste into nutrients and heal itself.

The following research project investigates an emergence of material research which studies the biological growth of naturally occurring mycelium. Rather than the industrialized chemistry and physical transportation of large quantities of material,[3] the following discussion presents a method where a material is grown and guided throughout its development. When combined with natural fiber, the mycelium acts as a natural binding agent producing a solid, biodegradable composite.

The motive of this thesis is grounded in the current demands of environmental /ecological material as well as advances in biological research. This has come largely from medicine and agriculture, where by-products are being used as a supply source of raw material at industrial scales. This field of material innovation offers added economic value to products previously considered as waste, supporting the development of an ecological economy. Secondly, the application of new biocomposite materials demands the interdisciplinary collaboration between architecture, ecology and material science, changing the way we approach future design. With increasing knowledge of our material world and its chemical processes, new levels of engagement are required of the designer. Rather than design for permanence and the resistance of time, architecture may choose to engage with its natural temporarilty, where a cyclical growth and decay of the material are incorporated as part of the plan.

[1] Andreotti, A., 2013. Interview - Rachel Armstrong, Innovative Scientist Who Wants to Grow Architecture. *Next Nature.* http://www.nextnature.net/2013/07/interview-rachel-armstrong-innovative-scientist-who-wants-to-grow-architecture/#comments (Accessed 15/12/2014).
[2] Spiller, N., Digital Solipsism and the Paradox of the Great "Forgetting". *Architectural Design*, vol. 80, no. 4 (2010): 133.
[3] Khan, O., An Architectural Chemistry. *Architectural Design*, vol. 81, no. 2 (2011): 52.

Pleurotus Ostreatus
mycelium is the reproductive cell structure of the fungal fruiting body.

thesis question

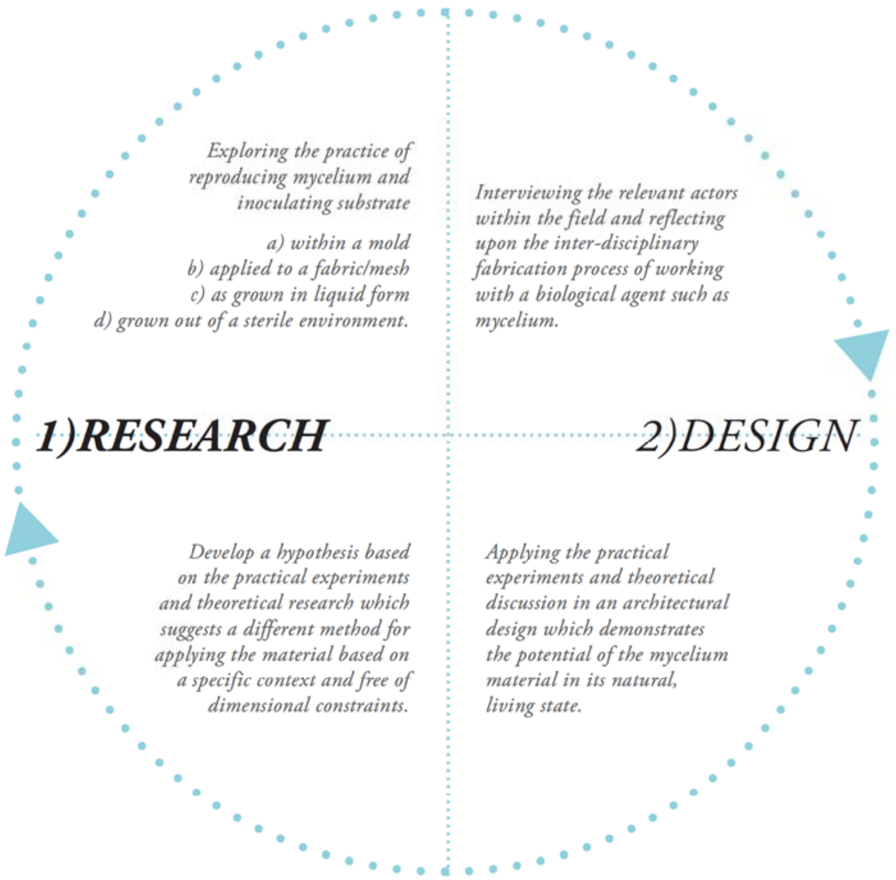
Can previous studies on mycelium as an inert material, coupled with practical experiments of our own, allow us to apply mycelium in its living state in an architectural context?

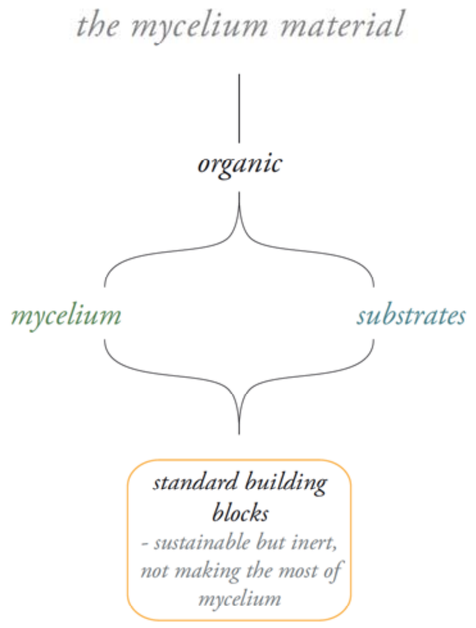
methodology

Previous explorations into the production of mycological materials have largely been concerned with its structural properties as an inert building block. The most developed method to date involves enclosing the mycelia within a mold, combined with a fibrous material, ensuring it grows to a designated shape. Once the mycelium reaches its fruiting stage - where it would normally produce a fruiting body (mushroom) - it is taken out of the mold and heat treated to halt the growth process. As a result the fiber is no longer loose; most of it has been transformed into hyphae while the undigested remains are held together by the, now inert, mycelium.[4] This results in a solid biocomposite material with a varying density depending on a number of environmental conditions.

While we have practiced this method throughout the thesis in order to learn about the process of growing the material, we have further explored an approach which diverts from the conventional method: Instead of creating inert blocks through molding the material, we suggest a new application technique of the mycelium composite in its living state in an architectural context.

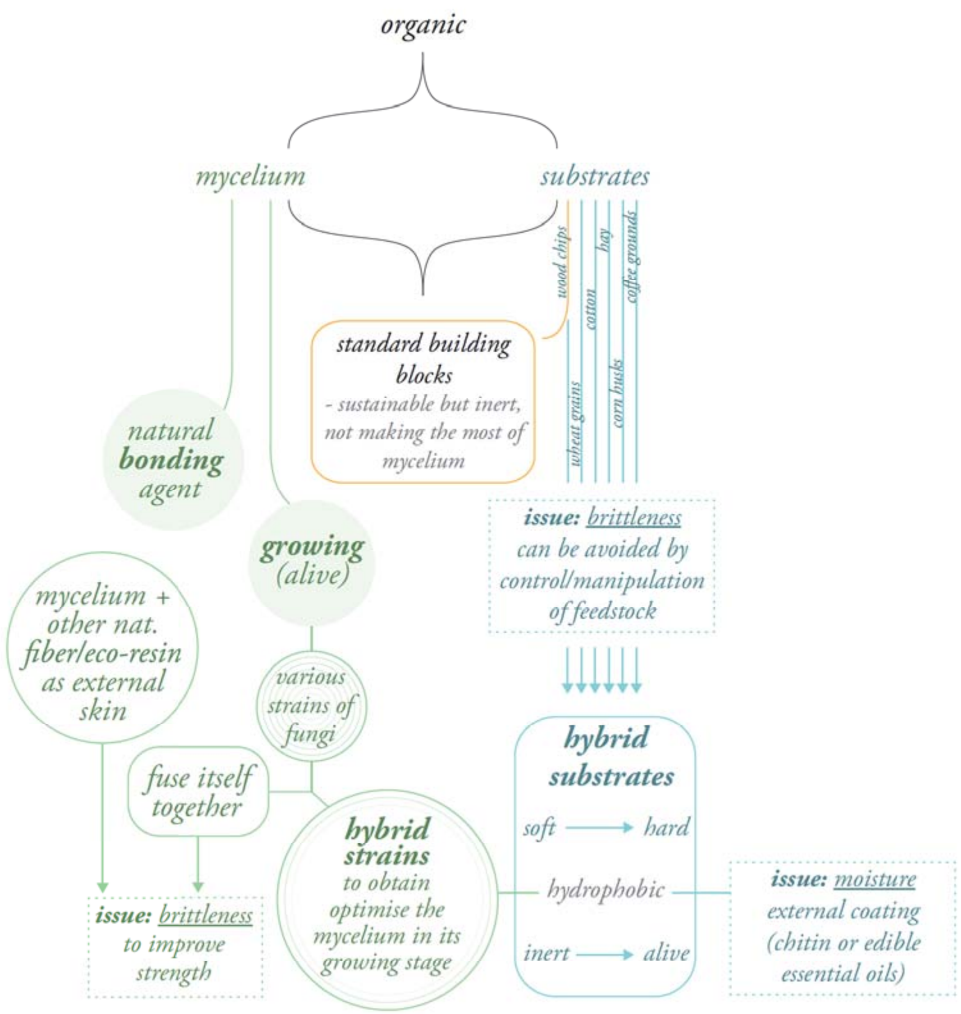
[4] Dharan, CKH., Noble, J., Ross, P., and Travaglini, S., Mycology Matrix Composites. *American Society for Composites - Twenty-Eighth Technical Conference*, no. 1 (2013): 1-20. http://www.mycoworks.com/wp-content/uploads/2014/04/UC-Berkeley-Mycology-Matrix-Composites-ASC-Conference-Paper-13-May-2013-2.pdf (Accessed 10/01/2015).

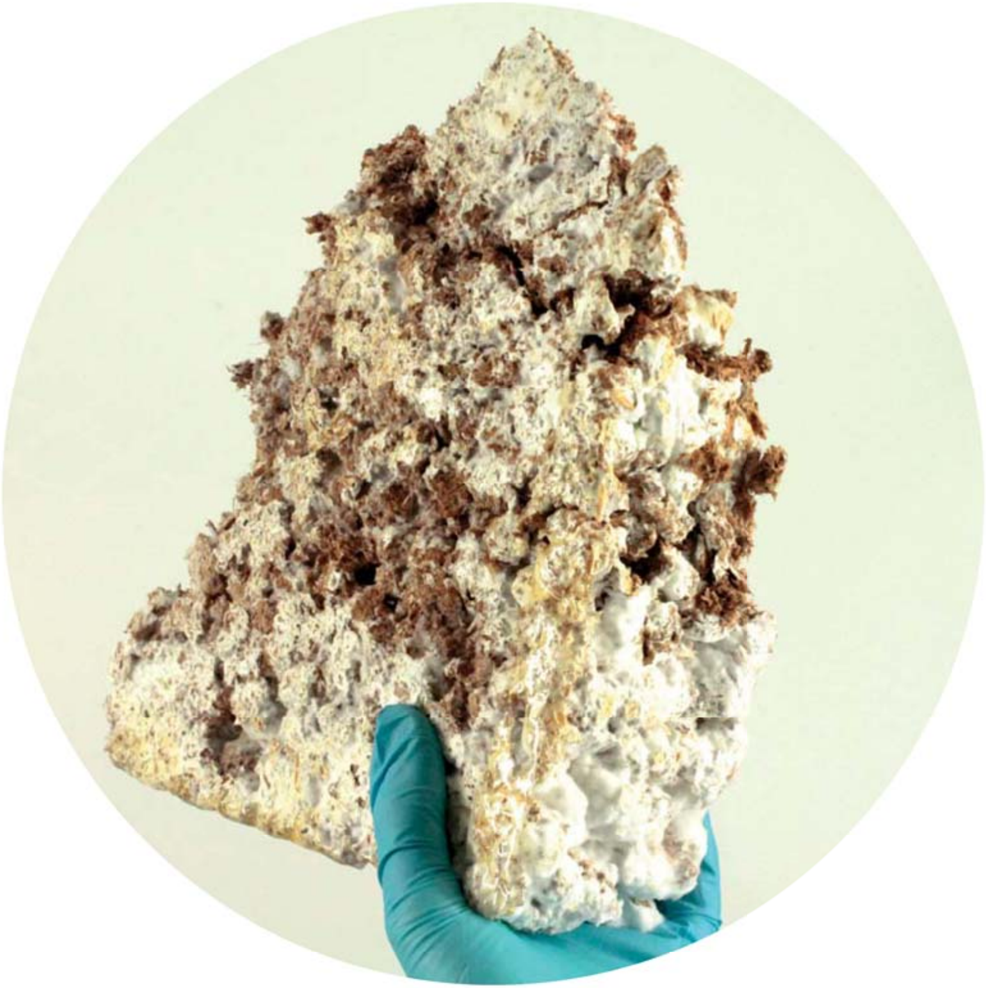




Above: The diagram illustrates how previous applications of mycological composites have been fabricated through a simple method for the purpose of producing solid blocks comparable to polymer foams.

Opposite page: The diagram shows the many areas within the fabrication of mycological composites which are yet to be studied, suggesting that the material can exhibit a variety of qualities which have not been researched.





Inoculated sawdust

delimitation

For the sake of this research project, we discussed, but did not attempt to prove that artificially derived materials are harmful to human health. We would like to emphasize that this project is rather an investigation into biological processes which can provide alternative choices for architectural issues.

Furthermore, inspired by the *Cradle to Cradle* vision[5], we believe that sustainable materials must account for all of the energy and resources which are required to extract the material from earth. The thesis reinforces this statement by going beyond a general exploration of biological production for architecture, and presenting a specific architectural scenario where naturally occurring mycelium is used to grow a material. These scenarios are presented in a natural environment, in the original habitat of the chosen mycelium strain, where the material potentially performs at its best.

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[5] Braungart M and McDonough W., *Cradle to Cradle*. New York: North Point Press, 2002.

result

Through conducted experiments and literature research we learned the procedures required to grow a mycelium based composite material.

Our aim was to reflect upon the scientific findings and theoretical studies, add to this body of research, as well as illustrate the possibilities of the mycelium material in an architectural context. The studied material properties and production methods have driven the framework of our hypothesis for a new application method of the material. This strategy advances one step further than the currently known* implementation methods by exploring a new way of fabrication based on lignin.

Compared to the previously tested molding technique performed inside the ventilated hood in the laboratory, our proposal suggests an in-situ spraying solution where the mixture is applied to a net mesh. The addition of lignin adds stickiness to the mixture which should help the substrate and mycelium to attach to the reinforcing mesh-structure. The mycelium is sprayed on whereby it is left to grow 'free-form', bonding the substrate to the mesh.

The developed hypothesis revolves around the qualities which lignin brings to the mixture, as well as how mycelium can be applied in its living state. While further investigation would be needed to actually test this proposal, it is based on research acquired through consultations and previously published studies. Furthermore, the design structures along the hiking trail *(as shown on page 117.)* are mere illustrations of four envisioned scenarios - a part of the overall application method - exhibiting how a material can both serve human and environmental needs.

**Based on our research.*

Material samples

reading instructions

Part one:
Introduction - Background
An overview of the thesis and a discussion around the main issues of our current use of artificial materials.

page 13 - 41.

Part two:
Plant-based
An introduction to biomaterials as well as a discussion around the growing market of biocomposite materials. This is followed by an explanation of mycelium and its potential applications.

page 45 - 63.

Part three:
Bio-production
Discussion around the opportunities of designers, engineers and architects walking alongside each other and what it actually means to grow a material.

page 65 - 97.

Part four:
Application
Introduction to the conceptual context where the proposed method of application is illustrated.

page 99 - 159.

Material sample with coffee grounds substrate

chapter II:
background

A Brief History of Material Science
Chemical Compounds

About plastic

Plastic is an extremely cheap and versatile material which has revolutionized the material industry. It can be processed in many different ways achieving a wide range of material properties, which is why it is so widely used in practically all industrial sectors. In addition, plastics are based on petroleum. The petroleum industry is receiving government subsidies which keep the production costs down and our dependency on plastic products up. With such a fast and inexpensive manufacturing process, it is difficult to argue for more sustainable alternative materials from an economic point of view.[6]

[6] Jacobsen, M., 2015. How You Can Help Companies Switch to Sustainable Packaging. *Ecovative Design Blog*. March 19. http://blog.ecovativedesign.com/2015/03/19/how-you-can-help-companies-switch-to-sustainable-packaging/ (Accessed 15/05/2015).

a brief history of material science

Prehistoric findings show evidence of our early determination to develop stronger and more durable materials. A progressive use of increasingly sophisticated tools allowed us to advance from the adaptation of existing objects, to mixing components, such as mud and straw to make brick. This was further developed in the metallurgy of the Iron Age[7]. The employment of structural concrete during the Roman Empire, more than two thousand years ago, made a significant leap in material science and our ability to manufacture at an industrial scale.[8]

The development of the glass lens and its scientific application in 16th century Netherlands revealed a scale of molecular construction beyond what was visible to the eye.[9] Yet, it was not until the 19th century that scientists established a fundamental understanding of the atomic structure and its direct relationship to the thermal and physical properties of material compounds.[10] The lens allowed us to see the molecular bonds in material, and investigate how one could recreate these links to fuse various elements and create new material composites.

This self-fueling industry has created vast families of plastics, semiconductors and biomaterials.[11] The demand for such technologies rapidly increased during the periods of war in the early 20th century.

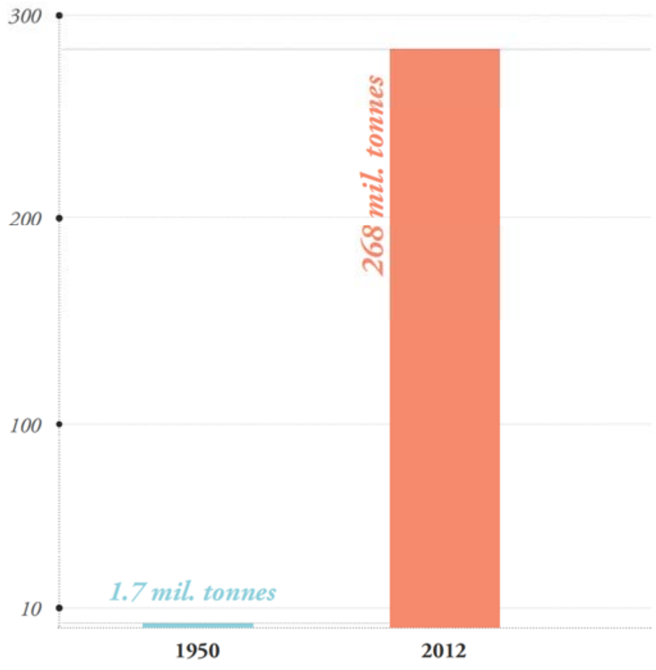
[7] Hummel, R., *Understanding of Material Science: History, Properties, Application*. New York: Springer-Verlag (2004), 4.
[8] Iowamoto, L., Line Array: Protocells as Dynamic Structure. *Architectural Design*, vol. 81, no. 2, (2011):115.
[9] Cahn, R.W., Precursors of Material Science, in *The Coming of Material Science*, Oxford: Pergamon Publishers, 2001, 57.
[10] Ibid., 59.
[11] Smith, C.S. M. Kranzberg, Materials and Society, in *Materials and Man's Needs: The History, Scope and Nature of Material Science and Engineering*, vol. 1, Wahington D.C: National Academy of Sciences, 1975, 50.

The military industry drove the frontier of chemical research and its technological application, creating a new industrial platform for design and innovation. The domestic application of these material technologies improved the living standards radically and nurtured a post-war design language born out of a desire to embrace a future of technical transformation.[12]

[12] Braungart M and McDonough W., *Cradle to Cradle*. New York: North Point Press, 2002, 37.

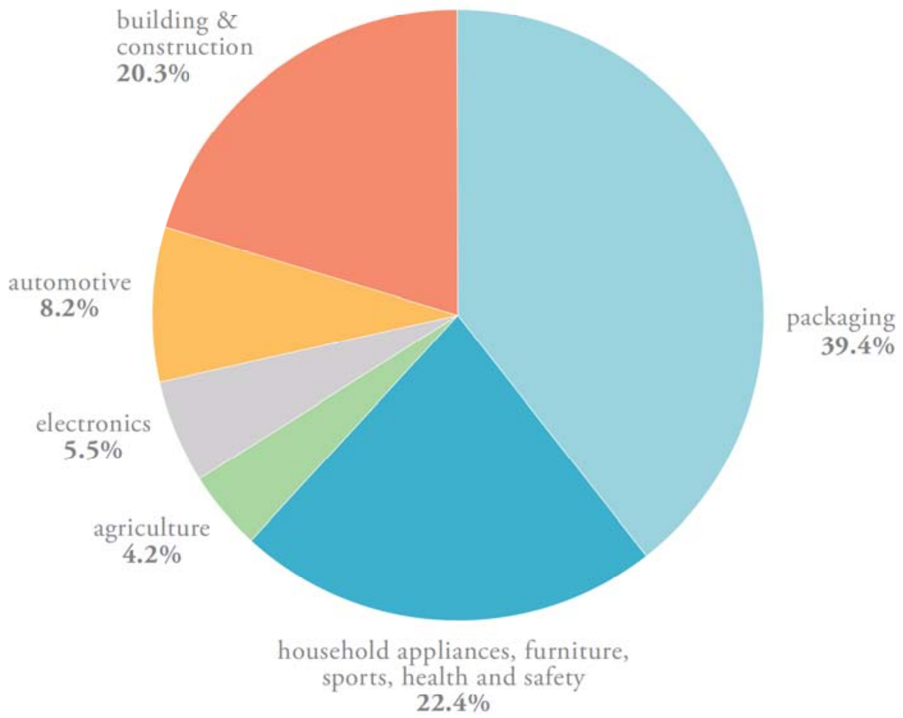
Image 01: *Ludwig Mies van der Rohe - Farnsworth house*

World Plastic Production*



Not including PET-, PA-, and polyacrylic-fibers.
Based on text by Engelsman, S., Peters, S., and Spalding, V., Plastics in Architecture and Construction, Basel: Birkhäuser GmbH, 2010.

European Plastic Demand in 2012



Adapted from: Plastic Europe: Plastics – the Facts 2012. 2012. http://www.plasticseurope.org/Document/plastics-the-facts-2012.aspx?FolID=2 (Accessed 07/04/2015).

chemical compounds

Our ability to understand potential health threats at a molecular level has on the other hand awakened a growing apprehension of our built environment. Architect William McDonough and chemist Michael Braungart, who collaboratively released the book Cradle to Cradle, shed light on the reality that our modern industry is using increasingly less natural material;

"to make an attractive product affordable which also performs well, one must turn to artificial substances."[13]

Braungart further expresses his concern for a design practice now aimed at creating highly energy efficient buildings: what we end up with is an air tight shell which traps chemicals and dust.[14] Let us look at the production of synthetic polymers for example, which occur through a chemical reaction called 'polymerization'. This process can result in leftover material, or residual monomers, and although these by-products are not bound to the polymer, they often 'hang on' to it.[15] Off-gassing, or chemicals being released from building products, has a substantial effect on the interior environment and can cause allergies and skin irritations.*

"out of the approximately eighty thousand defined chemical substances and technical mixtures being used, only about three thousand so far have been studied for their effects on living systems."[16]

* *In Denmark, the air quality is generally six to seven times worse inside buildings than outside. More disturbingly, the current industry is not conducting thorough investigations into the production compounds. Brangart and McDonough.,*

[13] Ibid., 42.

[14] Ibid., 38.

[15] Berge, B., Butters, C. and Henley, F. (trans.). The chemical and physical properties of building materials. In *The Ecology of Building Materials.* 2nd ed. Oxford: Elsevier Ltd., 2009, 59.

[16] Braungart and McDonough, 42.

