JÖNKÖPING UNIVERSITY
School of Engineering

industriDESIGN

The development of an acoustic insulation solution using mushroom mycelium as an alternative to synthetic foams

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Utvecklingen av en akustisk isoleringslösning med svampmycel som ett alternativ till syntetiska skum

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This degree project is performed at the School of Engineering in Jönköping in the subject field Product Design - Industrial Design. The project is a result of the master program Product Design - Industrial Design. The writers are responsible of the result, conclusions and reflections.

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Abstract

In the past decades, humanity is facing the consequences of the irresponsible production of plastics and the expansion of industries such as industrial agriculture, Therefore, the development of new sustainable alternative materials has become increasingly popular as a science field. That is the case of mycelium composites, a biodegradable material made out of agricultural and the thread-like roots of mushrooms called mycelium. The mycelium, when growing, binds all the particles of organic matter together, creating a stiff material that takes the shape of the mould where it was cultivated. The material is lightweight, fire resistance, provides acoustic and thermal insulation and has good behaviour under compression efforts.

So far, research has been conducted on testing the properties of the material, but there is a lack of knowledge on how to address this material from a design perspective. How to design with it, how to make it appealing to the users or how to value its intrinsic characteristics. For that, the design thinking methodology "Design thinking bootleg" was followed and theory and methods under the perspective of "Design for emotion" and the approach of "Material driven design" that facilitates design processes where the material is the main driver.

An acoustic insulation solution was developed as a result, since it was concluded to be the most competitive application among the different possibilities of mycelium composites. The product aims for a certain emotional response in the users, seeking the development of an emotional connection and creating awareness about the role mushrooms play in nature and the use of sustainable materials. Eventually, the product succeeded in transmitting more than mere curiosity, especially after explaining the story behind it. Overall, the product is still far from competing against plastics in terms of scalability and speed of production. However, research on this topic is increasing exponentially and the material proves to have a lot of potential, so it is expected to be improved in the next few years.

Keywords: mycelium composites, design thinking, design for emotion, sustainability, acoustic insulation, fungi, mushrooms.

Sammanfattning

Under de senaste decennierna står mänskligheten inför konsekvenserna av den oansvariga produktionen av plast och expansionen av industrier såsom industriell jordbruk. Därför har utvecklingen av nya hållbara alternativa material blivit alltmer populär som ett vetenskapsområde. Detta gäller till exempel mycelkompositer, ett nedbrytbart material tillverkat av jordbruksavfall och de trådliknande rötterna från svampar som kallas mycel. Mycelet binder samman alla partiklar av organiskt material när det växer och skapar en styv substans som tar formen av den form där det odlades. Materialet är lättviktigt, brandsäkert, ger akustisk och termisk isolering och har goda egenskaper vid tryckbelastning.

Hittills har forskning bedrivits för att testa materialets egenskaper, men det saknas kunskap om hur man angriper detta material ur ett designperspektiv. Hur man designar med det, hur man gör det attraktivt för användarna eller hur man värdesätter dess inneboende egenskaper. För detta följdes designmetodiken "Design thinking bootleg" och teorin och metoderna under perspektivet "Design för emotion" och tillvägagångssättet "Materialdriven design" som underlättar designprocesser där materialet är huvudmotorn.

En lösning för ljudisolering utvecklades som ett resultat, då det konstaterades vara den mest konkurrenskraftiga tillämpningen bland de olika möjligheterna med mycelkompositer. Produkten syftar till en viss emotionell respons hos användarna genom att söka utveckla en emotionell koppling och skapa medvetenhet om den roll svampar spelar i naturen och användningen av hållbara material. Till slut lyckades produkten förmedla mer än bara nyfikenhet, särskilt efter att ha förklarat historien bakom den. Övergripande sett är produkten fortfarande långt ifrån att kunna konkurrera med plast i fråga om skalbarhet och produktionshastighet. Men forskningen inom detta område ökar exponentiellt och materialet visar sig ha stor potential, så det förväntas förbättras under de kommande åren.

Nycklord: mycelkompositer, designtänkande, design för känsla, hållbarhet, akustisk isolering, svampar.

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1 Introduction

1.1 Background

Today's society has largely seen nature as an obstacle to dominate and overcome, a mere natural resource that has to be transformed through technology. Humanity seems to follow a path where the disconnection from nature is more and more noticeable. However, research proves that exposure to nature enhances human physical and mental health, performance, and well-being [1]. Moreover, through billions of years of evolution nature has proved to provide sustainable solutions that are good for the ecosystems. It seems that nature already provides the answer to today's modern society challenges. Many inventions have been inspired by natural mechanisms of nature, such as Velcro, camouflage, planes, and wetsuits, to name a few. It is a matter of observing what nature can teach us, about learning the technology of biology.