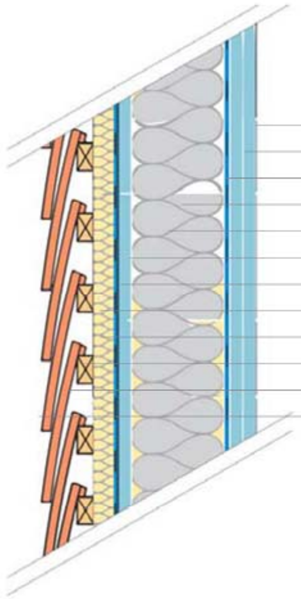
Although these fabrication methods have allowed us to efficiently produce materials at an industrial scale, we are taking a risk using chemicals which we do not understand the full effect of. Furthermore, there is the long-term issue of environmental contamination caused by material waste: Some of the most disposable materials used, such as expanded polystyrene foam or fiber-reinforced plastics, have an incredibly slow decomposition rate of 100, 000 years or more.[17] As a consequence, composite materials pile up in landfills and water reserves around the world. While some are burned in purifying incinerators, studies indicate leakage of compounds such as hydrogen chloride and heavy metals.[18]

In addition, current building methods help to perpetuate an industry which is largely focused on developing materials with task-specific physical properties. In the typical wall section *(illustrated on page 40)* we can identify twelve layers of materials, or eight if we include the pure timber elements as one. Aside from the timber frame, all of the components contain materials derived from metals, fossil fuels or artificial chemical substances. Technological developments are layered upon this simple construction element to provide optimal performance for a variety of different areas; structural, thermal, acoustic, fire retarding, finishing, weather proofing. However some of these elements are potential irritants and carcinogens when released into the air. In fact we have come so far in recent decades, simply in our understanding of the benefits of these systems, that we championed the energy saving value of the products above the scrutiny of their make-up.

[17] Bayer, E., Are Mushrooms the New Plastics? New York: TED Talk. 2010. http://www.ted.com/talks/eben_bayer_are_mushrooms_the_new_plastic?language=en

[18] Berge., 31.

a standard wall section



material		*quantity*	*weight*	*CO^2 footprint*	*recyclable*
01. Paint	01.	7 L	7 kg	3.5 kg per kg =24.5 kg	no
02. Plasterboard 2x12.5mm	02.	60 m2	498 kg	0.38 kg per kg =189 kg	yes
03. Vapour barrier (30m2)	03.	**0.03 m3**	**29 kg**	**1.9 kg per kg =55.1 kg**	**no**
04. 180mm mineral wool insulation	04.	**5.4 m3**	**243 kg**	**1.05 kg per kg =255 kg**	**yes**
05. Timber framing 184x35mm (90 l/m)	05.	0.58 m3	295 kg	0.46 kg per kg =135.7 kg	yes
06. 12-18mm OSB boarding (30m2)	06.	0.54 m3	405 kg	0.5 kg per kg = 202.5 kg	yes
07. Breathable membrane (30m2)	07.	0.03 m3	29 kg	1.9 kg per kg =55.1 kg	no
08. 50mm mineral wool insulation	08.	1.5 m3	67.5 kg	1.05 kg per kg =71 kg	yes
09. 50mm timber framing (90 l/m)	09.	0.2 m3	102 kg	0.46 kg per kg =47 kg	yes
10. 30x30mm timber battens (170 l/m)	10.	0.15 m3	77 kg	0.46 kg per kg =35 kg	yes
11. 200mm horizontal timber cladding boards (60m2)	11.	1.2 m3	612 kg	0.46 kg per kg =281 kg	yes
12. Paint	12.	7 L	7 L	3.5 kg per kg =24.5 kg	no
		total	*2371.5 kg*	*1375.4 kg*	

Looking specifically at insulation, for example, which is a product often made from fiberglass or rock wool: While made largely from recycled or industrial waste material, they are non-renewable materials with barely any post-use recycling systems in place. As a product which is out of sight, cheaply produced and required on large scales, it seems to receive less attention in discussions on sustainable building.[19]

[19] Berge., 242.

Vapour barriers, aluminum and paper or polyethylene based sheet material inserted to protect the structure assembly from moisture, is a product which is often entirely produced from non-renewable materials: Aluminum has a large amount of embodied energy and polyethylene is harmful for the indoor air quality. Adhesives and sealants used to install vapour barriers also provide potential risks.[20] Due to contact with pollutant substances recyclable materials drench dangerous ingredients, which may compromise future reuse.

[20] Berge., 245.

chapter III:
plant-based materials

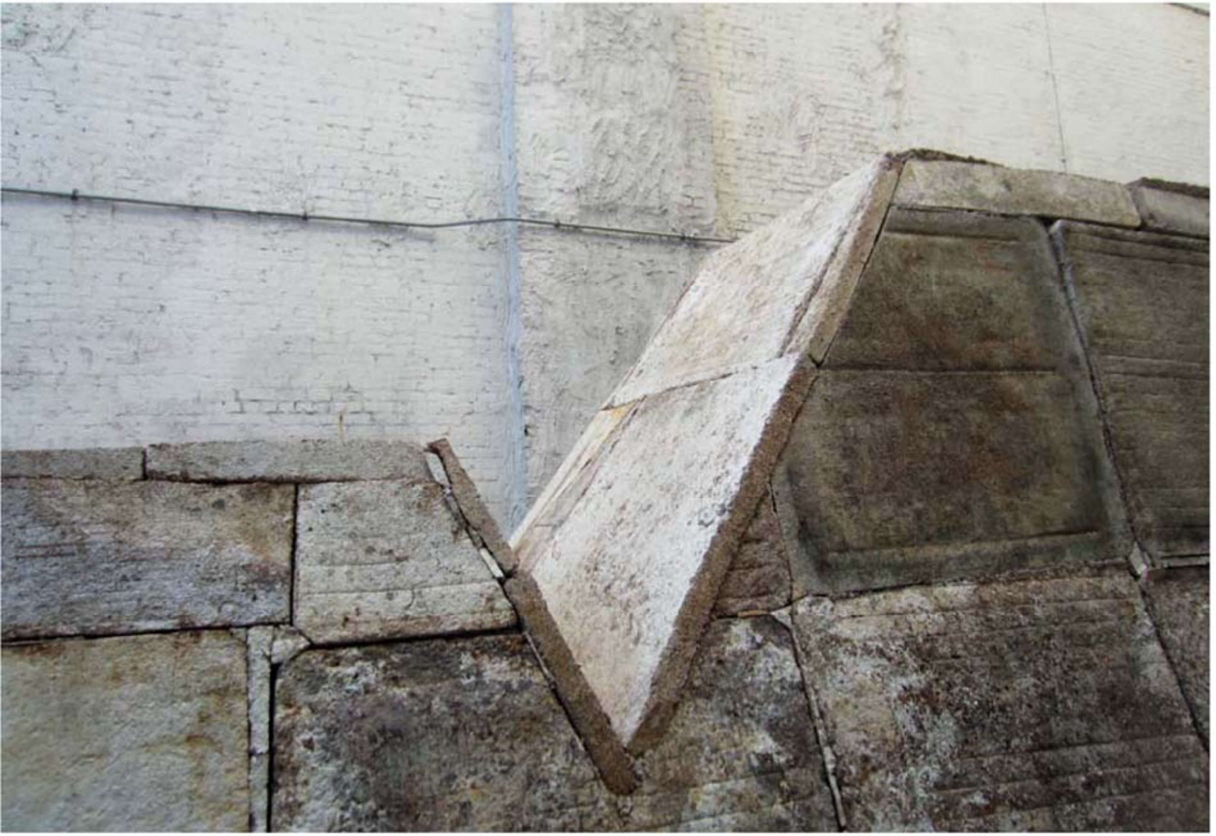


***Image 02:** 'The Accelerated Ruin' - A collaboration between Future Expansion Architects, painter Timothy Hull and Ecovative Design.*

architecture and its surfaces

Steel and plastics were introduced on the market around one and a half centuries ago, revolutionizing the building industry. Ever since, minerals and fossil oils have come to dominate composite materials. People have come to associate sleek austerity with newness and hygiene, preferring chemically processed materials to their organic counterparts. In reality, timber is still the most efficient material applied in construction, exhibiting qualities of lightness and strength. In fact, it is actually a more hygienic option to, for example, stainless steel; the growth of bacteria is lower on timber boards.[21]

There is, however, a stigma associated with natural products which can be traced back to a fear of dirt and diseases, as well as a remnant of the post-war desire to cut clean from the past. While busy clearing the path of debris following two World Wars, we developed "clinical" living environments which implied that the outside [nature] was a nonhuman, harmful place.[22] The evolution of our own hygiene has stepped us further from the natural world, with ever increasing expectations of cleanliness.[23] Despite this condition, architects still have an inherent desire to engage with the nature. This is reflected in our continuous misappropriation of architectural terms, such as 'raw' and 'organic', when describing an artificially produced environment.[24]

With non-renewable resources becoming increasingly scarce, and the raw material subsequently more difficult and expensive to extract, let us re-consider the benefits of naturally grown plant-based materials.

[21] Berge., p.157.
[22] Gissen, D., *Subnature: Architecture's Other Environment*. New York: Princeton Architectural Press, 2009, 211.
[23] White, M., 99.7 Per Cent Pure. *Architectural Design*, vol. 79, no. 3 (2009): 20.
[24] Gissen., 210.

common plant-based materials in the building industry:

Softwood and hardwood	Structures; wall cladding; flooring; roof coverings; windows and doors; pins and bolts; thermal insulation; fibers; cellulose; chemicals
Straw and grass	Roof covering; wall cladding; thermal insulation; minor structures; cellulose; chemicals
Grass turf	Roof covering; minor structures
Moss	Thermal insulation; joint sealant
Peat turf	Thermal insulation
Acetic acid	Disinfectant; bioplastics
Cellulose	Thermal insulation; sound insulation; paper products for wind proofing; wallpapers
Fatty acids	Paints; varnishes; adhesives; soap treatments; bioplastics
Fiber	Thermal insulation; sound insulation; building boards for cladding, underlay, wind proofing, vapour retarders etc.; reinforcement in concretes, plasters and biocomposites; sealing of joints; carpets
Lignin	Adhesives; additive in concretes; bioplastics
Methanol	Adhesives; paints; varnishes; bioplastics
Potash	Glass production; potassium water-glass
Silicates	Pozzolana in cements
Starch	Adhesives; paints; bioplastics
Turpentine	Solvent in paints and adhesives

Above: Information from The Ecology of Building Materials by B. Berge, 157-158.

Not only are they low in embodied energy and usually easy to transport; the distance which plants generally have to travel, from harvest to processing, is relatively short. In addition, plant-based materials often involve sustainable cultivation methods and non-toxic manufacturing.[25]

A relevant question for the building industry is: whether these materials could change the way we build? Not returning to primitive modes of fabrication, but developing more efficient systems altogether based on our current understanding of the chemical processes in ecology. The aesthetic outcome of such products would be relative to the performance of the system, similar to how a certain type of aggregate produces a certain quality of concrete.[26] Rather than forcing materials through an artificial process of production to fit predetermined demands, we could move towards a process based on co-design: Working for aesthetics which reflect the inherent properties of the material as well as shaping natural substrates to fit aesthetic preferences.

[25] Berge.,159
[26] Andreotti, A., 2013. Interview - Rachel Armstrong, Innovative Scientist Who Wants to Grow Architecture. *Next Nature.* (Accessed 15/12/2014).

***Image 03:** Wood from Victorian mountain ash*

biomaterials

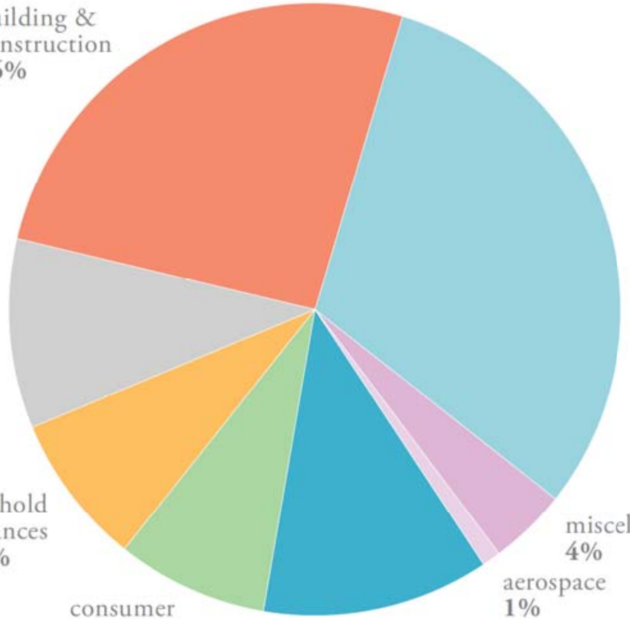
'Biomaterial' is a general term for materials which change or can be produced through biological systems. The term is commonly associated with the medical industry, however, it is being used more frequently in the general design community: Designers at all scales are investigating the use of biomaterials.[27] Within the construction industry, timber is a biomaterial which is already well understood and utilized as a structural and lining material.

Timber is one of the most versatile and widely used building materials today. It can be grown relatively quickly, processed with low-tech machinery and used for structural, exterior cladding, interior lining and insulation purposes. Furthermore, it is often locally manufactured and minimal to no toxins are used in many general purpose timber products. Engineered timber products are also advancing rapidly and providing structural solutions to compete with steel fabrication systems. Timber treatment methods are developing and we are seeing products such as *Accoya* which guarantees a forty-year life cycle for a product which can be grown in ten years.[28]

The global timber market is struggling however, to maintain environmental standards which guarantee timber products which are sustainably forested. Unlicensed deforestation threatens delicate ecosystems around the world. For this reason, the Forestry Stewardship Council (FSC)[29] has set an international benchmark for sustainable timber products. There is a debate over the regulation of this standard, and the timber industry which is still marred by

[27] Peters, S., *Material Revolution: Sustainable and Multi-purpose Materials for Design and Architecture*, Basel: Birkhäuser GmbH, 2013, 30.
[28] Accoya - Modified Wood by Accsyas Technologies: Creating the World's Leading Acetylated Wood. 2014. http://www.accoya.com/acetylated-wood/ (Accessed 03/01/2015).
[29] FSC Sweden: FSC:s betydelse. 2012. https://se.fsc.org/fscs-betydelse.191.htm (Accessed 03/01/2015)

Current Use of Fiber-reinforced Polymers



Adapted from: Natural Fibers, Biopolymers, and Biocomposites by Mohanty, A. K., 5.

corruption and black market trade, has a way to go before it provides truly sustainable building materials. Even so, the clear environmental benefits of timber over competing products have sparked an interest for research into biomaterials. The emerging field of science and engineering is further fueled by the environmental and economic interest in a low-carbon material industry: In the last couple of decades, investments into biofiber-reinforced composite materials have put new value on agricultural by-products, previously considered waste. As the demand for renewable resources is rising, the market of biomaterials is only expected to grow.[30]

biocomposites

A 'composite' is a material which is comprised of two or more substances. Similar to how artificial composite materials are tailored for specific applications, natural polymers and fibers can be combined to achieve equal properties.[31] The low embodied energy of biocomposite materials offers significant potential benefit for reducing the environmental impact of building products: The growth of a plant takes carbon dioxide from the air and traps it as biomass, this demonstrates the potential for biomaterials to be an effective method of carbon sequestration. Furthermore, the opportunity of using fiber from local environment, agriculture and industry,* presents a scenario where the traveling distance of a material can be minimized. Perhaps it may even encourage an awareness for local materiality and its origin.

* *Ranging from wheat straw, corn husk, flaxseed, wood fibers, etc.*

[30] Mohanty, A. K., Misra, M. and Drzal, L. T. (eds.) *Natural Fibers, Biopolymers, and Biocomposites.* Boca Raton: CRC Press, 2005, 6.

[31] Ibid., 4.

The basic principle of biocomposite materials; a polymer matrix holds the reinforcing biofibers together.

However, most of the biocomposite materials which are presently available on the market are not 100% bio-based.[32] On the contrary, the material is often reinforced with natural fiber whilst the polymer matrix is often petroleum or cement-based, resulting in a hybrid composite. While the conversion from synthetic composites to biocomposites is indeed a complex process which requires interest and financial investments from a range of different industries, all-natural biocomposites have many advantages: Their cost-efficiency, low density coupled with adequate strength and flexibility, chemical versatility not to mention their ability to biodegrade, makes them attractive alternatives to their synthetic counterpart.[33] Biodegradability is a particularly important issue for future sustainable development. In response to the recycling composite materials where the intertwining of substances is difficult to separate, the best solution is for the product to be entirely compostable.

[32] Ibid., 2.
[33] Berge., 161.

Inoculated coffee grounds

mycelium: a living polymer

The fine cell structure of fungi, called mycelium, can digest a variety of organic fiber, acting as a bonding agent holding the substrate together. The natural gluing properties of mycelium can produce a biocomposite material which is fully compostable; the material actually supports the local ecosystem in adding nutrition to the soil as it degenerates.[34]

The mycelium material further exhibits structural properties comparable to expanded polystyrene foam which indicate that the mycelium fiber could serve as a replacement for the polymers that are required in the plastic industry. As opposed to other bioplastics, however, which are based on sugarcane and corn starch, mycelium does not depend on photosynthesis to grow. On the contrary, mycelium is hardly affected by natural light and can easily be reproduced indoors at room temperature of 22 °C.[35] Mycelium is therefore a relevant alternative for northern countries with low level of annual sunlight. Moreover, due to its high growth rates and non-toxicity, mycelium should be considered in response to the growing demand for local production in urban areas, where fabrication could occur in underground laboratories or in unused spaces throughout the city.

[34] U.S Patent Documents. Ecovative Design, LLC: Method for producing rapidly renewable chitinous material using fungal fruiting bodies and product made thereby. 2011. http://www.patentgenius.com/patent/8001719.html (Accessed 09/02/2015).
[35] Ibid.

Image 04: *Mycelium*

morphology

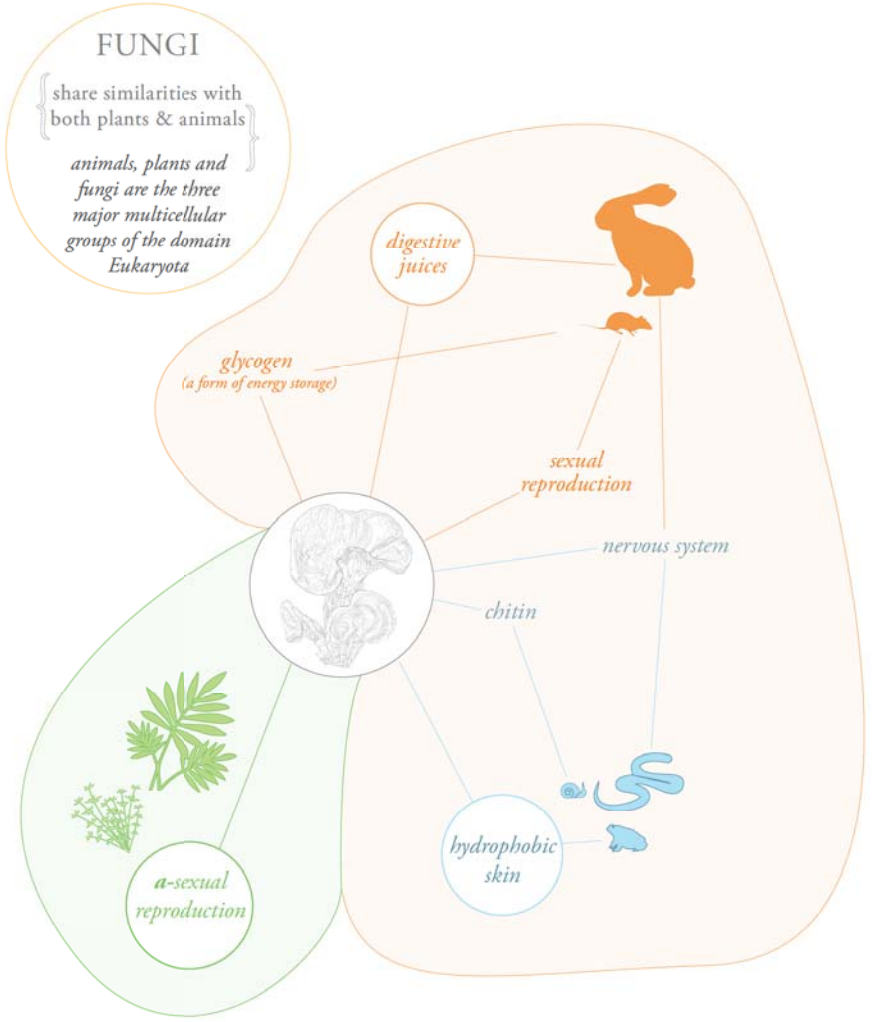
The mycelium matrix is composed of hyphae cords where fungal cells are organized in a lineal arrangement. Unlike plants, whose cells contain cellulose, fungal cells have chitin which allow them to emit digestive enzymes and acids into carbon matter. Primarily a non-photosynthetic organism, this process allows fungi to convert complex chemicals in the host-material into sugars which it can absorb.[36]

The hyphae are in continuous search for nutrition with no pre-determined trajectory and given the right substrate, mycelium can grow to an infinite network.* The hyphae sometimes split at the end to take different paths whereby they send out chemical signaling to the overall mycelium. This non-hierarchal growth with no defined entry or exit points, are in botany referred to as rhizomatic. In terms of employing biological processes for human production, rhizomatic organisms like mycelium are extremely efficient; a single spore can reproduce the entire organism.[37]

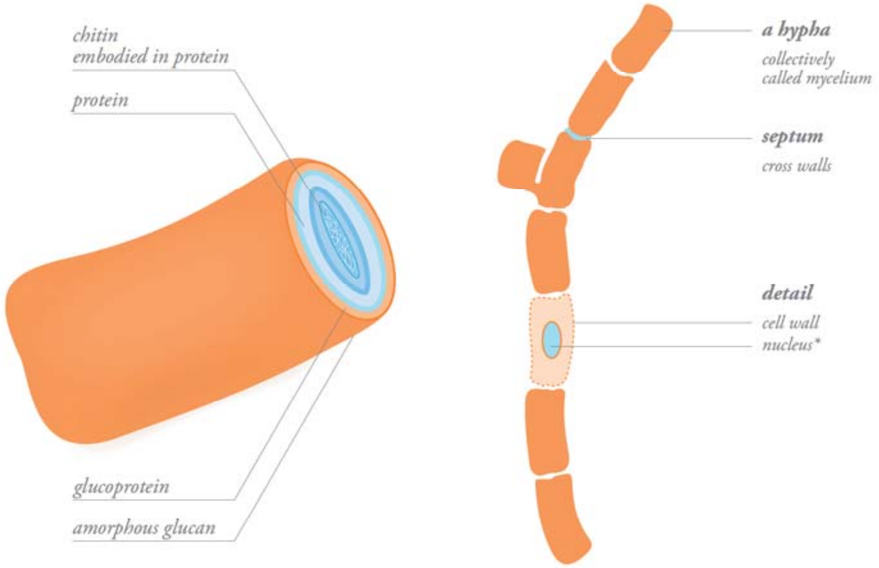
**Mycelium of the Armillaria gallica has been known to cover around 8.9 km2 in the Malheur National Forest, Oregon. (Source: Moore, D and Robson, G D. 21st Century Guidebook to Fungi. Cambridge: Cambridge University Press 2011, 11)*

[36] Dharan, CKH., Noble, J., Ross, P., Travaglini, S., Background. *In Mycology Matrix Composites*, 1-20. American Society for Composites, 2013, Berkeley, CA.

[37] Stamets, P., *Mycelium Running: How Mushrooms can Save the World.* New York: Crown Publishing Group, 2005. 17.