The concept of Biomimicry is brought up in this study as a way for creating more sustainable designs by emulating natural forms, processes and ecosystem strategies, bringing back the natural connection that humans have with nature [2].

Mushrooms has long been known for their indispensable role in recycling organic matter, especially in forest, for their key role in the development of antibiotics, such as penicillin, and for beer, wine, and bread production. In the last couple of years mushrooms has proved their potential in the development of sustainable materials, known as mycelium composites.

Mycelium composites are made of mycelium (a root-like structure of mushrooms consisting of thread-like hyphae), and agricultural waste. The mycelium takes nutrients from the agricultural waste and by doing so, it joints all the tiny particles of the organic substrate when is spreading, acting as a natural agglutinant. The result is a solid lightweight composite that takes the shape of the mold where is cultivated. Mycelium composites is an innovative lightweight material that presents promising properties such as fire resistance, acoustic and thermal insulation and high resistance under compression efforts [3]. Agricultural waste is valorized while creating a sustainable alternative to oil-based materials, that can come back to the soil after its life cycle, fulfilling the requirements of a circular economy, providing an optimization of the resources and of the energy consumption [4].

To qualify the material at hand not only for its interesting properties and applications but also for its key role in nature, for what it expresses to us and what elicits to us, a Material Driven Design approach will be followed. This will take designers on a journey that departs from a deep understanding of the material, goes through experimental practice with the organism and ends with the ability to create experiences with it and enhance its intrinsic values [5].

1.1.1 Role of mushrooms in nature

Fungus, together with bacteria, plays an important role in preserving the ecosystem of the forest. They are the agents that recycle the organic matter and transform it into proteins and carbohydrates that other organisms can take. That is why mushrooms are often seen growing in decaying wood, they are decomposing the trunk of a tree. Fungus were the first organisms to colonize the earth, approximately 1.3 billion years ago. By eroding rocks, they enriched the soil with the proper components to give birth to plants, which arose 700 million years ago [6]. Fungus is not only important for their role in degrading organic matter, but they also establish symbiotic relationships with plants known as Mycorrhiza, see Fig. 1, The mycelium attaches to the roots of plants and by doing so, they give them water, which they obtain from the deep underground where plants' roots cannot reach, and minerals such as zinc, ammonium, and phosphate, which they obtain from eroding rocks. In exchange, fungi obtain carbohydrates, sugar, and vitamins, that plants get from doing photosynthesis. It is estimated that 80% of plant species establish mycorrhizal relationships with fungi. Plants that established that relationship also get some other benefits such as higher resistance to pathogens, diseases, toxic metals, pests, and drought [7].

Fig. 1: (a) Mycorrhizal relationship between fungi and plants. (b) Exchange of nutrients between fungi and plant [8], [9].

Since mycelium can spread over various kilometres, one fungal species can be connected to the roots of multiple plants, even from different species, creating a complex network known as Common Mycorrhizal Network or Earth's natural Internet. Plants take advantage of this mycelial network to trade water, vitamins, sugar and other chemical components with each other. An example of this is how mother trees help younger trees to grow stronger and healthier. Since they are taller, they get more light from the sun, hence they produce more sugar by photosynthesis, younger trees are smaller, and they live under the shade of mother trees. Mother trees use the mycelial network to share sugar and some of their nutrients with younger ones. Moreover, when mother trees die, they use these natural networks to give away all their natural resources to the younger trees [6]. See Figure 2, to visualize a schema of how mother trees (hub trees) are connected to multiple young trees.