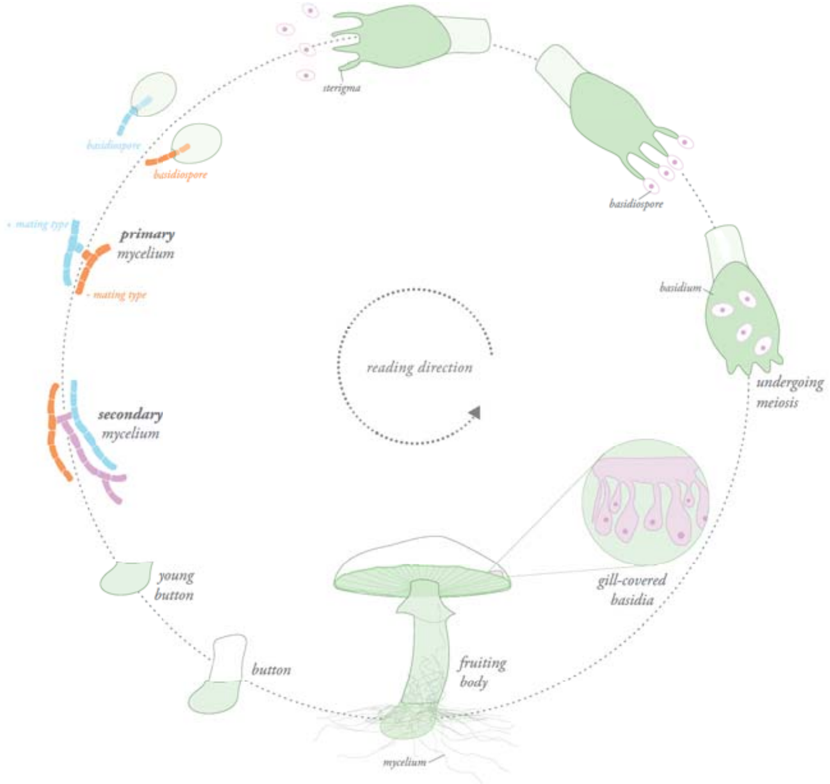


Detail of hyphal cell



** A membrane-enclosed organelle found in eukaryotic cells.*
Adapted from: Introduction to Mycology: http://www.microbiologybytes.com/introduction/myc1.html

Sexual reproduction of fungi



Adapted from: Fungi: http://classroom.sdmesa.edu/eschmid/Lecture13-Microbio.htm

the different strains

Over 100,000 different strains of fungi have been formally identified and categorized into several major taxonomic groups. Yet, the fungal "kingdom" is estimated to contain close to 1.5 million species or more which suggests that we have only scratched the surface of mycological research.[38]

For the purpose of producing mycelium-based composite material, previous studies of mycological composites suggest that it is important to preserve the natural bond between strain and substrate since the hyphae growth is governed by oxygen and nutrition availability. It has further been observed that wood-digesting strains coupled with sawdust, wood chips or shavings produced optimal material results in terms of mycelium density and fiber-reinforcement. [39]

The Ganoderma genus* falls under this category of fungi that thrive on wood and has previously been employed in mycological composites for its ability to produce a dense mycelium matrix. Species of the Ganoderma genus, however, are often found in tropical regions around the world and are therefore not well suited for our Scandinavian context. Instead, the P. Ostreatus, of the Pleurotus genus, was selected to be grown for testing for this research project. The P. Ostreatus is one of the more productive strains [40] of saprophytic** mushrooms and can be found in the leafy forests of southern Sweden.

** Including the strain G. Lucidum which was used in a study completed by Philip Ross*
*** Mushrooms which decompose plant tissue.*
[38] Bills, G. F., Foster, M S., Mueller, G. M. (eds.) *Biodiversity of Fungi: Inventory and Monitoring Methods.* London: Elservier Academic Press, 2004, 8.
[39] Dharan, CKH., Noble, J., Ross, P., Travaglini, S., 7.
[40] Stamets., 21.

PLEUROTUS
(referred to as P.)
is a genus of
gilled mushrooms

kingdom:	plylum:	class:	order:	family
fungi	basidiomycota	agaricomycetes	agaricales	pleuroraceae

chapter IV:
mycelium as a material

Mycological Composites
Material Qualities
Eco-economy

Image 05: Ecovative Design – Packaging blocks

mycological composites

Due to its relatively recent emergence on the commercial market, the mycelium material is not presently regarded as an established engineering material.[41] There is limited research into its mechanical properties as a composite material where the previous studies which have been conducted conclude that mycelium is most practically used for custom packaging solutions. American material science company, Ecovative Design, is currently leading the field of mycological composite materials with a patented growth method. This involves growing the mycelium material to a pre-determined shape, as defined by a mold. Ecovative Design further aims to expand their production of mycelium packaging to mycelium insulating panels and acoustical tiles.[42]

[41] Dharan, CKH., Noble, J., Ross, P., Travaglini, S., 7.
[42] Ecovative Design: Products and Application. 2015. http://www.ecovativedesign.com/products-and-applications/packaging/ (Accessed 05/01/2015).

Current applications:

long term application

2007-08:

Ecovative Design
Initial research focused on rigid board building insulation is tested in several buildings

2013:

Ecovative Design
- Myco Board panels
- Structural insulating panels
- Exterior insulating finishing systems
- Grow-in-place insulation
- Acoustic panels and ceiling tiles

household consumption

2009:

Ecovative Design
Commercial launch of 'Mushroom Packaging'

commercial products

2011:

Ecovative Design
Packaging for Dell Computers

2014:

Ecovative Design
Myco Board fins and surfboards

industrial products

2010:

Ecovative Design
Packaging for Steelcase

2012:

Ecovative Design
Packaging for Crate and Barrel as well as Sealed Air

2014:

Ecovative Design
Automotive Mushroom Materials

large scale exhibition

2009:

Philip Ross' Tea House
'Eat Art' Exhibition
Kunsthalle Düsseldorf

2013:

The Living's Hy-Fi Tower
'Young Architecture Competition'
MoMA PS1, New York

small scale exhibition

2013:

Officina Corpuscoli's Growing Lab
'The Future of Plastic'
Fondazione PLART, Naples

in development:

Terreform One
'Gen2Seat'
Coated Mycelium seating Project
New York

private experiment

2007-08: *Ecovative Design is founded*

2009: *Philip Ross grows his 'tea house'*

2012:

Merjan Tara Sisman & Brian McClellan
'The Living Room Project', School of Art & Design, Philipadelphia

2013:

Danielle Trofe
'Mushroom Lamp'
Independent project, New York

year: 2007-08 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | in development

material qualities

The exact physical properties of the mycelium based biocomposite have not been formally established. This partly depends on the density of the material which is determined by the combination of strain and substrate, and environmental conditions. Yet, the Department of Mechanical Engineering at Berkley, California, has done mechanical tests on an inert mycelium block reinforced with wood-chips using Standard test Methods for Flexible Cellular Materials (ASTM D3574).[43] The tests found that the material is most comparable to synthetic polymeric foams or softwoods such as balsa.[44]

The mycological composite material can further be conceptualized as expandable polystyrene foam, which keeps expanding. Its growth pattern is similar to how an expandable synthetic foam would naturally swell, merely controlled by gravity, pressure and additional substances which might have been added to the mixture. Mycelium has previously been identified as a non-directional rhizome with braces connected at tetrahedral points which suggests that it is a network with infinite growth opportunities given sufficient nutrition.[45]

[43] Dharan, CKH., Noble, J., Ross, P., Travaglini, S., 7.
[44] Ibid., 18.
[45] Ibid., 13.

Sensorial experience:

smell

Does not emit much of the 'fungi' smell thanks to the post heat treatment process, the material smells rather like sunshine.

colour

Its mycelium is white and longitudinal, and forms a tenacious cover around the substrates which can vary in thickness depending on how well the mycelium adheres to the given fiber. The amount of mycelium decreases towards the center of the composite, due to lack of oxygen, where undigested substrate causes a more brittle and fragile material.[46]

touch

Grainy texture which varies on the substrate used. The composite contains an average of 85-90% calcium which gives it a dense, insulating quality. However, the material exhibits different characteristics when it is inert vs. living. In deactivating the growth process, the material is left to dry and becomes a lightweight foam block, whereas it is more elastic and rubbery in its living state.

[46] Dharan, CKH., Noble, J., Ross, P., Travaglini, S., 16.

Mechanical results based on the study *Mycology Matrix Composites: ASC Conference*, Berkley, 2013:*

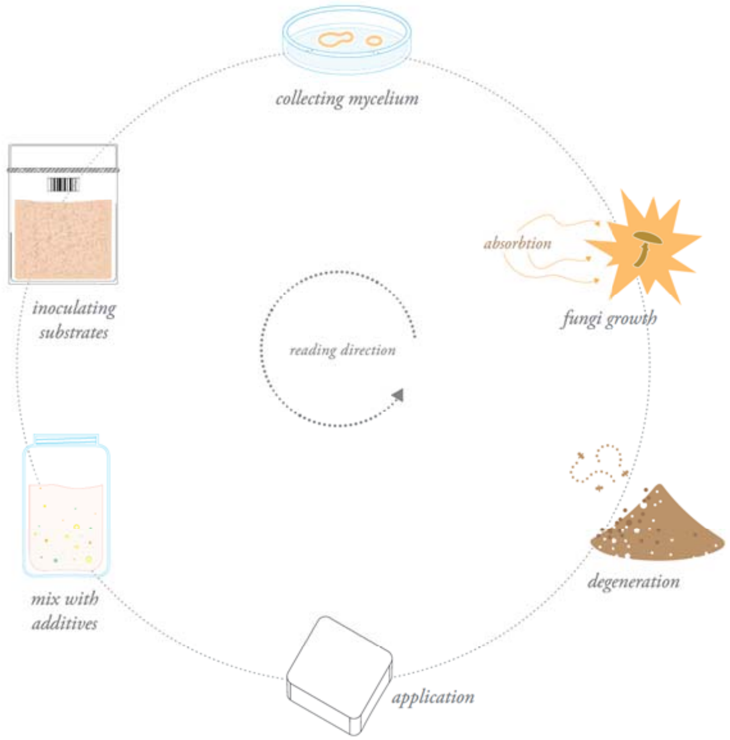
Material	Elastic Modulus, (MPa)	Density, ρ (kg/m3)	Yield Strength, S_{yc} (MPa)	Ultimate Strength, S_{utc} (MPa)
Present Investigation Mycelium	1.30	318	0.0475	0.49
Starch-based Foam w/fiber	180	260	1.18	1.09
Polystyrene Expanded Foam	5.70	41.2	-	0.179

Comment	Based on the above presented test results, the material is not good in tensile force but better in compression.

**Study was completed based on an inert mycological composite grown into a standard brick and following the 'Standard Test Methods for Flexible Cellular Materials (ASTM D3574 - 11)*

Image 06: Courtesy of Ecovative Design

The Life Cycle of the Mycelium Material*



* *When exposed to moist outdoor weather conditions, the lifespan expectancy of the material can decrease. To optimize its durability, natural exterior coatings (e.g. beeswax, resins, essential oils, bacteria cellulose, wood tar etc.) can be applied on the outer surface.*

eco-economical

At the present rate of consumption, the Earth is unable to replenish the resources we extract. For this reason, we should invest more in renewable resources, and particularly rapidly renewable resources such as mycelium, which are part of closed-loop systems. Reinforced with natural fibers, the mycelium composite is biodegradable and packed with mineral nutrients that support other living organisms.

Ecologist Julian Hadley works at Ecovative Design and has compared the nutrition content in carrots grown from soil mixed with two types of composted waste: from degenerated mycological composites and simple maple leaves,* both mixed with ordinary kitchen waste. Hardley noted that the nutrition levels in the carrots grown from degenerated mycological composites contained less calcium than the comparative soil. However, he also points out that the result is relative to the type of substrates used in growing the composite material. All in all, in reference to the table below, it can be concluded that soil mixed with mycological composites produce plants and vegetables with the desirable levels of nutrition.[47]

Nutrient element in carrots (%)	*Myco-composite soil*	*Maple leaf soil*	*Typical carrot*
Calcium	0.39	0.39	0.29
Magnesium	0.17	0.14	0.11
Potassium	3.1	3.1	2.8
Phosphorus	0.54	0.60	0.31

* *Maple trees contain a relatively high level of calcium.*

47. Jacobsen, M., 2015. The Nutrients in Mushroom Packaging Can Help You Grow Food. *Ecovative News Blog*. 1 April. http://blog.ecovativedesign.com/2015/04/01/the-nutrients-in-mushroom-packaging-can-help-you-grow-food/ (Accessed 28/04/2015)

***Table:** Adapted from* 'The Nutrients in Mushroom Packaging Can Help You Grow Food', www.blog.ecovativedesign.com

chapter V:
biological production

A New Area of Innovation
Interdisciplinary Collaboration
Inside the Laboratory
Technical Details
Compatible Media

What is 'self-assembly'?

Self-assembly is the most common term in use in the modern scientific community to describe the spontaneous aggregation of particles without the influence of any external forces.[48] Living organisms which can self-assemble into building blocks have opened up new grounds of research in biotechnology as well as architecture.

[48] Pal, S., *Design of Artificial Human Joints & Organs,* New York: Springer Science+Business Media, 2014, 55.

a new area of innovation

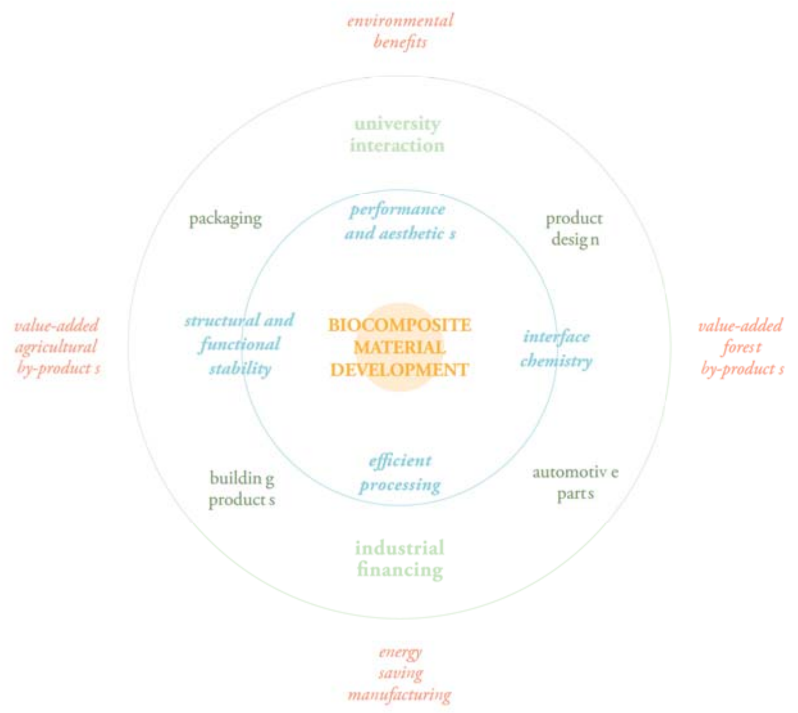
Biological efficiency refers to the amount of yield which can be produced from one strain or crop. For example, particular substrate compositions coupled with certain strains produce more or less dense hyphal growth.[49] We often measure the embodied energy in conventional building materials, e.g. the energy which goes into producing the material. Mycelium, however, is metabolic,* e.g. capable of regulating its own energy and adapt its consumption needs accordingly: Nutrition obtained through absorption is converted into matter and the mycelia is continually adjusting its growth and renewal in order to avoid decay. Compare, for example, the self-organizing growth process of mycelium to the metabolic process of concrete which is short and fatal: as the mixture of cement swells, hardens and cools it exhausts all of its energy in a relatively short reaction. The concrete has become a fixed, inert object which can only deteriorate from this point on.[50] Natural systems do not rely on human-made machines to provide external energy; they can thrive off sources such as the sun and carbon dioxide to go on living.

* *Term coined by Dr. Rachel Armstrong when referring to the matter produced through 'protocell technology'.*

[49] Shroomery, The Shroomery Mushroom Glossary. 2009. http://www.shroomery.org/5122/The-Shroomery-Mushroom-Glossary (Accessed 15/05/2015)

[50] Armstrong, R., How Protocells Can Make "Stuff" More Interesting. In *Architectural Design*, vol. 81, no. 2 (2011): 71.

Requirements of the Development of the Biocomposite Material Market



Adapted from: Natural Fibers, Biopolymers, and Biocomposites, p.22

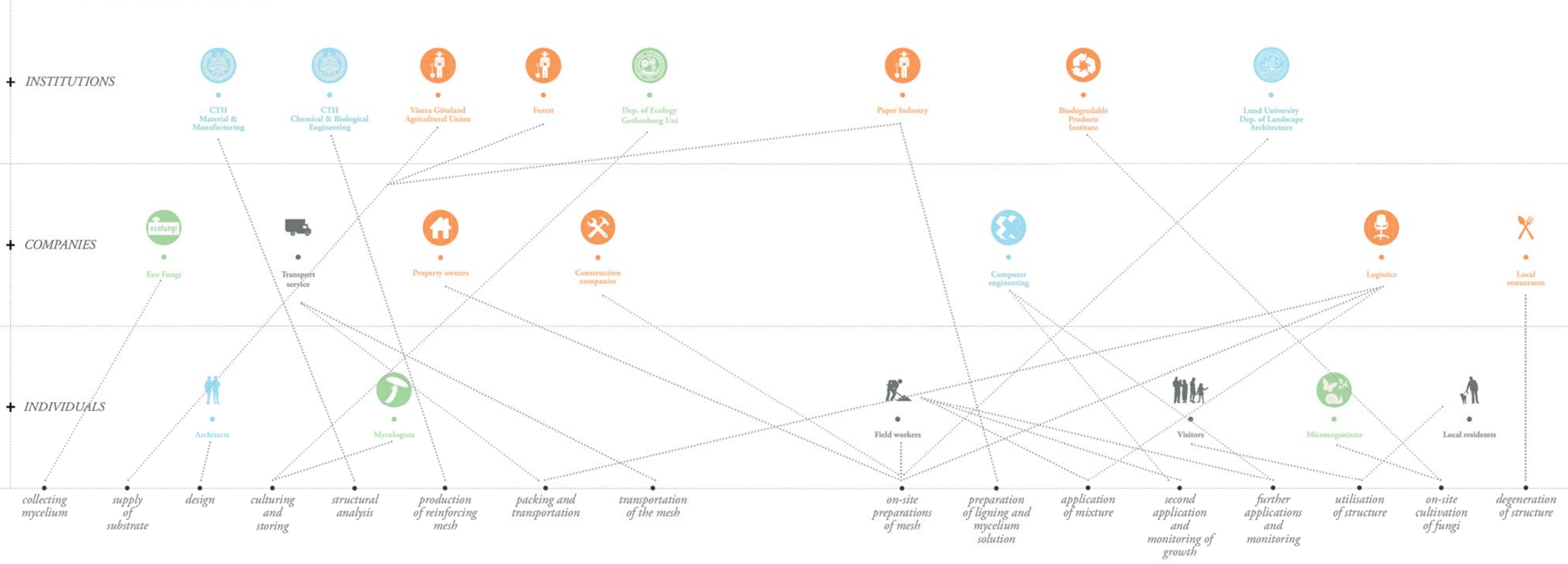
interdisciplinary collaboration

This 'metabolic' method of material production does not only present a new scenario for the production industry, it could potentially change the way architects and designers work as well. Some architects [51] have already begun to conceptualize the potential of naturally self-assembled composite materials in building, tapping into the field of biology for inspiration. The actual materialization of such proposals, however, requires collaboration between specialists.

Furthermore, it requires architects to introduce others into the design processes, moving beyond traditional architectural drawings. Interdisciplinary working environments, where several processes occur simultaneously (concept, prototyping, material testing, structural analysis and so on), is an important step in achieving environmental design beyond mimicking these systems. An ecologist would for example be able to understand the intricate processes which shape a system; an engineer may know how to apply it while the designer could envision a way for society to engage with it. Communication between disciplines supports the pursuit and application of new innovation, which is crucial for future social and environmental development.

[51] Cruz, M., Pike S., Neoplasmatic Design, *Architectural Design*, vol. 78, no. 6, (2008)

Potential actor network map



- design/engineering
- miscellaneous
- supply/economy
- biology

note: the listed tasks above are organised in a linear order, however some processes would be overlapping.

inside the laboratory

As mentioned in the study *Mycology Matrix Composites: ASC Conference*[52] it is near impossible to accurately pre-determine the relative ratio of mycelium matter to substrate matter in the composite. Since the basis of the production process is for the mycelia to digest large parts of the substrate, minor interruptions in the environment affects this development (as with any living organism), altering the final outcome of the material.

For our laboratory experiments, we used a wood-digesting strain of fungi called *Pleurotus Ostreatus,* which can easily be found in leafy forests with enough moisture. Growing it out of its natural environment, however, isolates the strain and weakens its resilience against contamination and other, non-mycological organisms. The mycelium taken from the strain is at its most fragile state before it has colonized the substrate. For this reason it must be kept in a sterile environment, such as a ventilated clean-box. All material brought into the clean-box should also be sterilized in an autoclave and all equipment sprayed with alcohol.

The fabrication process is separated into several preparatory stages, which take place before the actual inoculation, each with its own workspace:

- Collection of mycelium tissue *(see appendix page 297-299)*
- Sterilization
- Colonization *(see appendix page 191-217)*

[52] Dharan, CKH., Noble, J., Ross, P., Travaglini, S., 8.

Inoculated samples growing in the ventilation hood at the MC2 lab

technical details

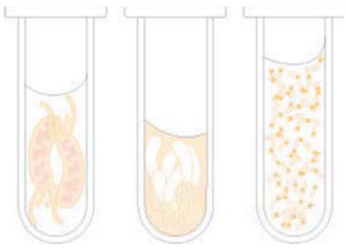
Ideal environmental conditions for growing:

relevant for producing a mycological composite (Inoculation of Substrates; Primordia Formation)

Duration: 15 -26 days

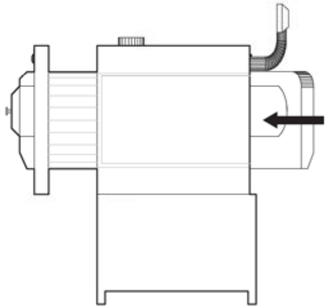
Inoculation of Substrates:	Incubation Temperature: 24° C Relative Humidity: 85-95% Duration: 12-21 days CO2: 5000-20,000 ppm Fresh Air Exchanges: 1 ac/h Light Requirements: n/a
Primordia Formation: 'Antler' stage	Initiation Temperature: 10-15° C Relative Humidity: 95-100% Duration: 3-5 days CO2: <1000 ppm Fresh Air Exchanges: 4-8 ac/h Light Requirements: 100-1500 lux
Fruitbody Development: 'Young button'	Temperature: 10-21o C Relative Humidity: 85-90% Duration: 4-7 days CO2: <1000 ppm Fresh Air Exchanges: 4-8 ac/h Light Requirements: 1000-1500 lux

Adapted from: http://www.shroomery.org/9410/Pleurotus-ostreatus (Accessed 20/03/2015).



mycelium tissue

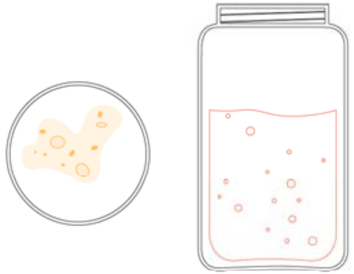
Spores from an already developed, but young, mushroom can be used to culture mycelium. *(see appendix page 183)* Once collected, the specimen is often fragile and should be preserved in a sterilized liquid medium inside a fridge.



sterilization

An autoclave is a pressure chamber used to sterilize equipment and supplies. *(see appendix page 187)*

Saturated steam: at 121 °C
Duration: 20 minutes or depending on the size of the load and the contents.



liquid culture

Previous studies[53] suggest that inoculation by liquid mycelium results in a faster conversion of fiber to hyphae. *(see appendix page 209-217)*

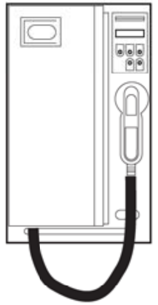
solid substrate

Mycelium taken from the P. Ostreatus can colonize a wide array of substrates *(see appendix page 182-183)*, yet should be limited to by-products from local industries. Our experiments, for example, are conducted using oat grain, coffee grounds, hay pallets and oak sawdust for mycelium reproduction.

[53] Dharan, CKH., Noble, J., Ross, P., Travaglini, S., 9.

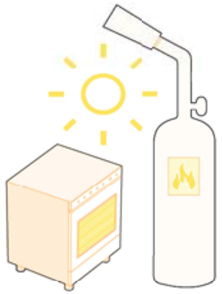
ventilation hood

Keeping the relative humidity within the ventilation hood *(see appendix page 186)* at a constant 95-100% is crucial for the mycelium to develop to the primordial formation stage. However, an excess of water in the mixture can lead to the development of microorganisms such as molds.



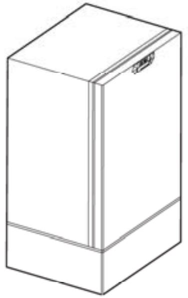
sterile water source

All the experiments need to be conducted with autoclaved and sterilized equipments and ingredients. It is crucial for the water source to be sterile too, in the laboratory a water purifier provides it. *(see appendix page 186)*



equipment for heat treatment

The growth process can be halted by exposing the mycelium composite to a heat treatment. *(see appendix page 186)* The moisture content should be reduced from 60-65% to 10-20%.



fridge

The original liquid mycelium culture is kept in a fridge on 8 °C. This slows down the multiplication process and allows the source to be used for a longer period.

Original mycelium culture

compatible media

liquid culture media

Malt Yeast Peptone

Oatmeal Yeast

Potato Dextrose Yeast

dextrose
brown sugar
rice bran
corn starch
wheat flour
blue mussel clams

Additional nutrition can lead to an increased mycelium production and a denser material.

pH-regulating:
gypsum

pH levels for optimal growth: 5.5 – 6.5

substrate media

Coffee Grounds
produces a fine, and dense composite

Oat Grains
optimal inoculation medium

Hay Pellets
optimal inoculation medium

Wheat/Barley Straw
adds structure and rigidity to the composite

Cotton
produces a light, soft and flexible material with good insulation properties

Rye
optimal inoculation medium

Hardwood Chips or Sawdust
adds structure, and rigidity to the composite

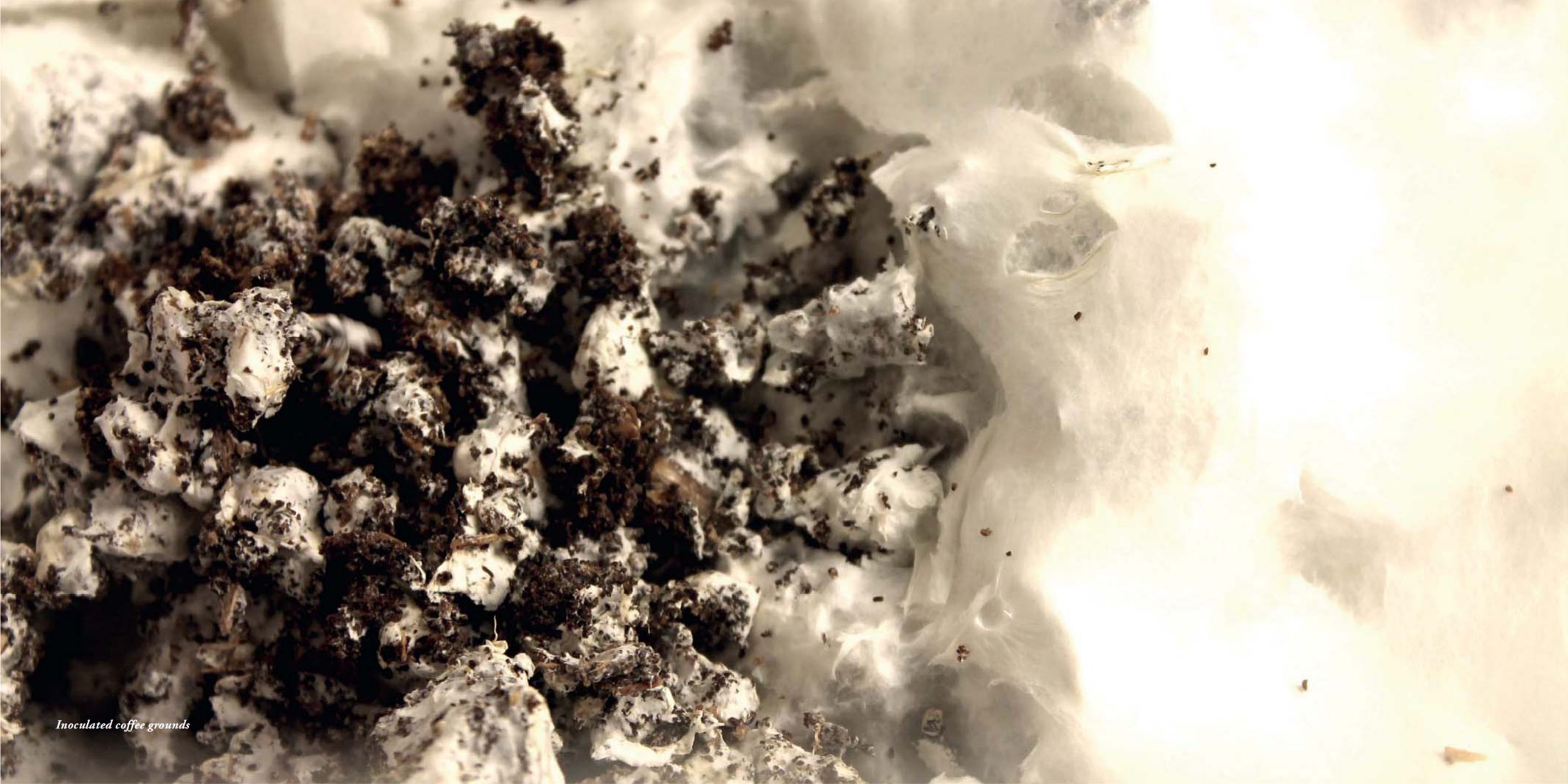
Sorghum
optimal inoculation medium

Based on: Shroomery, Pleurotus ostreatus. 2007. http://www.shroomery.org/9410/Pleurotus-ostreatus (Accessed 06/02/2015).

substrate mix

pH levels for optimal growth:
6.0 –8.0
(but should land on ca. 5.0 at the fruiting stage for optimal biomass)[54]

[54] Ibid.



Inoculated coffee grounds

chapter VI: application

Case Studies
Our Strategy

Material mixture *- used during our workshop at London Metropolitan University*

4 parts hardwood sawdust
3/4 part wheat straw
1/2 part organic oatmeal
1 part gypsum
1 and 1/2 parts distilled water

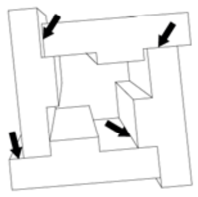
Hydrogen peroxide to eliminate threats of contamination.

Image 07: *The largest structure built out of the mycelium material in New York, 2014: 'The Hi-Fi Tower'*

case studies

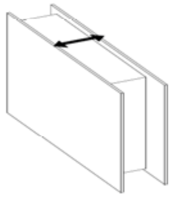
The following technical methods have been employed when building with mycelium:

a) modular



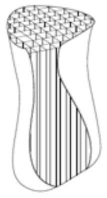
1. prefabricated bare modules
2. casting in mold
3. final assembly takes place on site
4. inert
5. Ecovative Design for The Living Architecture Firm & Philip Ross' Tea House
6. 2-4 weeks
7. wood chips, sawdust
8. reishi mushroom

b) sandwich panels



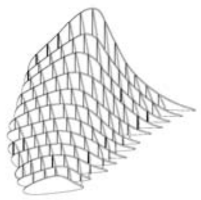
1. prefabricated panels
2. casting in compression
3. final assembly takes place on site
4. inert
5. Ecovative Design prototype
6. unknown
7. corn-husks
8. oyster mushroom

c) external scaffold



1. continuous growth inside 3D-printed skin
2. casting within skin
3. gradual assemblage through growth
4. Active
5. Erik Klarenbeek prototype
6. 5 days
7. organic waste, straw
8. oyster mushroom

d) internal scaffold



1. free-form growth along prefabricated structure
2. free growth guided by structure
3. gradual assemblage through growth
4. active
5. IAAC: Institute of Advanced Architecture of Catalonia
6. 3 months
7. sawdust
8. shitake, maitake

1. technique 2. method 3. fabrication 4. morphology 5. author 6. time 7. substrate 8. mycelium strain

Image 08: *Modular mycelium blocks - Tea House project by Philip Ross*

Image 09: *Mycelium sandwich panels - prototype by Ecovative Design*

Image 10: *Mycelium grown in scaffolding - Chair by Erik* Klarenbeek

Image 11: *Mycelium grown on scaffolding - Bench design by* IAAC: Institute of Advanced Architecture of Catalonia

conclusions

We can draw several conclusions from the case studies presented:

- The modular system in example *a)* is the only method where the final material is free of scaffolds, but this also means that it is more vulnerable to external weather conditions, particularly moisture. There is the additional risk that the mycelium do not adhere to the substrate, producing a material component with little or no hyphae towards the center. The depth of the desired module should therefore be considered.

- When coupled with external/internal materials - as seen in examples *b), c)*, and *d)* - the mycelium grows into the cavities providing rigidity to the structure.

- In example *c)*, the material grows into the tunnels of a 3D-printed structure, again filling in the cavities except here the mycelium is conformed to a pre-determined form (like methods *a), b)*, and *d)*,). However, method *c)* makes it difficult to stop the growth process of the mycelium without damaging the external scaffold. Therefore, it is expected that fruiting bodies will eventually develop and penetrate the surface of the structure.

Image 12: *'Mycelium Design' - An on-going research project initiated by Officina Corpuscoli in corporation with Utrecht Universiteit and Mediamatic*

e) cultivated surface

1. mycelium grown on top of a moldable fabric.
2. manual application to a surface.
3. casting
4. inert
5. Officina Corpuscoli
6. unknown
7. -
8. oyster mushroom

In summary, all case studies presented above are focused on the physical behavior of mycelium as a material which can be cast to a form or grown in place, exhibiting some structural properties. Its remarkable ability to utilize multiple forms of nutrients while rapidly digesting a given substrate is however being neglected. The dynamic relationship between substrate and mycelium could result in a material with a multitude of characteristics.

In addition, the specific ability of mycelium to bond and grow onto various surfaces has been explored in lesser degrees than its potential to produce an inert brick.

Possible Hybrid Membrane

1. individual components are assembled in a repeated pattern.
2. manual application to a surface.
3. casting
4. active

The proposed design concept will exhibit how the mycelium material is capable of bonding to several substrates: Substrates from several sources are independently inoculated with mycelium and applied to the reinforcing mesh.

Laboratory work

Area of investigation

first set of experiments:

Our first investigation includes testing how mycelium from the P. Ostreatus adheres to different types of substrates as well as a brief evaluation of the material samples produced. *(see appendix page 221-249)*

second set of experiments:

The second stage of experiments explore how certain inoculated substrates could be combined to achieve a multi-layered material. *(see appendix page 251-271)*

third set of experiments:

Finally, we move from growing within molds to growing on top of fabrics. Here, the ability of mycelium to bond to another material is tested; producing a membrane with the help of a guiding mesh. The latter is further elaborated in an architectural context. *(see appendix page 273-287)*

our strategy

Industrial processes have largely focused on producing biologically inactive materials; treating raw matter in ways to prevent it from interacting with its natural biological system of decay. This has obviously been done for sound reasons; to keep materials from rotting and preventing moisture getting inside of them.

In spite of its obvious advantages, the molding approach carries dimensional restrictions as well as a growth termination. Yet, mycelium as a living organism presents very interesting characteristics, for one it is a material which adds to itself by digesting waste matter. The intent of this design project is therefore to expand the possibilities of mycelium as a living material.

As opposed to letting the material grow in portioned modules whereby it is terminated in a heat treatment, we suggest keeping the substance alive within layers of mycelium material made of different substrates derived from various industries in the local area.

Therefore, from this point on, we aim to explore the employment of P. Ostreatus in its living state and investigate how it is affected by different substrates and how these substrates might be layered in order to achieve certain material results. The proposed design concepts will exhibit how the mycelium material is capable of growing in-situ in an open environment as well as its ability to bond several layers of different substrates.

Layered material sample

chapter VII:
design for a local context

Introducing the Design Concept
Along the Hiking Trail
Atmospheric Conditions
Our Proposed Fabrication Method
Design Illustrations

introducing the design concept

The material shall be presented in it's natural environment, hosting a temporary function, allowing a seasonal renewal for the structure to take place. The main construction should primarily be made out of the mycelium material in its living state, where it is continuously adding to itself. All reinforcing fiber must come from local industries and free of insecticides, fungicides, hormone additives and synthetic fertilizers.[55]

functional:

- resting spot
- short-term occupancy
- shelter from weather conditions

structural:

- reinforcing mesh / mounting
- wind shielding surface
- hydrophobic surface
- semi-closed

environmental:

- made of organic biocomposites
- degrades back to the earth on the site
- low embedded energy

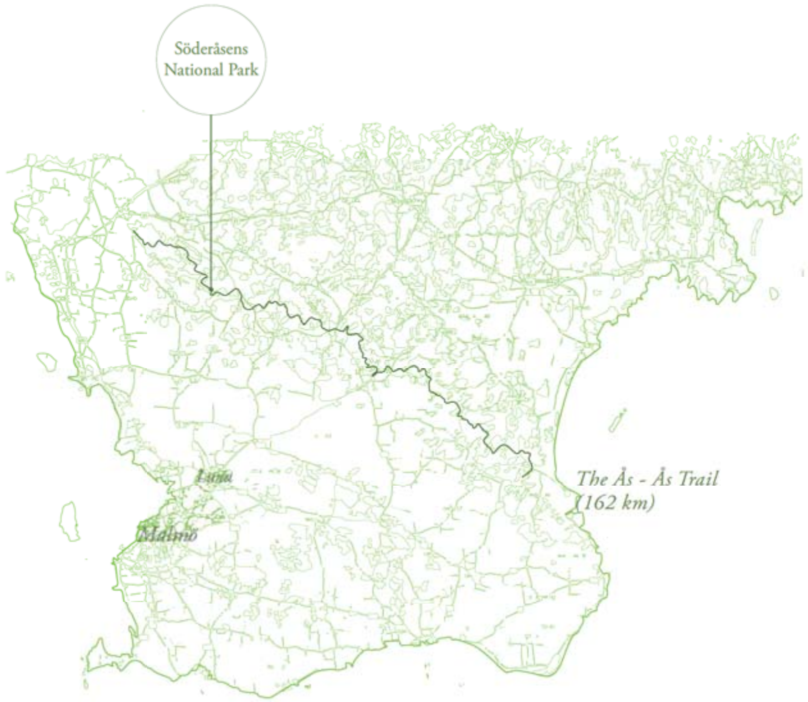
[55] Berge., 161.

along the hiking trail

We envision the shelters to be placed along the hiking trail *Ås to Ås,* which is part of the larger trail called *Skåneleden.* This boreal region in Skåne is further the native habitat of the selected strain, P. Ostreatus, on which we have based our material experiments.

The hiking season is at its peak during the spring and summer months, and we expect the shelters to be utilized annually between April - October. These facilities usually become neglected in the colder seasons and are often left unused even in the peak seasons: Visitors may come and sit under the shelter for a few hours at a time, enjoying a picnic while admiring the scenery. The proposed design, grown out of mycelium, emphasizes the shifting seasons through its gradual emergence and decay, where it transforms from human artifact to nutrients for the natural ecosystem.

The trail is also rich in historical heritage with the remains of villages and farms scattered about the leafy woodlands and open fields. The region holds history of farming and breeding grazing livestock in the woodlands. One can find trees nibbled by the farm animals. It takes several days to discover the trail in it's whole length. The hikers need to rest from time to time, therefore there are some established camping spots but additional wind shelters would be appreciated.



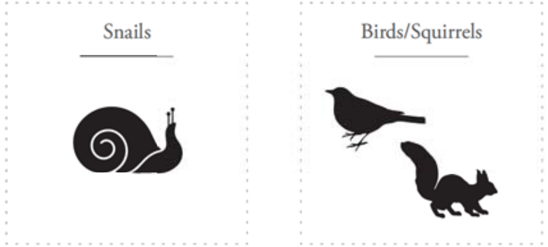
Söderåsen National Park

Söderåsen National Park is 1 625 ha big and supports one of the most diverse ecosystems in Sweden.[56] The deep, leafy forests and high rocky slopes are the homes to large animals like deer and wild boars, to eagles, woodpeckers and unique mix of microorganisms. The slopes towards the north, which line the valley of Skäralid (see next page) is especially rich in species of the fungi "kingdom" with around 400 species formally identified in the area.

1. Åstorp
2. Hålebäck
3. Krikaskog
4. Klåveröd
5. **Söderåsens National Park**
6. Jällabjär
7. S. Hultarp
8. Maglebjär
9. Onsvalakällan
10. Bjeveröd
11. Ekeröd
12. Timan
13. Rebbetuaröd
14. Agusa

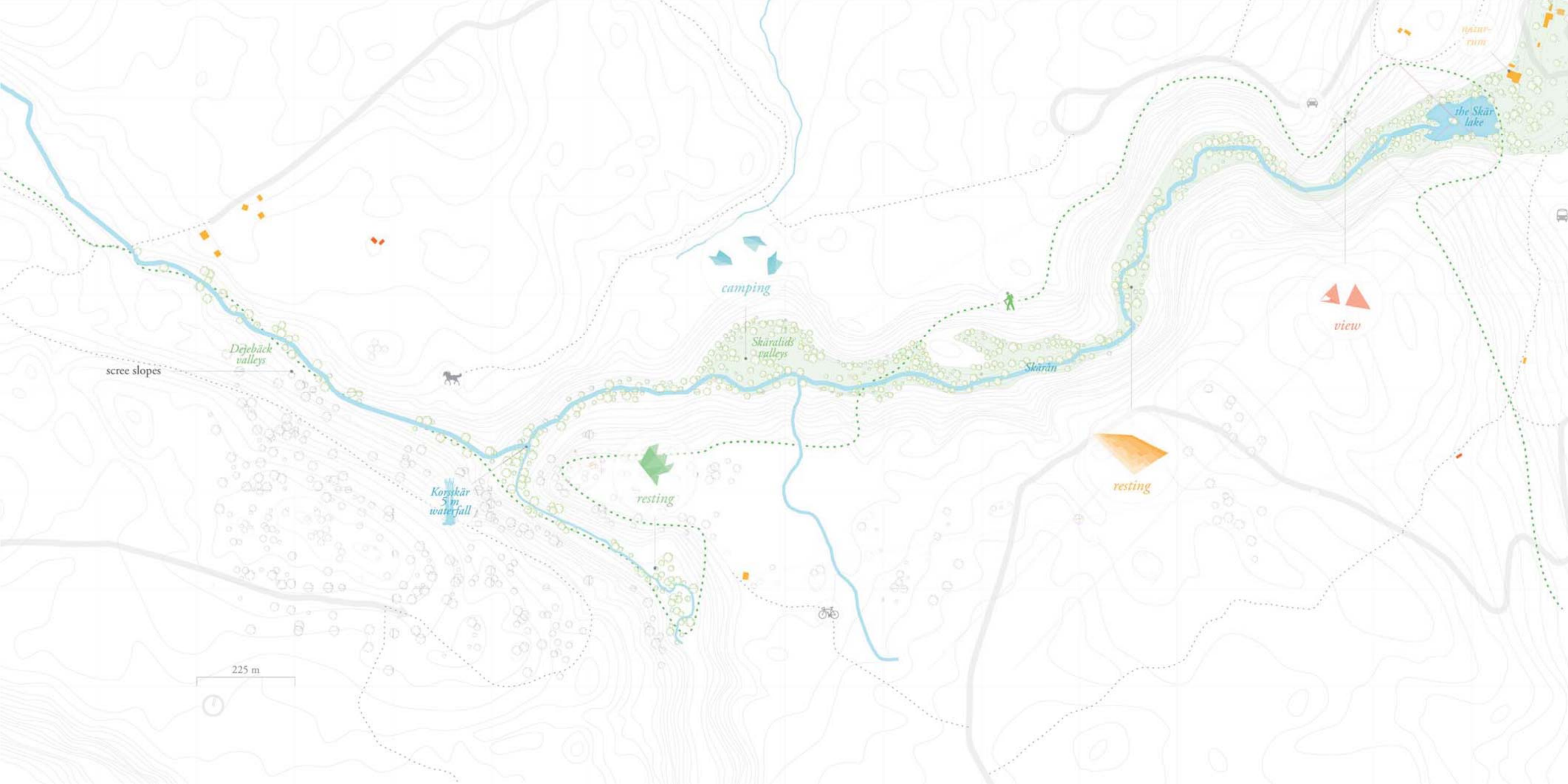
[56] Skåneleden, http://www.skaneleden.se/leden/sl-3-as-asleden/ (Accessed 02/05/2015)

local species which may be threatening to mycelium



The P. Ostreatus is one of the more aggressive species, dominant enough to overcome most fungal parasites. However, the catalogue above lists common fungi and insects which attack wood and therefore also pose a threat to most saprobic, or wood-decomposing strains.[57]

[57] Statmets., 64.


natur-
rum
the Skär
lake
camping
view
Dejebäck
valleys
scree slopes
Skäralids
valleys
Skärån
Korsskär
5 m
waterfall
resting
resting
225 m

atmospheric conditions

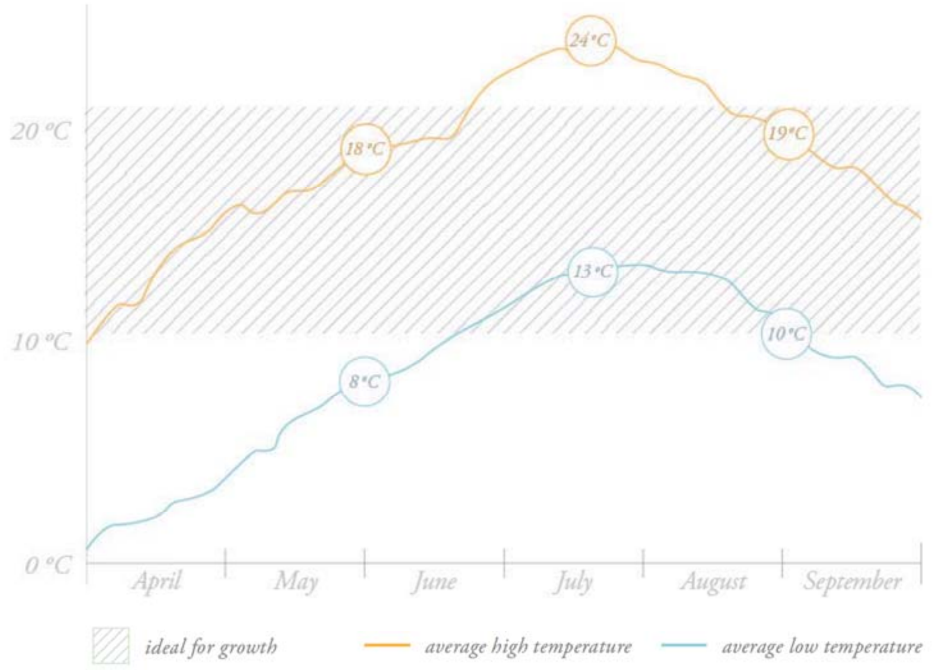
Levels in temperature, air humidity, carbon dioxide and UV-light are all factors which affect the growth of mycelium.[58] Changes in these conditions during the growth process can affect the production of fungi primodium, speeding up the development of hyphae.* Yet, although atmospheric conditions can be controlled within the conformed space of a laboratory, they are a natural part of the outside world and should ideally be involved as part of the fabrication method: It is a laboratory and a tool-box in itself and should not be considered an enemy of the material.[59]

There is further the issue of ecological integration when dealing with a living material. Even native species could pose a threat to the host environment if introduced in large quantities, whereas parasites, insects, infections and other fungi would likely attack the new organism. The on site application of the material should therefore occur in stages, starting with a thin membrane.

Primordia Formation: 'Antler' stage	Initiation Temperature: 10-15 °C Relative Humidity: 95-100% Duration: 3-5 days CO2: <1000 ppm Fresh Air Exchanges: 4-8 per hour Light Requirements: 100-1500 lux
Fruitbody Development: 'Young button'	Temperature: 10-21°C Relative Humidity: 85-90% Duration: 4-7 days CO2: <1000 ppm Fresh Air Exchanges: 4-8 per hour Light Requirements: 1000-1500 lux

Such measures have for example been used by commercial material science company, Ecovative Design, to speed up the growth process.
[58] Dharan, CKH., Noble, J., Ross, P., Travaglini, S., 9.
[59] Ibid., 18.

Average temperature

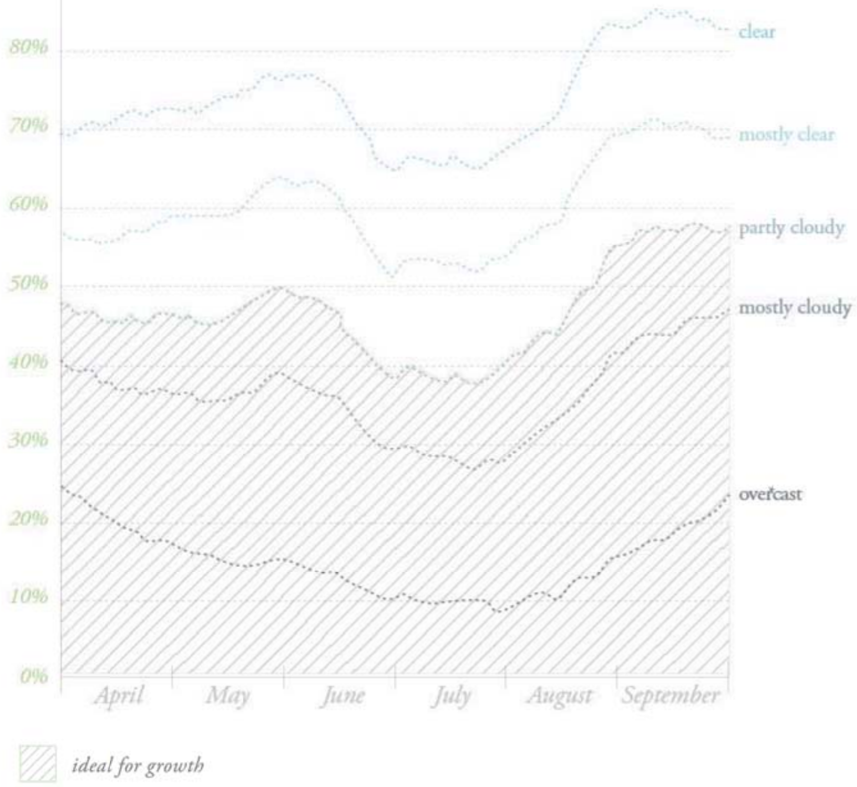


Adapted from: https://weatherspark.com/averages/28933/Malmo-Skane-Sweden

Relative humidity

Adapted from: https://weatherspark.com/averages/28933/Malmo-Skane-Sweden

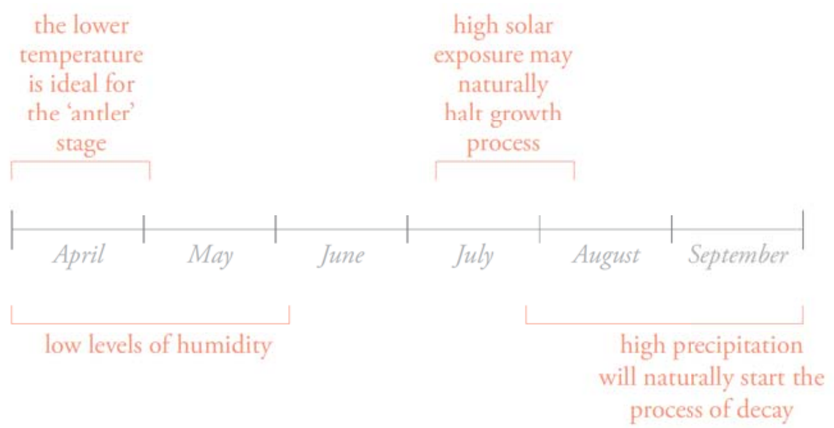
Cloud cover types



* *Typical overcast day - midday: 1,000 - 2,000 lux*

Adapted from: https://weatherspark.com/averages/28933/Malmo-Skane-Sweden

Critical atmospheric factors



our proposed fabrication method

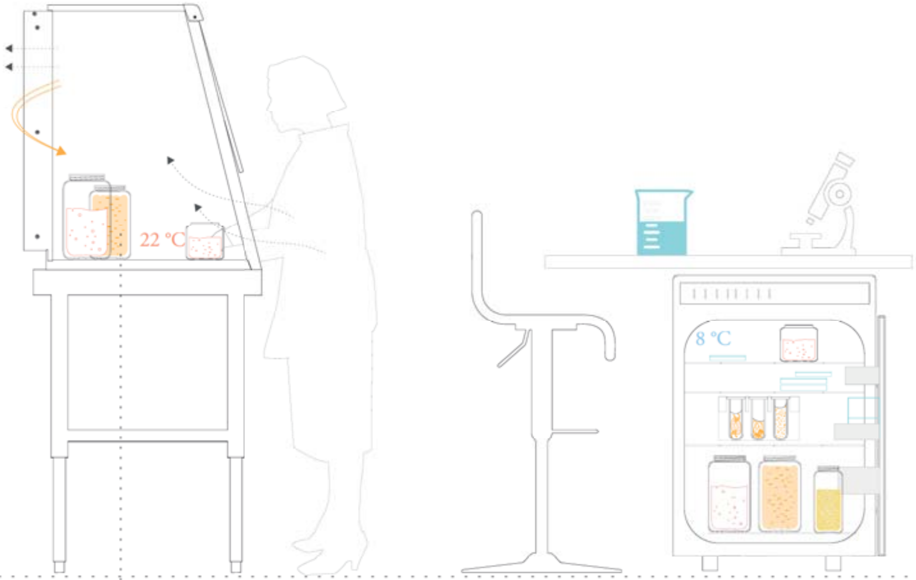
The growth of the mycelium can be directed alongside defined paths. In fact, that is how the mold based manufacturing gives a shape to the material. It is possible to cultivate mycelium on surfaces such as cardboard and certain organic textiles, but instead of using closed containers for castings, the frame of the growing path can be formed through an organic fibrous network which remains in the material as part of the structure.

1) Laboratory preparations
Lignin mixed with mycelium and substrates which is inoculated and cultured within a sterile environment.

2) Site preparations
The meshes, which is made of organic fiber, are hung at several points and held in a tensile force in-between the existing trees on the site. Nodes add density to certain areas in the mesh.

3) Structural
Layered substrates: Lignin + mycelium + substrates sprayed on: The structure of the designed facility can be established through a defined time-period by applying the different substrates layer by layer. This way the final section performs as a combination of the properties of the single sheets. The time offset of application helps the bonding of the different layers, since the previous layer already has established a dense network of hyphae.

4) Environmental
Decay: The material is grown from indigenous, waste-products from local industries. Our intention was to use only locally available ingredients. This way after decomposition all the decayed components become part of the upper fertile soil layer, without introducing a new aggressive life form to the regular biological cycle. Therefore after the structure has reached the end of its life-cycle, provided that the substrates did not contain any pesticides or other agricultural toxins, it will simply begin to decompose on the spot. As the material breaks down, it adds nutrients to the soil which it sits upon, supporting the surrounding wildlife.

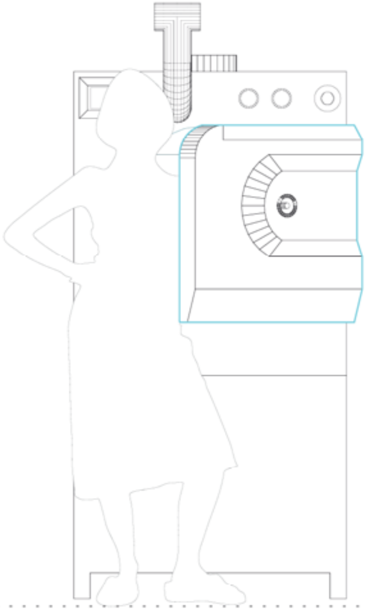


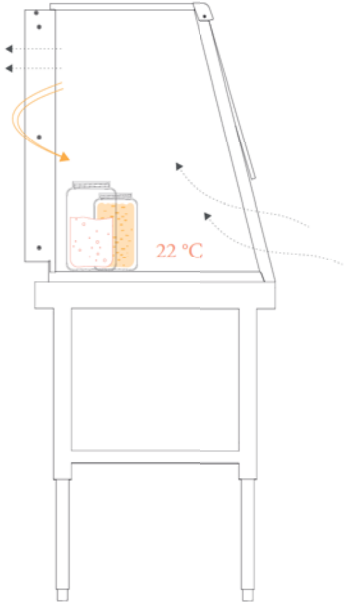
collecting mycelium

Spores from an already developed fruiting body in the forest could be used to culture mycelium. Even the smallest of spores, if nurtured right, is able to re-produce the whole organism. Once collected, the specimen is often fragile and special care should be taken when maintaining and preserving it.

reproducing and storing

A fume hood is a type of local ventilation device that is designed to limit exposure to hazardous or toxic fumes. To temporary halt the growth of hyphae, the mycelium can be stored in a regular fridge of a minimum of 8 °C. It is most effectively reproduced in liquid form, sterile water mixed with a liquid culture media and nutrients.





sterilization

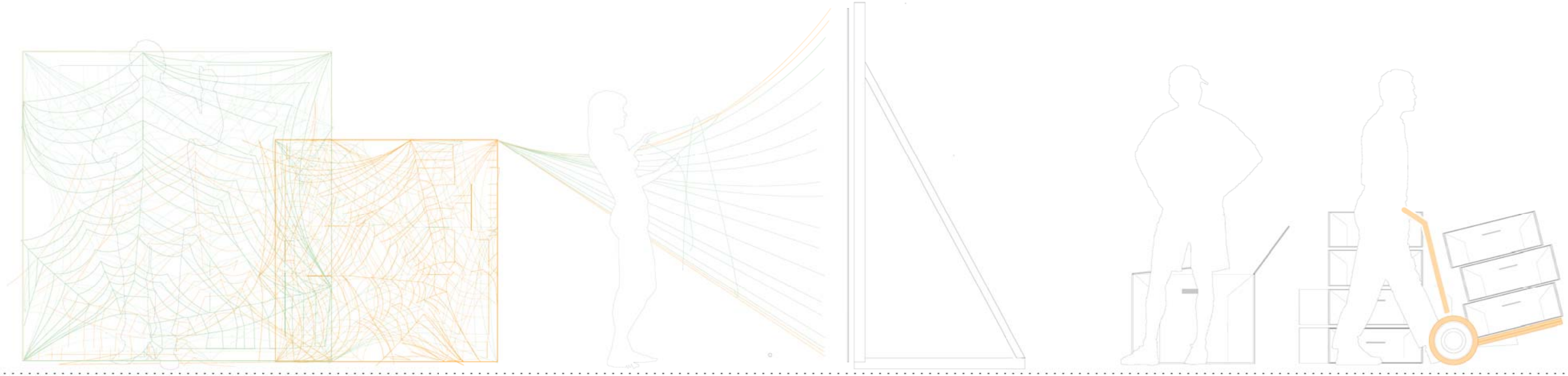
An autoclave is a pressure chamber used to sterilize equipment and supplies.

saturated steam: 121 °C

duartion: 20 minutes or depending on the size of the load and the contents.

inoculation of substrate

There is no established method to determine the ratio of mycelium matter to substrate matter and nutrition in mycelium composites. However, our experiments have shown that simply layering (as opposed to mixing) about the half amount of the substrate produces a denser material faster.



design of the mesh

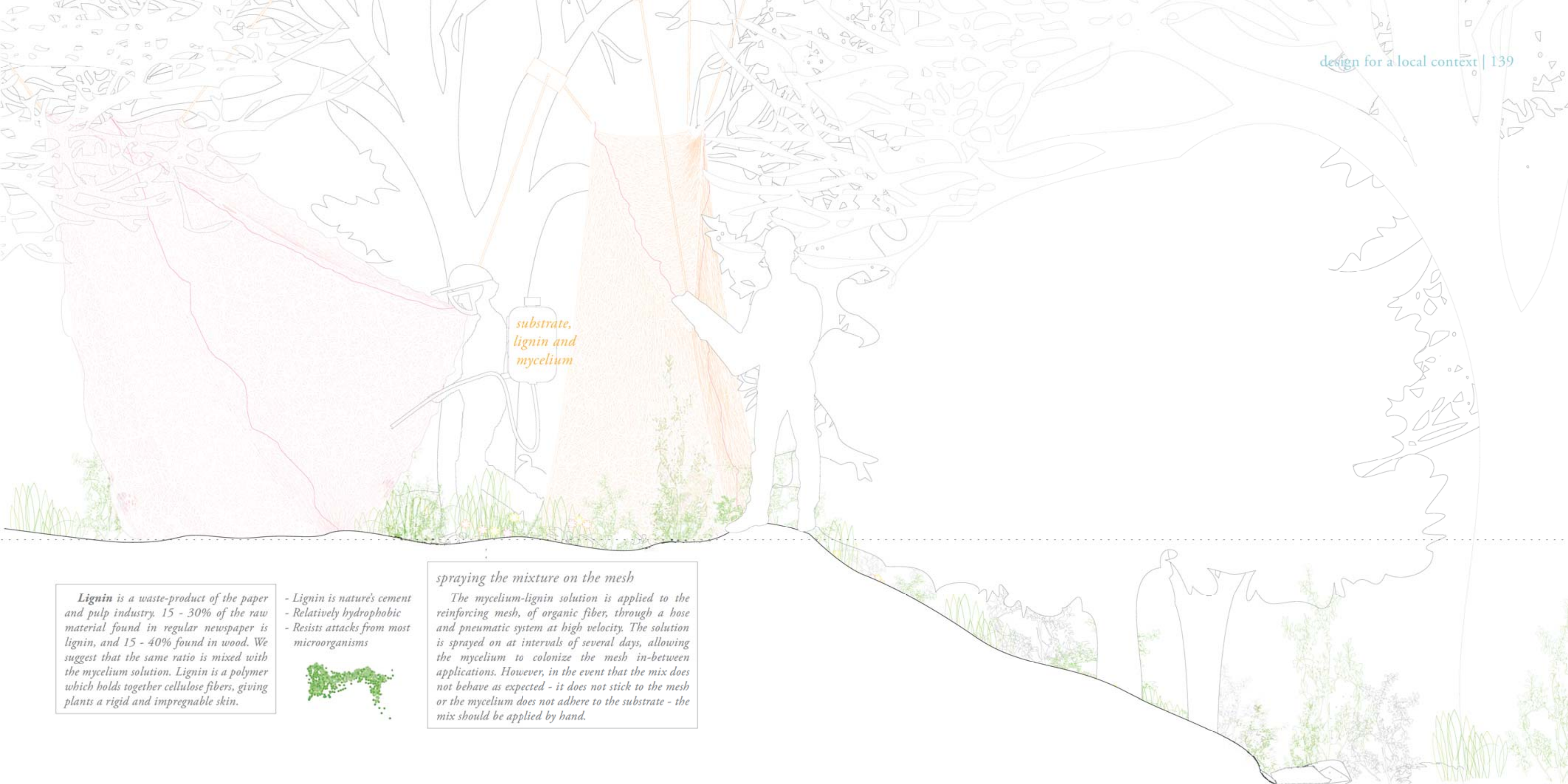
The shape and structure of the mesh can be designed parallel to the inoculation process. Later this mesh will be hung and serve as a remaining cast for the applied mixture solution.

packing and transporting

The final mesh could be packed in small portions and transported to the site to be assembled into the designed shape. Ideally the production of the mesh happens close to the site, thus the transportation does not require high costs, lots of time or energy.

hanging the mesh

The application of the mesh is organized and instructed by the designer. Natural elements -such us trees, big rocks or the ground - can be used as anchorage. Additional mounting brackets can be prefabricated and assembled.



Lignin *is a waste-product of the paper and pulp industry. 15 - 30% of the raw material found in regular newspaper is lignin, and 15 - 40% found in wood. We suggest that the same ratio is mixed with the mycelium solution. Lignin is a polymer which holds together cellulose fibers, giving plants a rigid and impregnable skin.*

- *Lignin is nature's cement*
- *Relatively hydrophobic*
- *Resists attacks from most microorganisms*

spraying the mixture on the mesh

The mycelium-lignin solution is applied to the reinforcing mesh, of organic fiber, through a hose and pneumatic system at high velocity. The solution is sprayed on at intervals of several days, allowing the mycelium to colonize the mesh in-between applications. However, in the event that the mix does not behave as expected - it does not stick to the mesh or the mycelium does not adhere to the substrate - the mix should be applied by hand.

fruiting and use

After the final spraying application is completed, the shelters can be utilized. The main season for occupancy is between June and August. During this time mushrooms grow on the surface and the hikers find cover from the elements or rest spots on their way to the camping sites.

decay

After the main season, the shelters naturally start to decompose. This process is further helped by the weather conditions. Rains, and the risen level of humidity trigger the decay of the mycelium based composite. The mounting brackets can be removed and the structures are left for the nature to absorb.

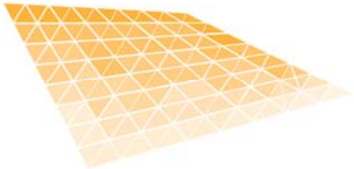
design illustration

scenario #1

the lookout

- on a high spot for optimal viewing
- short-term stay
- wind protection
- varied thicknesses in membrane structure

scenario #2



the resting cave

- becomes part of the existing rock structure
- daytime visit
- semi-open structure, protection from wind and rain
- membrane grown on top of a fabric scaffold.

KEY
- *area*
- *timespan*
- *function*
- *material characteristics*

scenario #3

the resting place

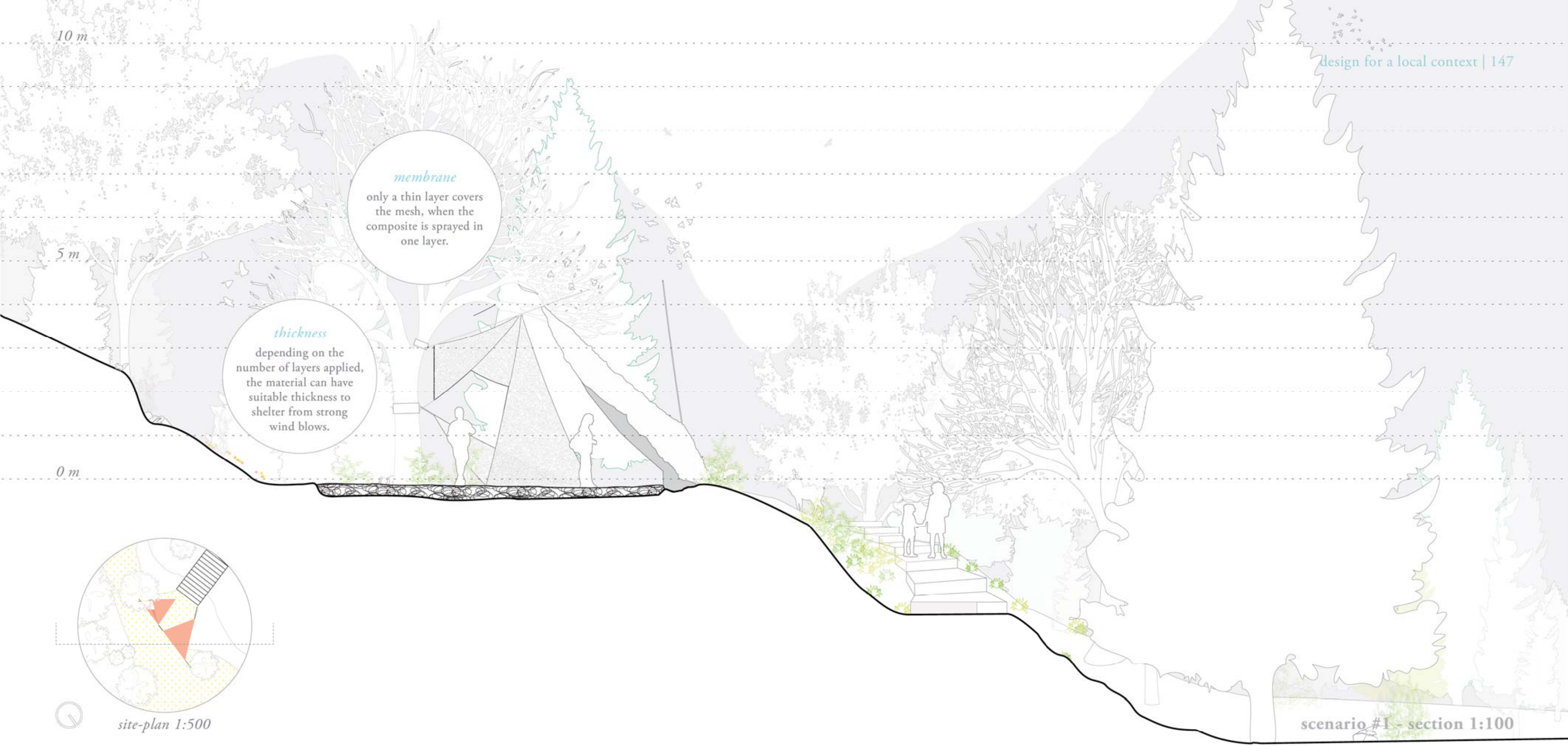
- situated in-between two over-night camps
- daytime visit
- protection from wind and rain
- multi-layered membrane with a hydrophobic exterior layer

scenario #4

the camping spot

- on a sheltered spot in the valley, next to the river
- overnight stay
- protection from all elements
- thick, multi-layered membrane with different types of fibers

Although the proposed designs are presented on specific sites, it is more about the method of implementation for an ecological context which we see ideal for this particular strain.

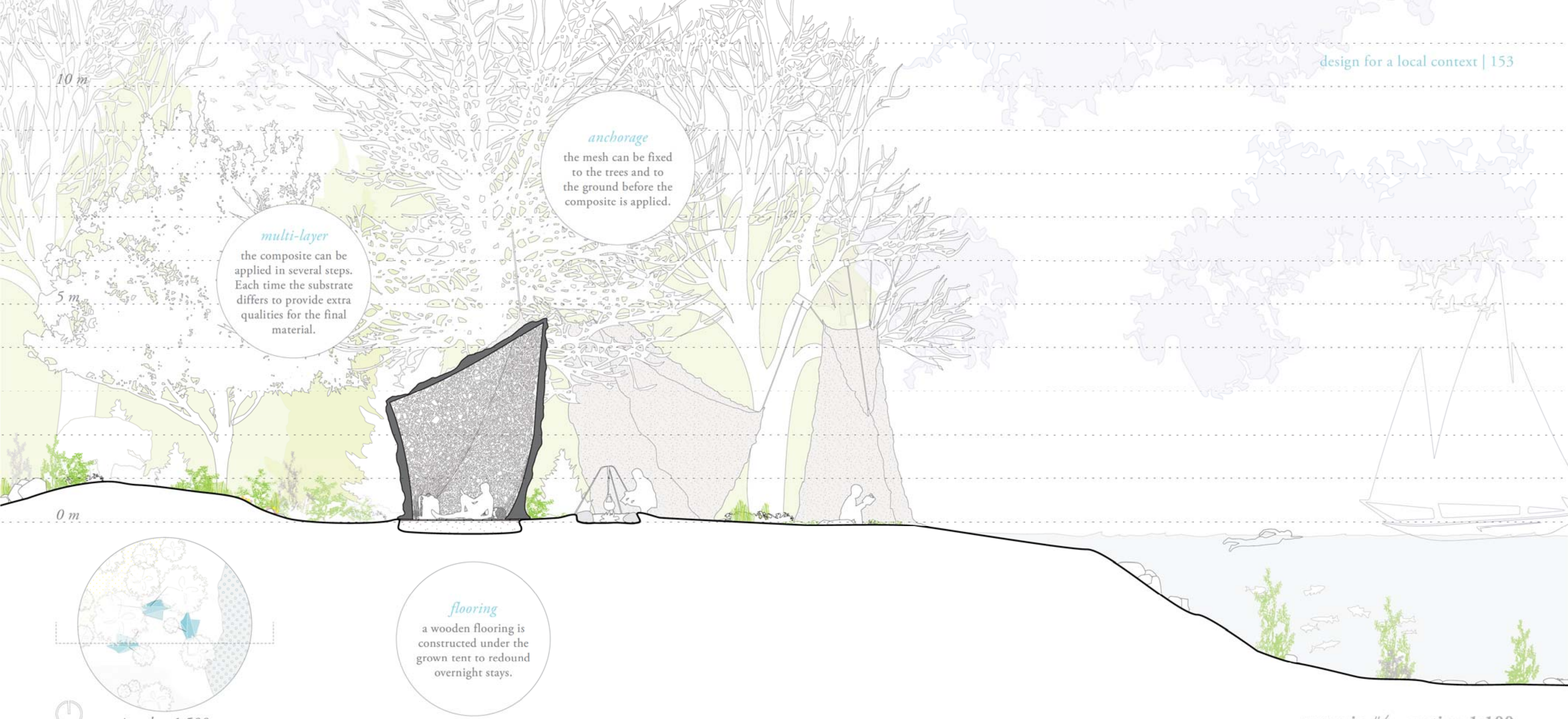


scenario #1 - section 1:100

scenario #2 - section 1:100

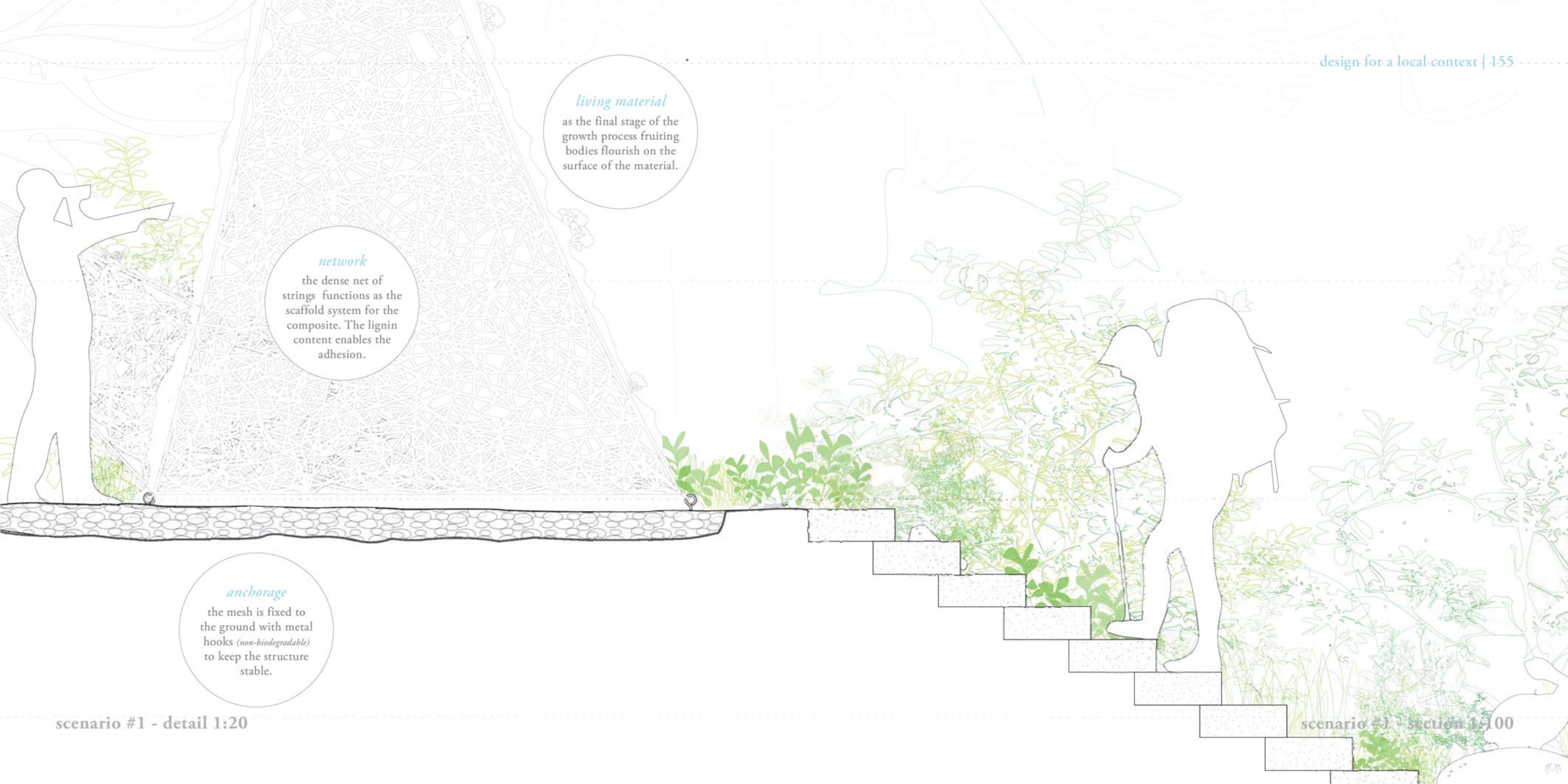
site-plan 1:500

scenario #3 - section 1:100



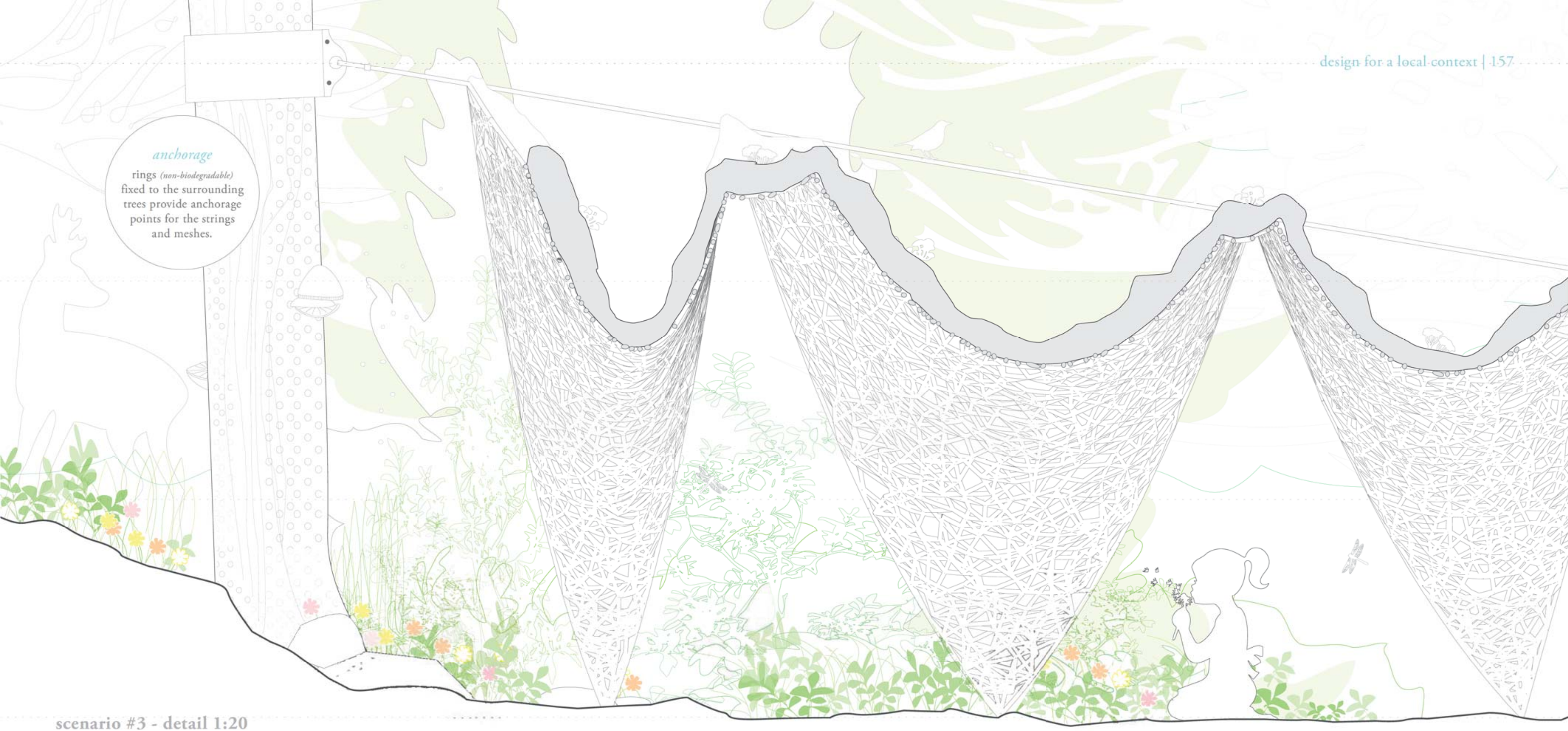
site-plan 1:500

scenario #4 - section 1:100

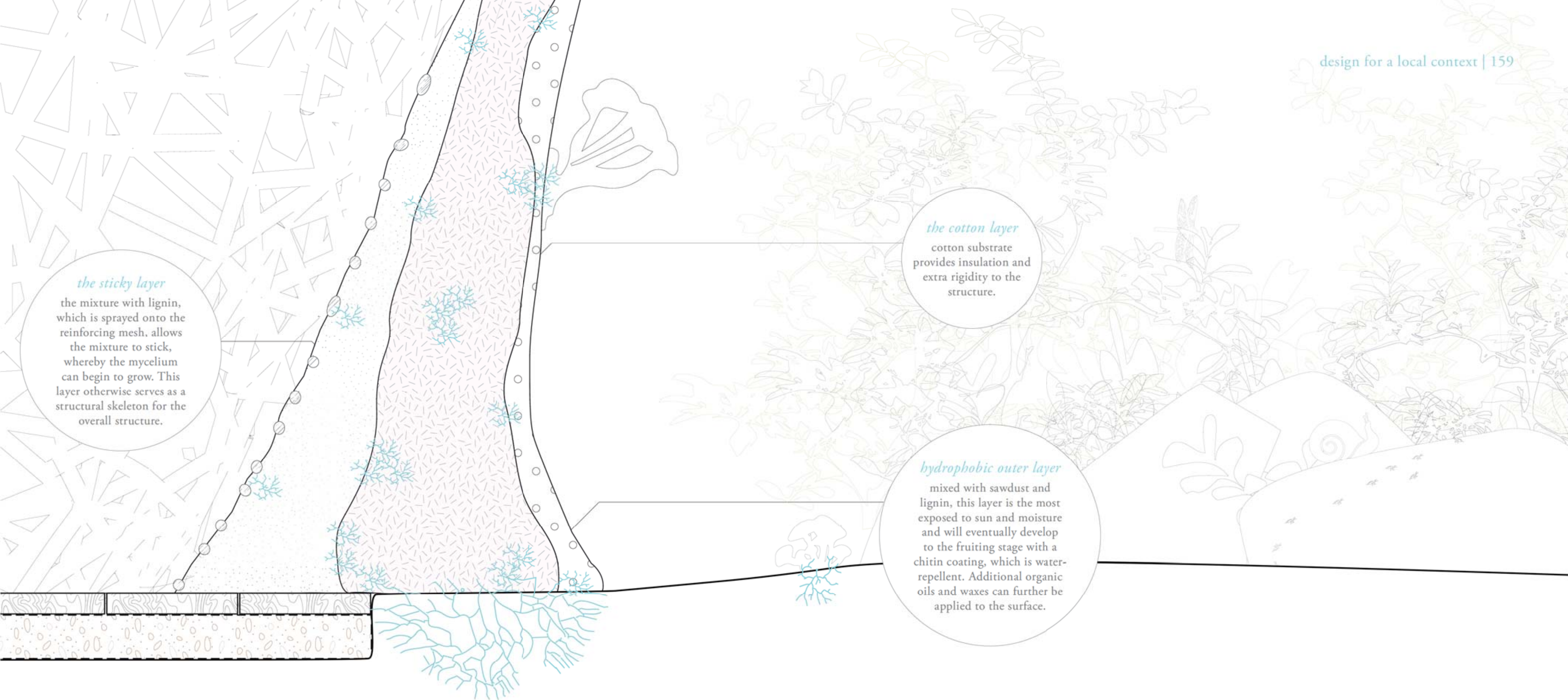


scenario #1 - detail 1:20

scenario #1 - section 1:100



scenario #3 - detail 1:20



scenario #4 - detail 1:5

chapter VIII:
reflection

An Orchestrated Process
Responsive Systems
Further Research
Our Work Flow

an orchestrated process
reflecting upon the thesis question:

Can previous studies on mycelium as an inert material, coupled with practical experiments of our own, allow us to apply mycelium in its living state in an architectural context?

Mycelium is a crucial organism for the ecosystem, channeling nutrients and water to other root systems in the ground. It also produces edible mushrooms and has played an important role in generating some of the most widely used medicines, like penicillin. Moreover, this research project aims to highlight mycelium as a living polymer, from which a new range of biocomposite materials can be derived.

As stated previously, the material has up to this point been predominantly developed for the purpose of packaging: Grown into a pre-determined shape where the mycelium growth is terminated by means of heat treatment. Going back to the primary investigation of this thesis; the feasibility of applying mycelium in its living state to a designed structure, let us first re-examine the question; is there a sound reason for keeping the mycelium alive? Does it add to the quality of the material, or limit its application?

If the aim of the project was to apply mycelium to conventional building methods, as a component part of a standard wall system, the answer would be no. Yet, we are not merely interested in mycelium as an inert bonding matrix, but also concerned with its growing, rhizomatic behavior which is responsive to its surrounding. However this approach demands a re-thinking of the whole process, from design to implementation, as illustrated in our drawings. The design is influenced by the growth of the material and the ongoing forces around it, where the architecture synchronizes with the temporality of its natural environment. Built every year in April and remaining until early autumn, the material follows the annual cycle of nature. The decay of the structure occurs along with the surrounding summer species, which simultaneously begin to degenerate after each season. Our decision to work with a living material is also reinforced in the whereabouts of the site, which is native to the P. Ostreatus. The material is thus dependent upon the symbiosis and diversity of its context. In an urban context, it would be more complicated to integrate such a material successfully without high-tech and costly human assistance.[60]

Nevertheless, the structure is man-made and although environmentally integrated, it is intended to stand apart from the natural surrounds as an artifact of order. The introduction of a living system guided through human activity can be compared to how the gardener engages with the processes of his plants; he follows the changes in the garden and nurtures its development.[61] It demands a more engaged relationship with the architecture and requires an in-depth understanding of the material.

Also, less focus on the determined form suggests more attention will be given to designing the framework. The architect does not only prepare for a responsive structure, but also for the conditions around it: How the material integrates with the site. Even as a native species, the mere scale of this intervention could disrupt the existing ecosystem, hence, there are many factors to be taken into account. The process is rather orchestrated, as opposed to planned, and perhaps this means that we (the architects) must let go of the traditional sense of authorship, embracing the co-dependency of all of the forces and actors engaged in the production.

[60] Borasi, G., Clement, G. and Rham, P., *Environment: Approaches for Tomorrow.* Montréal: CCA publication, 2006, 41.
[61] Armstrong., 72.

Finally, The development of architecture through biology would have implications on the way we perceive the structure over time and space. The mycelium membrane illustrates how other, similarly responsive, metabolic materials might imply a psychological shift in our relationship to architecture; as something more than an objective enclosure. One could picture how the human skin conveys subtle changes in response to sunlight, moisture and different temperature levels, as opposed to the unnaturally glossy surfaces which we enclose ourselves in today. In a sense, by responding to interior and exterior 'stimulation', the building skin communicates a deeper, sensorial understanding of atmosphere.

> "We desire to live in a more ecologically connected world where human development may be good for, not bad for, our biosphere. So, we desire more lifelike technologies... In fact, this kind of collective appetite may be thought of as innovation driver in which technology follows, not leads invention." [62]
>
> - Dr. Rachel Armstrong

[62] Andreotti, A., 2013. Interview - Rachel Armstrong, Innovative Scientist Who Wants to Grow Architecture. *Next Nature.* (Accessed 15/12/2014).

responsive systems

The growing of building fabric could allow for a system which learns from its native surrounding as it grows. The hyphal cells in the mycelium membrane are, for example, automatically programmed to receive information from their environment. They communicate back and forth within the mycelium matrix through an enzymatic and chemical response system which can sense changes happening around it.[63] Even when a mycelia organism reaches a huge mass, spanning over several hectares, it manages to stay in constant molecular communication within the network.

If we aim to use living mycelia for building we must consider its responsiveness as part of its properties. This means that our ability to monitor its development as well as feed information to the system would affect the determination of the hyphal growth and the outcome of the material. This scenario allows us to design on a molecular scale, potentially manipulating the gene-setup of our strain to achieve a more resilient material.

This could be done through modern IT processes which allow real-time data analysis and response in agricultural systems. Depending on the instantaneous conditions, the material is automatically fed with water and nutrients. These systems have the potential to autonomously guide the growth of the material to respond to specific factors. This could be beneficial in the growth of mycelium materials where environmental conditions are susceptible to change. This technology could also drive responsive growth molds which ensure the material grows at required structural densities or proportions.

[63] Statmets., 4.

further research

It is relatively recent that designers have discovered mycelium, with Ecovative Design reaching out to the masses through their inspiring TED-talk in 2012.[64] Since then, we have seen a range of interesting applications of the material, from lamp shades to building blocks. Yet, there is much more to be explored with mycological composites.

In regards to our ambitious project plan; examining the material in different environmental conditions (testing its properties and time of degradation), the course of our thesis took a slightly different turn halfway throughout the semester. (We had also found studies carried out at Berkeley which provided us with relevant information with the mechanical properties of mycological composites.) Based on a conversation with a member - Gavin Jeffries - of the MC2 lab, we decided to look into the benefits of adding lignin to the mycelium composite. This led us to focus less on a finished design, and more to developing a method of application.

Although the hypothesis is grounded in research, it has not actually been tested. However, the suggested mixture of fiber, mycelia and lignin adds a new paragraph to the topic of mycelium which could lead to further research in the field. In conclusion, our developed method takes on the previous research and discussions around the mycelium composite, yet aims to highlight the potentials of the material as a living organism.

[64] *Bayer, E., Are Mushrooms the New Plastics? New York: TED Talk. 2010. http://www.ted.com/talks/eben_bayer_are_mushrooms_the_new_plastic?language=en (Accessed 03/02/2015).*

our work flow

Our process would fall under the category of 'research for design'. Through hands-on experiments, crossing over to disciplines like ecology, mycology, engineering and sometimes even a little chemistry, led us to be able to draw several conclusions about the topic of mycelium as a building material.

It was different to previous design processes in that we had an agenda to follow, laboratory experiments, which were as much based on our own planning as the biology of our material. The time-pressure coupled with the specific nature of our topic, pushed us to seek guidance from experts outside of Chalmers. We spoke to mycological researchers, ecologists and architectural practices who are also become interested in biocomposites.

The latter especially presented us with an exciting world, engaged in the practical implementation of these materials. We felt part of a community of people who are inspired by the potential which these materials offer our generation of architects, and consumed by the excitement of making it happen.

termenology & references

relevant terminology

Agaricales: A particular fungal order, also known as 'gilled mushrooms'.[65]
Agaricomycetes: A particular class of fungi.[65]
Amorphous: Lacking a crystalline structure, something without solid form.[66]
Antler stage: A stage of fungi reproduction, when the mycelium roots are growing and branching.
Basidiomycota: A sub-kingdom within the kingdom of Fungi.[65]
Basidiospore: A reproductive spore generated by sexually reproducing fungi.[65]
Basidium: A microscopic, spore-producing structure found on the gills under the cap of the mushroom.[65]
Biomaterial: Any matter that has been derived from natural sources.[65]
Bioefficiency: The productivity of the strain, measured in the amount of mushrooms generated from a particular type of fungi.[65]
Button: A growth stage in the development of certain types of fungi, where the mushroom body has just begun to develop.
Carbon sequestration: The capturing and long-term storage of atmospheric carbon dioxide.[65]
Chitin: A characteristic component in the cell walls of fungi,provides structure of the cells as well as a hydrophobic layer on the exterior skin surface.[65]
Composite: Materials which comprise of at least two ingredients.[65]
Embodied energy: The sum of all the energy required to produce any goods or services.[65]
Eukaryote: Any organism whose cells contain a nucleus and other organelles enclosed within membranes (animals, fungi).[65]
Filamentous: Thread-like structures (such as mycelium).

[65] Shroomery, The Shroomery Mushroom Glossary, http://www.shroomery.org/5122/The-Shroomery-Mushroom-Glossary (Accessed 15/05/2015)
[66] Vocabulary.com, The dictionary, http://www.vocabulary.com/dictionary/amorphous (Accessed: 03/06/2015)

Gill: The lamella-like structures under the cap of the mushroom.
Glucan: A glucan molecule is a poly-saccharide of D-glucose monomers.[65]
Glycoprotein: Proteins that contain oligosaccharide chains.[65]
Glycogen: A multi-branched polysaccharide of glucose that serves as a form of energy storage.[65]
Hydrophobic: A physical characteristic of a surface or molecule which allows it to repel water.
Hyphae: The long, branching thread-like cords in fungi, collectively called mycelium.[65]
Inoculation: The fertilization of different natural media with mycelia.
Lignin: A complex polymer of aromatic alcohols known as monolinguals. Fills the spaces in the cell wall between cellulose, hemicellulose, and pectin components.[65]
Matrix: The material or tissue between cells in which more specialized structures are made up.[65]
Meiosis: Cell division, which reduces the chromosome number by half. [65]
Membrane: A flexible thin layer.
Mesh: The casting net structure for the application of mycelium mixture.
Mold: Casting form.
Mycelium: The vegetative cell structure of fungi.[65]
Mycology: The branch in biology concerned with the study of fungi.[65]
Nucleus: A membrane-enclosed organelle found in eukaryotic cells.
Oligosaccharides: Saccharides polymer, containing a small number of simple sugars. They can play a role in cell-to-cell recognition.[65]
Organic: Harvested from natural sources, free from any toxic processing.

Pathogen: Any organism or substance capable of causing disease, such as bacteria or fungi.[65]
Physiology: The scientific study of the natural functions in living systems.[65]
Pleosporaceae: A particular family of fungi.[65]
Pleurotus: A genus of gilled mushrooms.[65]
Plylum: A taxonomic rank of fungi, below 'kingdom' and above 'class' (a.k.a 'division').[65]
Polymer: A large 'macro-molecule' composed of many repeated sub-units.
Polymerization: A process of reacting monomer molecules together in a chemical reaction to form polymer chains or three-dimensional networks.[65]
Primodium: Simplest set of cells capable of triggering growth of an organ.[65]
Rizomorph: An organism, such as mycelium, which is made up of a network of cords with no determined beginning or end.
Saprophytic nutritions: Involved in the processing of dead or decayed organic matter.[65]
Septum: A wall (for example in a hyphal cell) dividing a cavity or structure into smaller parts.[65]
Stipe: The stem supporting the cap of a mushroom.[65]
Sterigma: A small supporting structure in the basidum, carrying the spores at its tip.[65]
Substrate: The structural content of the mycelium based composite and the feedstock for mycelia. (e.g. sawdust, straw, cotton or coffee grounds)
Surface: The external layer of structures.
Synthetic: An artificial matter or process (non-organic).

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myco

an investigation into growing building materials

appendix

summary

This appendix is a documentation of the conducted experiments, as a part of the overall thesis work. The project explores methods of reproducing naturally occurring mycelium, or the vegetative root structure of fungi, with the aim to create a building material.

The report collects all the experiments which were developed throughout the thesis in order to understand the characteristics of mycelium-based composites. The conducted experiments test how a particular strain of mycelium adheres to different types of substrates, which - when combined - can potentially produce a multi-layered material. Several methods are explored using molds, scaffolding and textiles. The found results are presented as part of the design process.

In addition, several study trips are summarized in this booklet to demonstrate the learning outcomes of the meetings, interviews and workshops arranged.

sammanfattning

Denna bilaga är en dokumentation av genomförda experiment och utgör en del av examensarbetet. Syftet med experimenten var att testa metoder som kan reproducera naturliga förekommande mycel, eller den vegetativa delen hos fungus, för att producera ett byggnadsmaterial.

Följande rapport innehåller alla experiment som genomfördes under hela projektet för att kunna bedöma samt vidareutveckla egenskaper hos mycelbaserade kompositer. Experimenten testar de bindande egenskaperna av mycel till olika typer av substrat som, i kombination, potentiellt kan producera ett material med flera enskilda skikten och egenskaper. Flera metoder testades med hjälp av moduler, stödställningar och textilier. De bedömda resultaten presenteras som en del av design processen.

Avslutningsvis, sammanfattas även de genomförda studieresorna i denna bilaga med dokumenterad möten, intervjuer och arrangerade workshops.

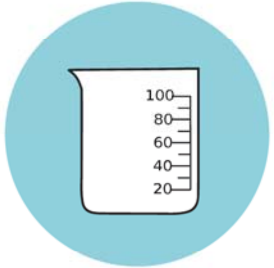
content

Documentation of experiments

Study trips


oat grains
sawdust
straw
coffee grounds
cotton
carton board
hemp
crochet


hyphea
liquid mycelium
wholemeal wheat flour
oat bran
malt agar
corn starch
dextrose
water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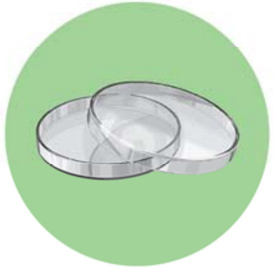
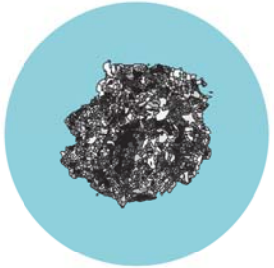
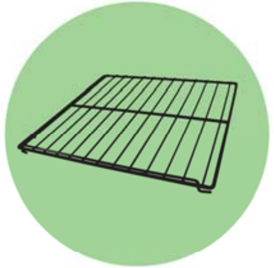




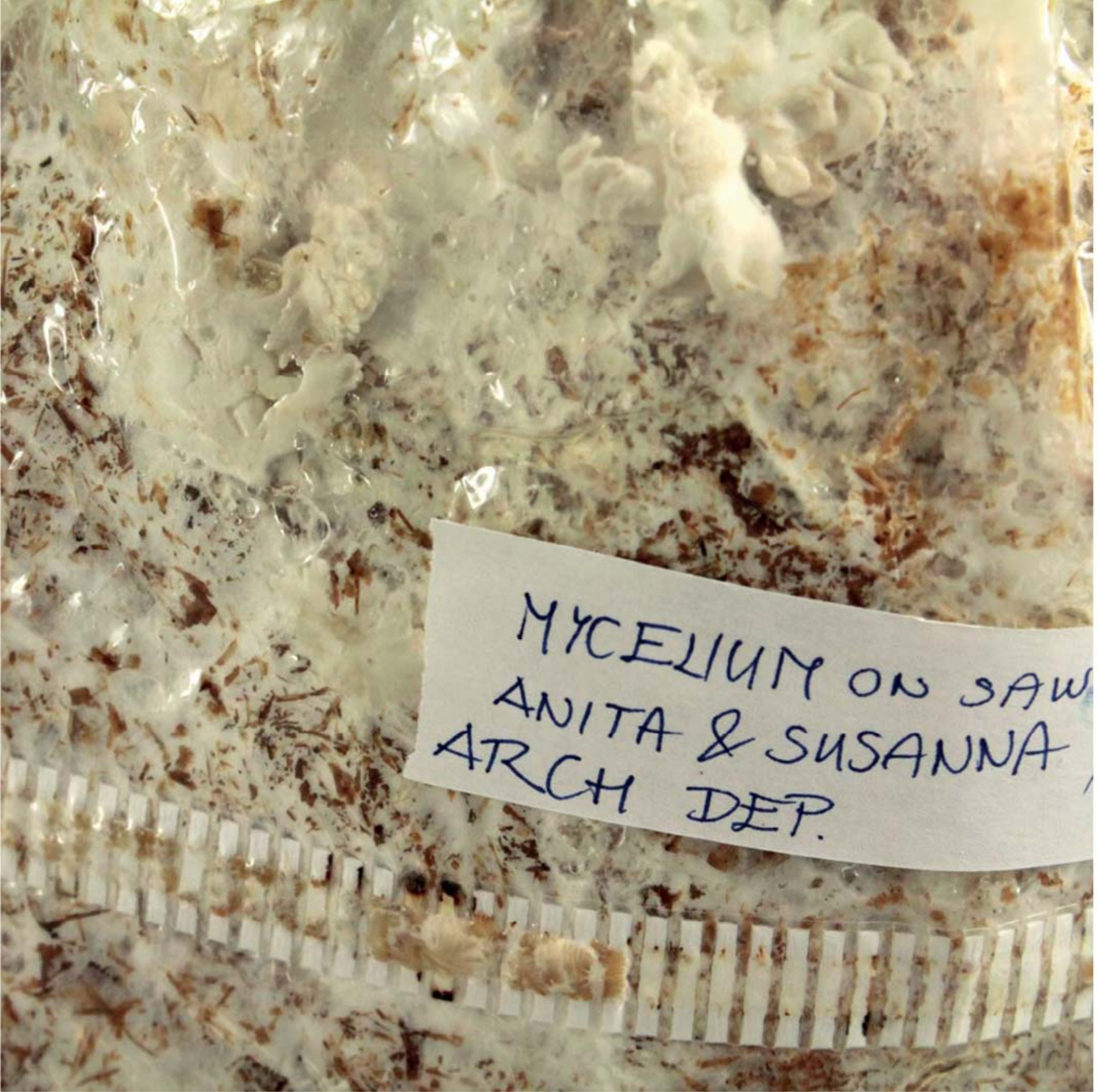



sterile water source
storage
ventilation hood
oven
dishwasher
work stage


ventilation hood
autoclave
work stage

chapter I
reproducing mycelium

Sawdust
Grain
Coffee Grounds
Liquid Culture



sawdust
experiment #1

Ingredients:
- *0,5 kg sawdust pellet*
- *20 g inoculated grain seeds*
- *1,8 l water*

Equipment:
- *injector*
- *scalpel*
- *water jug*
- *air filtered plastic bag*
- *plastic clip*

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment. (bag, scalpel, jars, pipettes…)
Under the ventilation hood pour the sawdust into the bag.
Add the grain seeds to it. (the more you add the faster it grows)
Mix it thoroughly.
Slowly add the water to the mixture. Let it soak.
Give the mixture 10 minutes rest.
Close the bag with the plastic clip.
Label the bag. (name, date)
Let it rest for 3-4 weeks.

experiment conducted on 28/01/2015

injecting 1,8 litre of water into the bag of sawdust

sealed and labelled bag filled with sawdust mixed with inoculated grains

four weeks old inoculated sawdust

six weeks old inoculated sawdust

Notes:

16th of February - The bag's content slowly turns white, indicating the spread of the mycelium. Although the sawdust is still visual, which means there is still space for the mycelium to grow around. We might need to wait more than 3 weeks.

25th of February - On the top of the bag's content small mushrooms start to appear. At this point we removed the sawdust from the bag, and placed it into a plastic box. We cut the mushrooms off, and loosened the mixture in order to re-oxygenize. The box was closed with an air filtered lid.

2nd of March - The mycelium keeps multiplying fast. The outer surface has already been covered with hyphae in 5 days. We will use the inoculated sawdust to create new material samples. Meanwhile the efficient oxygen flow will be provided for a constant growing.

Conclusion:

Altogether it took 4 weeks to reach the stage when we could cultivate the mycelium grown on this amount of sawdust. The content of the bag did not became infected by other organisms, and the process needed minor interference on our behalf.

grains
experiment #1

Ingredients:
- *500 g oat seeds*
- *5 ml mycelium culture*
- *water*

Equipment:
- *500 ml jars*
- *cotton balls*
- *injector*
- *scalpel*
- *water jug*

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (injector, scalpel, jars, ...)
Autoclave the grains.
Under the ventilation hood divide the grains in 3 jars.
Add a little water to it to keep the culture moist.
Suck up 15 ml of the liquid mycelium culture into an injector.
Pour 5 ml into each jar.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the jar with the lid.
Shake the jar so the liquid culture spreads around.
Label the jars. (name, date)
Let it rest for 2-3 weeks.
Every 3-4 days shake it to break the seeds apart.

---

experiment conducted on 29/01/2015

filling the jars with oat grains

adding water to the grains

liquid mycelium culture

injecting mycelium onto the oat grains

Notes:

29th of January - The tree jars were filled with different amount of water. (50 ml, 100 ml and 150 ml).

2nd of February - We noticed that the jars filled with 100 and 150 ml of water started to grow quickly, and produced almost the same amount of mycelium in the same time. The jar with the least of water did not started to grow at all. The mycelium dried out and conserved on the grains.

16th of February - The content of the jar - which originally was filled with 100 ml of water - was used to create new material samples. After two weeks we added more water to the jar which originally had the least amount of water and had dried out since.

2nd of March - The content of the jar - which originally was filled with 150 ml of water - was used to create new material samples. In the meantime the content of the jar - which was originally filled with the least amount of water - has begun to multiply.

Conclusion:

This amount of grains (approximately 150 g) should soak in at least 100 ml of water during the growing process. To re-oxygenize the mixture frequently is an effective way to accelerate the multiplication of the mycelium.

On the bottom of the jars a concentrated liquid mycelium culture is gathered. This fluid also can be used for inoculation, and since it is an intense form of mycelium, the inoculation is rather successful.

one week old sample

two weeks old sample

three weeks old sample

inoculated oat grains

experiment #2

Ingredients:

150g oat seeds
5 ml mycelium culture
20 ml wholemeal wheat flour
10 ml corn starch
100 ml water

Equipment:

500 ml jars
cotton balls
injector
scalpel
water jug

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (injector, scalpel, jars, ...)
Autoclave the grains.
Under the ventilation hood pour the grains in the jar.
Add 100 ml water to it to keep the culture moist.
Suck up 5 ml of the liquid mycelium culture into an injector.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the jar with the lid.
Shake the jar so the liquid culture spreads around.
Label the jar. (name, date)
Let it rest for 2-3 weeks.
Every 3-4 days shake it to break the seeds apart.

experiment conducted on 16/02/2015

two weeks old sample

three weeks old sample

four weeks old sample

six weeks old sample

Notes:

18th of February - In order to reach a faster growth of the mycelium, we mixed additional nutritions (wheat flour and corn starch) to the grains.

2nd of March - By visual observation we noticed that the additional nutritions (wheat flour and corn starch) did not speed up the growth process of the mycelium.

16th of March - The mycelium is now well developed and filled the air-gaps between seeds. Although there is still space for the mycelium to grow.

23rd of March - At this moment the upper surface of the culture got infected by green mold. The jar was immediately removed from the ventilation hood.

4th of May - The inoculated sample was stored in room temperature to observe the further process. The oyster mushroom managed to control the green mold contamination and at the moment there is no more visual sign of the mold.

9th of May - The mycelium kept on multiplying and ultimately overgrew the green mold contamination.

Conclusion:

The additional nutritions did not support the growth of the mycelium culture. In fact the additives slowed down the process and resulted in a low quality mycelium which resistance against contamination was not efficient. Although later the oyster mycelium - by the time it developed well enough - overcame the contamination.

coffee grounds

experiment #1

Ingredients:

500 g coffee grounds
inoculated sawdust
water

Equipment:

plastic box
cotton balls
scalpel
water jug

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (box, scalpel, jars, ...)
Autoclave the coffee grounds.
Under the ventilation hood pour the coffee grounds into the plastic box.
Mix the inoculated sawdust with the coffee grounds.
Add water to keep the culture moist.
Gently mix the compound again.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
Let it rest for 2-3 weeks.
After a week break the coffee grounds apart.

experiment conducted on 05/02/2015

one week old sample

three weeks old sample

four weeks old sample

nine weeks old sample

Notes:

5th of February - The collected coffee grounds were mixed with the inoculated sawdust and left to rest in a plastic box with an air-filter on top

16th of February - On the surface of the coffee grounds the mycelium started to multiply. We noticed a slight discolored pattern. We assume that this is caused by the strong tint of the medium. The mixture was steered gently to enable the center to receive enough oxygen.

25th of February - The inoculated coffee grounds were placed into a bigger box. The tight mixture was loosened and left to rest again.

5th of March - The mycelium formed a block out of the coffee grounds. By touch it has a rubber-like flexible consistency. The mixture was broken into pieces to provide oxygen for the continuous growth.

7th of April - The inoculated culture is still vital and multiplies fast. The content of the box was broken into pieces again to oxygenize the inner parts.

Conclusion:

Coffee grounds are great primary commodity for mycelium multiplication. The discolored pattern disappeared after the first weeks and the white mycelium grew over the medium.

liquid culture

experiment #1

Ingredients:

10 g dextrose
12 g malt agar
300 ml water
10ml liquid mycelium culture

Equipment:

500 ml jar
cotton balls
injector
scalpel
water jug

Protocol:

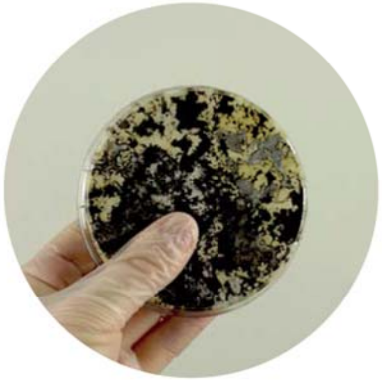
Wear gloves, goggles, lab coat.
Sterilize all your equipment (jars, scalpel, injector…)
Mix the dextrose, malt agar and water in a glass bottle.
Cover the top with alu-foil.
Put the bottle in the autoclave.
Under the ventilation hood pour the liquid into the sterilized jar.
Inject 10 ml of liquid culture with an injector into the jar.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the jar with the lid.
Cover the jar with alu-foil and leave it in the ventilation hood.
Label the jar. (name, date)
Let it multiply for 2-3 weeks in darkness.
From the 4th day swirl around to re-oxygenate. Do it every day!

experiment conducted on 18/02/2015

mycelium on malt agar mixed with inoculated sawdust

mycelium on malt agar mixed with inoculated coffee grounds

one week old sample – sawdust



one week old sample – coffee grounds

Notes:

18th of February - After the liquid was taken out of the autoclave and started to cool down, the mixture begun to congeal.

25th of February - By observation, the content of the jar is solid but flexible. The experiment did not resulted in the expected way, but the mycelium multiplied on the agar's surface. We decided to use the gel-like material in a new experiment. We mixed it with inoculated sawdust and coffee grounds.

9th of March - All the sawdust samples became infected by green mold. The samples were removed from the ventilation hood, and were destroyed.

20th of March - The coffee grounds based samples developed an extensive mycelium layer around the surfaces.

17th of April - The mycelium layer is well developed at this point. Thus the samples were removed from the ventilation hood and left to rest for two days to dry out.

20th of April - In the oven the samples were baked on 95 °C for half an hour. Due to the high temperature the malt agar content melted and departed from the samples. It resulted in a major shrinking of the original volume.

Conclusion:

The additional malt agar gel could be useful to create voids inside of the blocks, when it is structurally or aesthetically beneficial.

infected sample – sawdust

three weeks old sample – coffee grounds

four weeks old sample – coffee grounds

five weeks old sample

experiment #2

Ingredients:
- *10 g dextrose*
- *400 ml water*
- *10ml liquid mycelium culture*

Equipment:
- *500 ml jar*
- *cotton balls*
- *injector*
- *water jug*

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (jars, injector, …)
Mix the dextrose and the water in a glass bottle.
Cover the top with alu-foil.
Autoclave the liquid in the bottle.
Under the ventilation hood pour the liquid into the sterilized jar.
Inject 10 ml of liquid culture with an injector into the jar.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the jar with the lid.
Cover the jar with alu-foil and leave it in the ventilation hood.
Label the jar. (name, date)
Let it multiply for 2-3 weeks in darkness.
From the 4th day swirl around to re-oxygenate. Do it every day!

experiment conducted on 26/02/2015

multiplying liquid mycelium

one week old sample

three weeks old sample

five weeks old sample

Notes:

6th of March - A slow multiplication of the mycelium occurred during the past week.

20th of March - A slow multiplication of the mycelium occurred during the past week.

7th of April - The mycelium particles aim to grow together and form a block. Although the multiplication is very slow. This might be due to not enough nutritions provided at the beginning of this process.

4th of May - No further progress could be observed.

Conclusion:

Additional nutritions should be provided. Several video sources suggest malt, dextrose and calcium-carbonate.

chapter II
material samples

Straw
Coffee Grounds
Cotton
Layered Samples
Hemp
Crochet

straw

experiment #1

Ingredients:

40 g straw (1-3 cm long)
15g wholemeal wheat flour
15g corn starch
inoculated sawdust
water

Equipment:

metal bowl
scalpel
molds (plastic boxes)
cotton

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (mold, scalpel, bowl…)
Soak the straw in boiled water for 30 minutes.
Drain the straw.
Mix the straw, flour and corn starch.
Autoclave the mixture.
Under the ventilation hood mix the straw, inoculated sawdust and water.
Fill the mixture into the mold tightly.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the mold.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minutes.

experiment conducted on 30/01/2015

inoculated sawdust

opening autoclaved bags filled with straw

mixing the ingredients

straw mixed with inoculated sawdust

Notes:

16th of February - We took one sample out of the mold and left one in it to start the drying process. We waited to perform with this step, because we hoped the mycelium will spread more and fill out the mold completely.

18th of February - We found different descriptions suggesting different temperature for the baking process.* We started the baking with one of the samples. The brick was placed in the oven for 45 minutes on 65 °C. After we took it out and let it cool down, the sample was still moist. We repeated the baking with the second sample, this time on 95 °C for 60 minutes. The sample became solid and dry.

Conclusion:

The substrate (straw) pieces were too long (1-3 cm). In order to reach a higher density and let the mycelium grow tighter we need to cut the subtract smaller.

The baking process for such a volume of a sample should last for 60 minutes on 95 °C.

* ***For example:*** *Patent of Ecovative design*
Mycology Matrix Composites by Dharan, CKH., Noble, J., Ross, P., and Travaglini, S.,

mold filled with the mixture

one week old sample

two weeks old sample

sample taken out of the mold

experiment #2

Ingredients:

40 g straw (5-10 mm long)
20 ml wholemeal wheat flour
10 ml corn starch
inoculated oat grains
100 ml water

Equipment:

metal bowl
scalpel
molds (plastic boxes)
cotton
water jug

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (mold, scalpel, bowl…)
Mix the straw, flour and corn starch.
Autoclave the mixture.
Under the ventilation hood add inoculated wheat grains to the mixture.
Add water and mix it gently.
Fill the mixture into the mold tightly.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name,date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minute.

experiment conducted on 16/02/2015

mixing straw with inoculated grains

the filled mold

two weeks old sample

four weeks old sample

Notes:

25th of February - By visual observation a slower growth pace was identified. We assume that due to the higher density of the sample the mycelium receives less oxygen than previously.

5th of March - The mold was left open for a couple of days in order to let the mycelium breath.

23rd of March - The mycelium begun to develop more efficiently and the sample starts to be covered with the white layer of the organism.

7th of April - The sample was removed from the ventilation hood and left to rest two days to dry out.

20th of April - The sample was baked in the oven on 95 °C for an hour.

Conclusion:

In order to achieve the required result the three most important factors are: density, moisture level and the right amount and combination of nutritions.

experiment #3

Ingredients:

40 g straw (5-10 mm long)
10 ml wholemeal wheat flour
10 ml corn starch
inoculated sawdust
100 ml water

Equipment:

metal bowl
scalpel
molds (petri dishes)
cotton
water jug

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (mold, scalpel, bowl…)
Mix the straw, flour and corn starch.
Autoclave the mixture.
Under the ventilation hood add inoculated sawdust to the mixture.
Add water and mix it gently.
Fill the mixture into the mold tightly.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name,date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minute.

experiment conducted on 05/03/2015

straw mixed with inoculated sawdust

one week old sample

two weeks old sample

three weeks old sample – dried out

Notes:

5th of March - The mixture was divided and filled into several petri dishes. The previous sample was compressed to reach a higher density, but this resulted in a slower multiplication of the mycelium. This time the sample is less compressed leaving air-gapes and oxygen for the mycelium to grow.

23rd of March - The multiplication of the mycelium is steady and progressive.

2nd of April - The samples dried out and the development of the mycelium layer stopped due to the lack of water content in the samples.

Conclusion:

The air gap left to ensure the oxygen flow for the mycelium appeared to be too wide. This led to the dehydration of the samples, which eventually stopped the growth process.

experiment #4

Ingredients:

40 g straw (5-10 mm long)
10 ml wholemeal wheat flour
10 ml corn starch
inoculated coffee grounds
300 ml water

Equipment:

metal bowl
scalpel
molds (plastic boxes)
cotton
water jug

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (mold, scalpel, bowl…)
Mix the straw, flour and corn starch.
Autoclave the mixture.
Under the ventilation hood add inoculated coffee grounds to the mixture.
Add water and mix it gently.
Fill the mixture into the mold tightly.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name,date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minute.

experiment conducted on 06/03/2015

mixture filled in the mold

one week old sample

two weeks old sample

baked sample

Notes:

6th of March - Two plastic boxes and a petri dish were filled with the mixture.

16th of March - The mycelium started to multiply, no contamination can be observed.

23rd of March - On the outer surface of the sample the mycelium developed further. If the pace of the process remains the same, the sample will be ready in a week. On the other hand the sample in the petri dish is ready to be dried and baked, thus it was taken out of the ventilation hood.

7th of April - The samples were removed from the ventilation hood to rest for two days to dry out.

20th of April - In the oven the samples were baked for 60 minutes on 95 °C.

Conclusion:

The sample is heavier and seems structurally more stable compared to the ones which were made with inoculated sawdust. The inoculation medium shall be chosen depending on the pre-set physical requirements and the future application method of the material.

The volume of the samples effects the time needed for the growth process to be completed. As expected, the smaller the sample the faster it is finished.

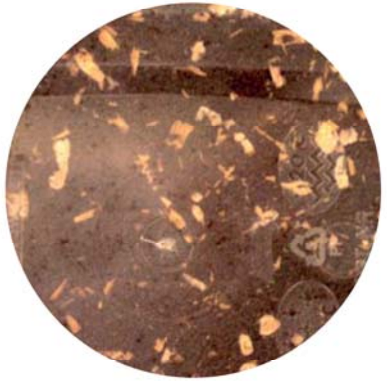
coffee grounds
experiment #1

Ingredients:
500 g coffee grounds
inoculated sawdust
water

Equipment:
metal bowl
mold (plastic box)
cotton balls
scalpel
water jug

Protocol:
Wear gloves, goggles, lab coat.
Sterilize all your equipment (molds, scalpel, jars, bowls…)
Autoclave the coffee grounds.
Under the ventilation hood pour the coffee grounds into the metal bowl.
Mix the inoculated sawdust with the coffee grounds.
Add water to keep the culture moist.
Gently mix the compound again.
Fill the mold tightly.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minute.

experiment conducted on 05/02/2015


coffee grounds mixed with inoculated sawdust


one week old sample


three weeks old sample


four weeks old sample

Notes:

16th of February - Due to the high density of the sample, the mycelium performs a slower multiplication. We decided to partly open the lid of the mold to enhance a better oxygen flow.

25th of February - We noticed that the mycelium has grown extensively on the side where the lid was open from time to time. On the other hand, the opposite side of the sample shows a slower improvement.

5th of March - The mold was left open for overnight before the sample is removed.

6th of March - The sample was taken out of the mold and left under the ventilation hood to dry for two days.

9th of March - The block was baked for 60 minutes on 95 °C.

Conclusion:

The mycelium grew over the coffee grounds in a varying thickness. On the parts where the mycelium was thin on the surface, the block of coffee grounds opened in cracks during the baking process. The material's weakness lies in its porous consistency.

cotton

experiment #1

Ingredients:	***Equipment:***
cotton (torn into pieces)	*metal bowl*
40 ml wholemeal wheat flour	*mold (plastic box)*
20 ml corn starch	*cotton balls*
inoculated oat grain	*scalpel*
water	*water jug*

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (mold, scalpel, bowl...)
Mix the cotton, flour and corn starch.
Autoclave the mixture.
Under the ventilation hood put the cotton into the metal bowl.
Mix the inoculated oat grains with the cotton.
Add water to the compound and mix it gently.
Fill the mixture into the mold tightly.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minute.

experiment conducted on 16/02/2015

mixing cotton with inoculated grains

filling the mold with the mixture

two weeks old sample

five weeks old sample

Notes:

16th of February - During our visit at GXN an interesting sample have been shown to us. In this sample the substrate was cotton, which allowed a flexible consistency to the material. This triggered our curiosity and we mixed a sample on our own.

5th of March - This time the growing process is less efficient then in the previous experiments. This could be caused by the high moisture level of the sample.

23rd of March - The sample was infected by mold. Thus it was removed from the ventilation hood and destroyed.

Conclusion:

The high moisture content stopped the mycelium multiplication and created a suitable environment for mold to develop. The cotton soaked and held too much water. This substrate shall be mixed with less water.

experiment #2

Ingredients:

cotton (torn into pieces)
inoculated oat grain
water

Equipment:

metal bowl
mold (plastic box)
cotton balls
scalpel
spray bottle (for water)

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (mold, scalpel, bowl…)
Autoclave the cotton.
Under the ventilation hood put the cotton into the metal bowl.
Mix the inoculated oat grains with the cotton.
Spray water onto the compound and mix it gently.
Fill the mixture into the mold loosely.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minute.

experiment conducted on 08/04/2015


inoculated oat grains


mixing the cotton with the inoculated grains


spraying water on the top surface


after the growth process is complete

Notes:

15th of April - The moisture content seems to be suitable for the mycelium to develop. No contamination observed on the sample.

22nd of April - After two weeks the mycelium bondage between the substrate particles expanded and the growth process is completed. The sample remains in the mold for two more days.

24th of April - The sample was removed from the ventilation hood and left to rest for two days to dry out.

27th of April - For an hour the sample was baked in the oven on 95 °C. After the block has cooled down it still kept a flexible soft consistency.

Conclusion:

This substrate can provide proper insulation qualities for the material, while performing as a flexible, thus pliable substance.

layered samples

experiment #1

Ingredients:
- *paper carton*
- *inoculated sawdust*
- *water*

Equipment:
- *metal bowl*
- *mold (plastic box, petri dish)*
- *cotton balls*
- *scalpel*
- *water jug*

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (mold, scalpel, bowl...)
Cut the carton in the right shape and autoclave them.
Under the ventilation hood pour water into the metal bowl.
Dip a piece of carton in the water.
Place the first layer of carton into the mold.
Spread inoculated sawdust on top in 5 mm width.
Repeat the layering 2 more times and cover it with the last carton.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minute.

experiment conducted on 25/02/2015

layered in our standard mold

layered in a petri dish

one week old sample

one week old sample

Notes:

25th of February - The layers were created in two different molds, one plastic box and one petri dish.

5th of March - In a week the mycelium started to grow over the carton layers and bond the different materials.

20 of March - The samples were removed from the ventilation hood and left to rest for two days to dry out.

23 of March - In the oven the samples were baked on 95 °C for an hour. The smaller sample was removed after half an hour.

Conclusion:

The mycelium is capable to bond multiple layers of organic material sources (in this case: cardboard and sawdust). This ability could be exploited to develop a multi-layered material performing different required properties for building construction.

experiment #2

layer #1 - straw

Ingredients:

- *45 g straw*
- *inoculated oat grains*
- *200 ml water*
- *20 ml wholemeal wheat flour*
- *20 ml corn starch*

Equipment:

- *metal bowl*
- *molds (plastic boxes)*
- *cotton balls*
- *scalpel*
- *water jug*

layer #2 - sawdust

Ingredients:

- *100 g raw sawdust*
- *inoculated sawdust*
- *500 ml water*
- *20 ml wholemeal wheat flour*
- *20 ml corn starch*

Equipment:

- *metal bowl*
- *molds (plastic boxes)*
- *cotton balls*
- *scalpel*
- *water jug*

layer #3 - cotton

Ingredients:

- *25 g cotton*
- *inoculated oat grains*
- *50 ml water*
- *10 ml wholemeal wheat flour*
- *10 ml corn starch*

Equipment:

- *metal bowl*
- *molds (plastic boxes)*
- *cotton balls*
- *scalpel*
- *water jug*

experiment conducted on 02/03/2015

layer #1 – straw

layer #2 – sawdust

layer #3 – cotton

filled mold

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (mold, scalpel, bowl…)
Mix the different substrates with the right amount of nutritions.
Autoclave the three mixtures separately.
Under the ventilation hood create the final mixture of the three layers, add the rest of the ingredients to the substrates.
Place the first layer (straw substrate) into the mold.
Continue with the second (sawdust substrate) and third (cotton substrate) layers.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minute.

one week old sample

one week old sample

two weeks old sample

three weeks old contaminated sample

Notes:

2nd of March - Two samples were created in same size of molds.

9th of March - The samples develop as expected. The mycelium started to bond the substrates in the block. Although the middle (sawdust based layer) seems to improve slower mycelium multiplication.

16th of March - Most certainly due to a high moisture content the samples were infected by green mold. Both boxes were removed from the ventilation hood and destroyed. The experiment will be repeated with chung amount of added water.

Conclusion:

Once again the proper moisture of the samples proved to be important. Also we can assume that once mold occurs in the sealed isolated environment, the chance of further contamination of the new samples is higher than before. After each discovered mold infection the ventilation hood has been and will be cleaned with ethanol to lower the risk of further contamination.

experiment #3

layer #1 - straw

Ingredients:
- *45 g straw*
- *inoculated oat grains*
- *200 ml water*
- *20 ml wholemeal wheat flour*
- *20 ml corn starch*

Equipment:
- *metal bowl*
- *molds (plastic boxes)*
- *cotton balls*
- *scalpel*
- *water jug*

layer #2 - cotton

Ingredients:
- *25 g cotton*
- *inoculated oat grains*
- *50 ml water*
- *10 ml wholemeal wheat flour*
- *10 ml corn starch*

Equipment:
- *metal bowl*
- *molds (plastic boxes)*
- *cotton balls*
- *scalpel*
- *water jug*

experiment conducted on 02/03/2015

cotton based layer on the top

straw and cotton layers

straw based layer on the bottom

one week old sample

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (mold, scalpel, bowl…)
Mix the different substrates with the right amount of nutritions.
Autoclave the two mixtures separately.
Under the ventilation hood create the final mixture of the two layers, add the rest of the ingredients to the substrates.
Place the first layer (straw substrate) into the mold.
Continue with the second (cotton substrate) layer.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minute.

three weeks old sample

three weeks old sample

five weeks old sample

baked sample

Notes:

9th of March - The mycelium bondage begun to develop around and between the substrates.

20th of March - Due to the slow multiplication of the mycelium we decided to open the lid to provide extra oxygen flow for the organisms. The lids were closed again when we left the laboratory.

7th of April - At the moment no contamination can be seen and the mycelium growth seems promising.

14th of April - The block was removed from the ventilation hood and left to rest for two days to dry out.

16th of April - The sample was baked in the oven on 95 °C for 60 minutes.

Conclusion:

The layers made of two different substrates bonded coherently through the mycelium. The cotton based layer provides a soft surface with potential insulating qualities while the straw substrate gives structural strength to the multi-layered composite.

experiment #4

layer #1 - cotton

Ingredients:
25 g cotton
inoculated oat grains
25 ml water

Equipment:
metal bowl
molds (plastic boxes)
cotton balls
scalpel
water jug

layer #2 - straw

Ingredients:
50 g straw
inoculated sawdust
150 ml water
10 g dextrose
20 g of oat bran

Equipment:
metal bowl
molds (plastic boxes)
cotton balls
scalpel
water jug

experiment conducted on 16/04/2015

mixing the autoclaved compounds

adding water to the mixture

filling the mold

filled mold

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (mold, scalpel, bowl…)
Mix the different substrates with the right amount of nutritions.
Autoclave the mixtures.
Under the ventilation hood create the final mixture of the layers, add the rest of the ingredients to the substrates.
Place the first layer (cotton substrate) into the mold.
Continue with the second (straw substrate) layer.
Add the last layer (cotton substrate) on the top.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 60 minute.

prepared sample

one week old sample

top layer – cotton substrate

three weeks old sample

Notes:

16th of April - The sample was layered in a tall plastic box.

23th of April - The mycelium matrix develops fast and bonds the different layers together.

4th of May - The sample was removed from the ventilation hood two days ago to let it dry. It was baked in the oven on 95 °C for 60 minutes.

Conclusion:

In this experiment the water content was reduced and as a result no contamination occurred. In thick volumes it is crucial to keep the right moisture level to prevent foreign organisms to develop.

hemp
experiment #1

Ingredients:
hemp textile
inoculated sawdust
water

Equipment:
incubator (plastic box)
cotton balls
scalpel
spray bottle (for water)
metal clips

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (boxes, scalpel, clips…)
Cut the hemp textile into the required pieces and autoclave them.
Under the ventilation hood spray water onto the hemp.
Place the textile into the incubator and fix it in the required shape with the metal clips.
Spread inoculated sawdust on top in 5 mm width.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.

experiment conducted on 08/04/2015

spraying water on the hemp textile

applying inoculated sawdust onto the hung surface

the sample in the incubation box

dried sample

Notes:

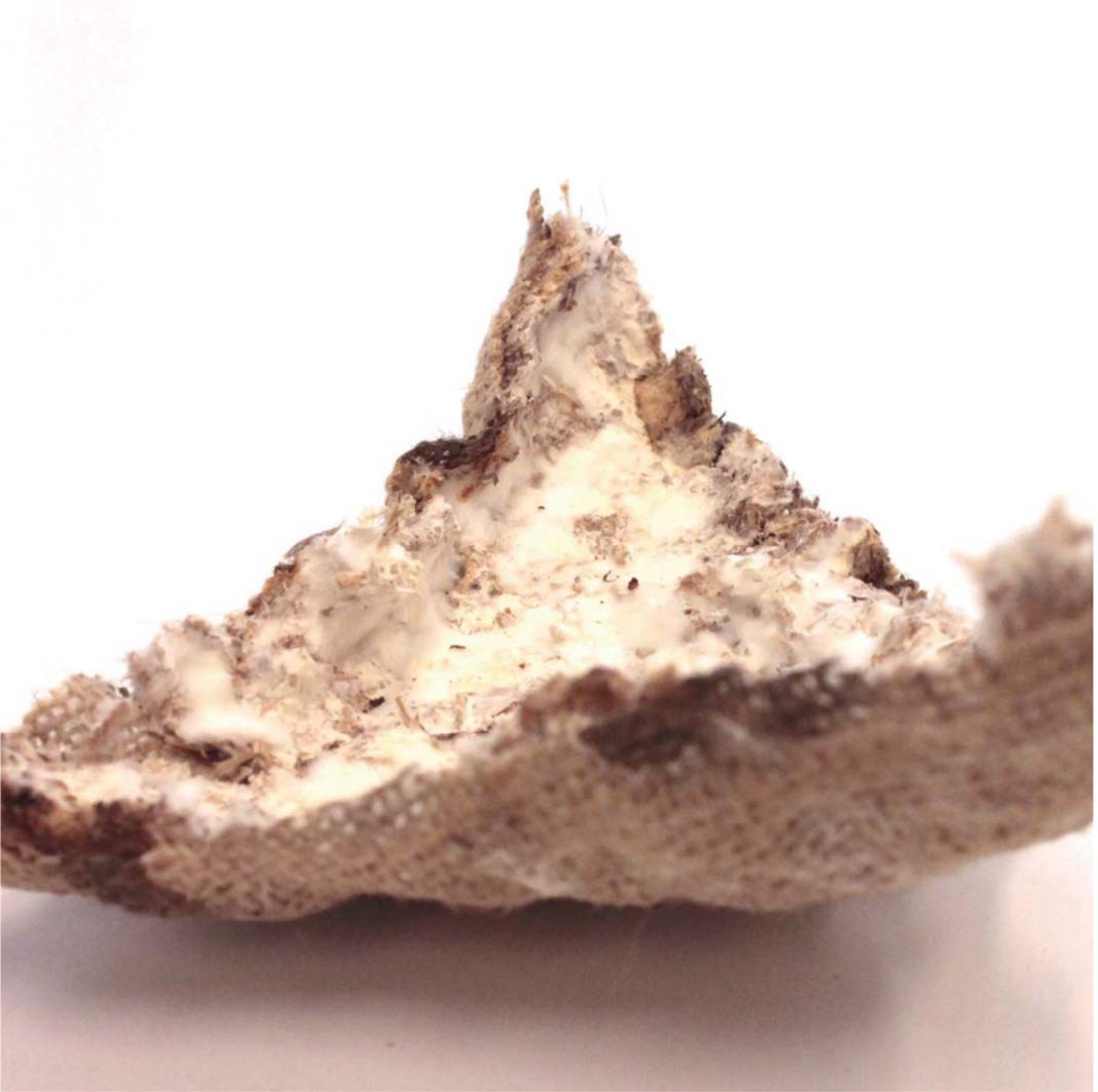
8th of April - The sample was hung in a plastic box, functioning as an incubator and ensuring a semi-sealed growing environment.

16th of April - By visual observation the mycelium started to multiply and stick to the surface of the hemp textile.

23rd of April - Due to the small volume of the applied inoculated substrate, the sample's growth process is already complete. Thus it was removed from the ventilation hood and left to rest to dry out. This time no post-factum heat treatment was performed.

Conclusion:

To make the inoculated sawdust stick to the surface of the hemp was a challenge in this experiment. Even though only a small percentage of the sawdust stuck to the material, after the completion of the growth process the dried mycelium kept the shape of the hung textile.



experiment #2

Ingredients:

hemp textile
inoculated sawdust
liquid mycelium culture
water

Equipment:

incubator (plastic box)
cotton balls
scalpel
spray bottle (for water)
metal clips

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (boxes, scalpel, clips…)
Cut the hemp textile into the required pieces and autoclave them.
Under the ventilation hood spray water onto the hemp.
Place the textile on a tray.
Apply inoculated sawdust in 5 mm of width on the surface of the hemp textile. Spread liquid mycelium drops on the top.
Hang the mesh into the incubator and fix it in the required shape with the metal clips.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.

experiment conducted on 08/04/2015

spraying water on the hemp textile

spreading liquid mycelium drops on the top of the inoculated sawdust

hung hemp textile with inoculated sawdust

one week old sample

Notes:

8th of April - The sample was hung in a plastic box, functioning as an incubator and ensuring a semi-sealed growing environment.

16th of April - By visual observation the mycelium started to multiply and stick to the surface of the hemp textile.

23rd of April - The mycelium developed well and the bondage between the particles of the substrate and the hemp strengthened.

30th of April - The sample was removed from the ventilation hood and left to rest and dry out. No post-factum heat treatment was performed.

Conclusion:

Applying the substrate before the hanging helped the sawdust to stick better to the surface. Although some pieces have fallen off when the mesh was shaped. The developed mycelium bonded the substrate to the hemp and thus the shape held its form after the drying phase.

experiment #3

Ingredients:
hemp textile
liquid mycelium culture
water

Equipment:
injector
incubator (plastic box)
cotton balls
spray bottle (for water)
metal clips

Protocol:
Wear gloves, goggles, lab coat.
Sterilize all your equipment (boxes, scalpel, clips…)
Cut the hemp textile into the required pieces and autoclave them.
Under the ventilation hood spray water onto the hemp.
Place the hemp on a tray.
Spread the liquid mycelium on the surface with an injector.
Hang the textile into the incubator and fix it in the required shape with the metal clips.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.

experiment conducted on 08/04/2015

spraying water on the hemp textile

dropping liquid mycelium culture on the hemp surface

green mold contamination

green mold contamination

Notes:

8th of April - The sample was hung in a plastic box, functioning as an incubator and ensuring a semi-sealed growing environment.

16th of April - The sample dried out since the hemp wasn't capable of holding the applied water content. To reactivate the mycelium culture more water was sprayed on the surface of the sample.

23rd of April - The previously applied extra water provided a great environment for green mold. Thus the sample was contaminated. It was removed from the ventilation hood and destroyed.

Conclusion:

The hemp textile alone is not enough to provide sufficient nutritions, growing medium and environment for the mycelium.

crochet
experiment #1

Ingredients:

crochet
inoculated sawdust
water

Equipment:

incubator (plastic box)
cotton balls
scalpel
spray bottle (for water)

Protocol:

Wear gloves, goggles, lab coat.
Sterilize all your equipment (boxes, scalpel, clips…)
Autoclave the crochet.
Under the ventilation hood spray water onto them.
Place the crochet on a tray.
Spread the inoculated sawdust on the surfaces.
Place the disks into the incubators.
Create an air-filter on the lid. Drill a hole and place cotton in it.
Close the box with the lid.
Label the box. (name, date)
When the whole mixture is white, wait another 1-2 days.
Take the block out of the mold, and rest it on a rack for 2 days.
Bake it on 95 °C for 30 minutes.

experiment conducted on 04/05/2015

inoculated sawdust on top of the crochet

four days old sample – bottom

four days old sample – top

four days old sample – side

Notes:

4th of May - Two similar samples were created. They were laid in a plastic box, functioning as an incubator and ensuring a semi-sealed growing environment.

8th of May - The samples were not placed in a tight mold to fill out all the provided space. Even though the mycelium multiplication seems to carry on as desired and bonds the inoculated substrate to the strings. One of the samples was formed into a curved shape.

11th of May - Thanks to the small volume of the applied inoculated substrate, the sample's growth process is already complete. Thus it was removed from the ventilation hood and left to rest to dry out. Later they were baked in the oven on 95 °C for 30 minutes.

Conclusion:

Placing the inoculated sawdust onto the crochets surfaces was still challenging. Otherwise the experiment was successful. The mycelium bonded the sawdust to the crochets' net system. Both the flat and the curved sample kept its form after the drying process.

conclusions

The presented experiments were conducted as an investigation into the characteristics of the mycelium material and to get a deeper understanding of the required production process. Below is a summary of the conclusions drawn from each session of experiments:

reproducing mycelium - All the inoculation procedures were managed from the 200 ml liquid culture that we purchased in January. The most effective way to enhance fast mycelium growth in the material samples is to use pre-inoculated medium. Each of the substrates tested - oat grains, sawdust, coffee grounds, etc. - were derived from local sources and proved to be suitable for hosting and nurturing a thick mycelium growth.

Reproducing the original liquid culture, however, was a more challenging process. The mycelium needs the right and adequate amount of nutritions to grow its hyphae.

air quality conditions - After reading several papers, the Ecovative Design patent and publications about the mycelium based composite, it became clear that an indoor production of this material requires a well-monitored environment. The a steady level of moisture and oxygen flow are the most important external factors to simulate in the ventilation hood when attempting to grow the mycelium composite. However, due to lack of sufficient knowledge in this area, we did not attempt to experiment with atmospheric changes and kept to the original settings of the ventilation hood in the laboratory.

mixture content - We saw that too much water led to the development of molds and tended to slow down the growth of hyphae. However, the chosen species - Pleurotus Ostreatus - is an aggressive strain which sometimes was able to 'outgrow' the contamination. Yet, in retrospect we believe that the sterile, isolated environment contributed to the risk of contamination developing. On the other hand, a low amount of water content could lead to dehydration, resulting in an underdeveloped mycelium layer on the surface and to poor physical material qualities.

Another crucial factor is the right combination and amount of nutrients provided in the mixture. The mycelium 'feeds' off the nutrients provided in the substrate, but added minerals (e.g. calcium carbonate from blue mussel clams) can stimulate a faster multiplication of hyphae.

growing method - The most widely used growing method of the mycelium composite is to pack it in molds or on scaffoldings. We started our experiment session with replicating this procedure. It proved to be efficient, but forced dimensional constraints on the mycelia, conforming it to the conventional building method of brick laying. On the contrary, we wanted to explore the possibilities of the mycelium composite based on its inherent qualities as a free-form expanding, or growing, material. Thus we decided to focus on its ability to bond to natural fiber and open surfaces, which proved to be an efficient method of implementation. Instead of a sealed mold the samples were placed in an incubator for the growth process. The advanced state of the mycelium grown on substrate prevented contaminations and completed the growth apace.

physical qualities - The material at the current stage of development has physical properties comparable to polystyrene foams.[67] However, different substrates provide different qualities in the final product. In our case, the examined substrates resulted the following observations:

sawdust - Besides that it is an efficient inoculation media, sawdust gives to the compressive strength of the material. The particles are small enough to result a dense consistency, but allow a light weight.

straw - Straw provides structural strength through the interweaving filaments. The low density of the substrate also gives a light weight to the material.

cotton - The imbrication of the light, soft fibers results flexibility and low density. Furthermore such substrate can enhance good properties as an insulation material.

coffee grounds - The particles can be packed in molds densely, thus the final material has heavy weight. The result of molding the material made of this substrate provides a brick-like solution.

Combining the different layers on top of each other merge the various qualities in the final material. The experiments show that the mycelium bonds beyond the layers and keeps the substrates converged.

We based our theory of the introduced application method (see thesis booklet page 131) on the observed conclusions of the experiments and the studied papers published by several researchers and designers.*

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[*] ***For example:*** *Patent of Ecovative design*
Mycology Matrix Composites by Dharan, CKH., Noble, J., Ross, P., and Travaglini, S.,

[67] Dharan, CKH., Noble, J., Ross, P., Travaglini, S., *18.*

Vienna - University of Applied Arts
study trip #1

date: 07/01/2015
interviewee: Viktor Gudenus - Research Associate
aim: visit at the project group Growing as Building (GrAB)
focus: discuss projects of GrAB

The project GrAB investigates biological patterns with the aim of applying the learning outcomes as living structures in architectural contexts. An interdisciplinary group experiments with several organisms and potential building systems, materials.[68] Their experiments have quite a wide range; from algae, through beans to banana leaves, and of course fungi.

Through their performed experiments they used both mycelium of Pleurotus Ostreatus (oyster mushroom) and Ganoderma Lucidum (reishi). The performed application methods differed within the molding solution using natural casts (e.g. avocado peal), petri dishes, 3D printed forms, carved foams or stockings made of organic thread.

Viktor Gudenus was my host for the visit and he persistently answered all my questions. He explained about the whole process of growing material using mycelium: What it likes to feed on, how important it is to get the right temperature and level of humidity, and above all things how crucial it is to establish a sterile growing environment.

[68] *GrAB, Growing As Building, http://www.growingasbuilding.org (Accessed: 28/12/2015)*

mycelium material block

mycelium material in avocado peal casting

mycelium material with paper substrate

live mycelium material with oyster mushroom

Malmö - Ecofungi

study trip #2

date: 23/01/2015

interviewee: Christina Persson - Mycologist

aim: visit at Ecofungi mushroom-farm

focus: purchase liquid mycelium culture
processes regarding mycelium

The profile of the company Ecofungi * includes culturing liquid mycelium, inoculating substrate media (e.g. sawdust pellet, organic waste product) with the aim of trading kits at this stage of the growth or cultivating the developed fruiting bodies to sell to local supermarkets.

We purchased a portion of liquid mycelium culture from Christina, which proved to be sufficient throughout our experiments. In addition we received an inoculation kit, which contained a bag of autoclaved sawdust pellet, and inoculated wheat grains. The product of the kit has been later utilized in several material sample experiments.

Christina shared her knowledge of mycology with us, especially about the procedures how to reproduce the liquid culture, keep it alive and use it for inoculation purposes. Her step by step written manual helped us later to perform our first inoculation experiment.

* *www.ecofungi.se*

bags filled with inoculated sawdust

shiitake mushroom

overgrown mycelium

liquid mycelium culture

Copenhagen - GXN
study trip #3

date: 13/02/2015
interviewee: Morten Norman Lund - Engineer
aim: visit the architecture office 3XN_GXN
focus: practical application approaches of biocomposites

GXN was established as the internal devision of the Copenhagen based architectural office 3XN. This department focuses on implementing architectural research of green materials and building technologies in their design approaches.[69] GXN maintains a wide network and collaboration with several researchers, material developers and manufacturers.

Through this study trip we had the chance to discuss the issues regarding our thesis topic with professionals, who have an extended view on the practical application of biocomposites in the built environment. GXN holds a great material library representing a wide range of several biomaterials, among others: variations of mycelium based biocomposites.

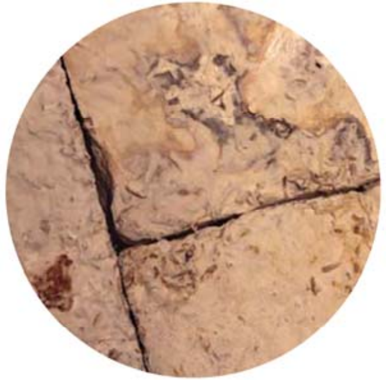
During the interview we examined samples made of different substrates. This meeting inspired new ideas for developing our material experiments. Afterwards we investigated how different layers bond together through mycelia to create a combination of advantageous qualities.

[69] *GXN, internal division of the architectural practice 3XN, http://gxn.3xn.com/#/about-us/vision (Accessed: 16/02/2015)*


degrading wood


amorim – insulation cork board


burned wood


sample collection – Ecovative

London - London Metropolitan University

study trip #4

date: 24-29/03/2015

interviewee: Conor Scully - architect student
Ana - Laura Mohirta - architect student

aim: workshop on mycelium based material

focus: participate in discussions regarding the material's development

At the beginning of March we contacted another London-based master thesis couple. During the conversations, information exchange and discussions, we received an invitation from them with the purpose to participate at a shared workshop. The aim of the common work was to share the experiences we gained separately and through the united effort of the two teams deepen the knowledge regarding our common topic.

Their work is aimed to investigate how a mycelium based material can be used as a contractual element, such as a wall-panel. The recipe of the applied material mixture was based on the patent of Ecovative and the study by Philip Ross.

Since they had no access to a sterile laboratory to conduct their inoculation exercises, they established a workshop in the attic of their university. Thus the pre-conditions of the experiments differed from ours, which provided an insight on how the growth process could be handled among non-sterile circumstances.

mixing the compounds

baging the substrates

bags waiting for heat treatment

filling the molds

New York - Terreform ONE
study trip #5

date: 20/04/2015

interviewee: Melanie Fessel - architect, urban designer
Director at Terreform ONE

aim: visit the non-profit design group Terreform ONE

focus: learn practical information about the production and post-treatment of the mycelium based material

During our research phase we came across projects, which went beyond theoretical discussions and showcased the mycelium based material through physical objects. One of these projects is 'Mycoform', a design initiative focusing on establishing a self-sufficient construction technology through combining mycelium with natural substrates.[70] They showcased their outcomes by a bench design grown onto a plywood scaffolding. (see picture to the left)

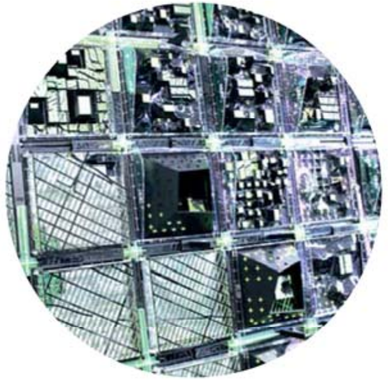
We contacted the project leader - Melanie Fessel - in hope to meet and learn from their experiences. The interview added to our thesis by absorbing their knowledge of the material, leading our experiments in further directions. We gained a better understanding of the material's behavior, and a hands on experience how they produce their material to reach the wished properties.

[70] *Terreform ONE, Nonprofit Organization for Philanthropic Architecture, http://www.terreform.org/projects_habitat_mycoform.html (Accessed: 21/04/2015)*

bench prototype – made of mycelium material

project – Super Docking

project – Urban Farm Pod



project – Post Carbon City