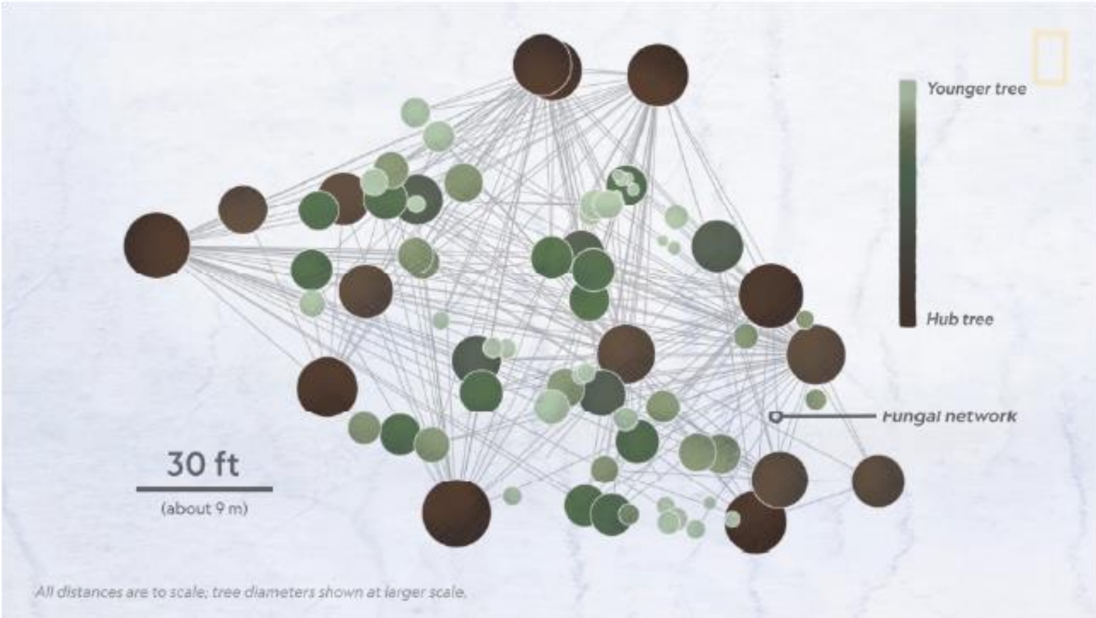


Figure 2. Mycelium network schema between hub trees and younger trees [9].

Lately, plants can send signals to other plants, through electrical impulses. If, for instance, one plant is attacked by a pest of insects, it can send that message to other plants so they can get prepared ahead for the upcoming danger by releasing their natural chemical components that protect them against insects [10].

To conclude, it is possible to affirm that mycelium creates complex bio-communities undersoil, giving birth to life, recycling organic matter, and connecting plants together. See Fig. 3, to visualize the similarities between other networks and the mycelial networks [6].

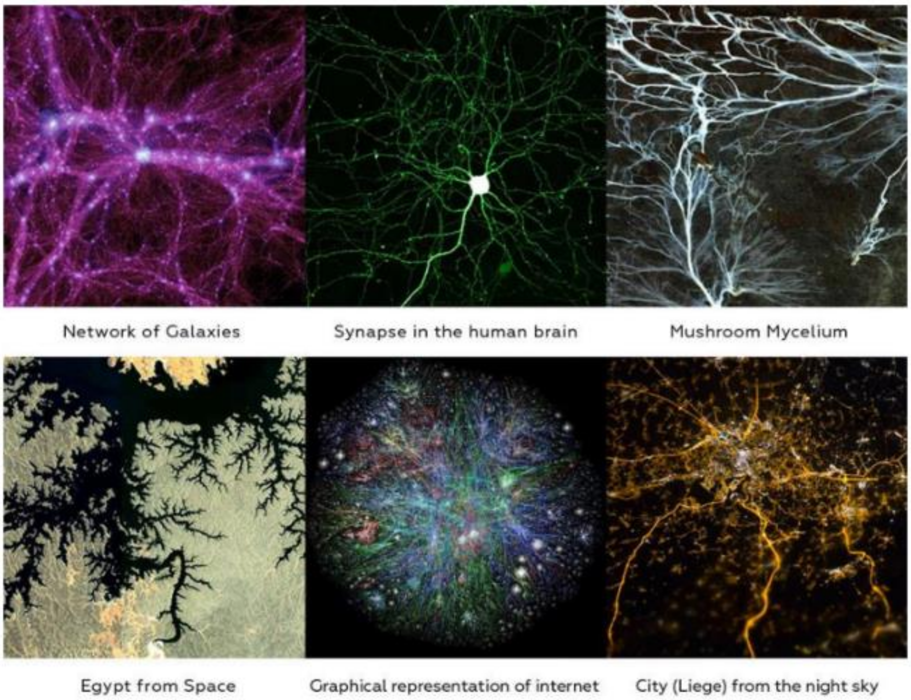


Fig. 3. Comparison between mycelium network and other known networks [6].

1.1.2 Mycelium composites

Over the last decades, biomaterials have become increasingly popular as a sustainable alternative to oil-based materials even though there are still challenges for large scale production [11]. According to Lelivelt. R.J.J, a bio-based material is defined as “a material of which at least one of its components can be biologically grown and is fully renewable” [12]. Mycelium composites are considered a group of biomaterials lately introduced in the fields of construction, architecture, product development and design.

Mycelium is a dense network of thin strands called hyphae, if a comparison is made between mushrooms and plants, the mycelium will correspond to the roots of a plant. However, the spreading capacity and densification of the mycelium network are much higher than the plant’s roots, being capable of spreading throughout thousands of acres in the forest [6]. Mycelium invades and degrades the organic matter that if finds, binding everything together. When mycelium is cultivated inside a mold with lignocellulosic biomass and water, it gradually colonizes the substrate and bind its particles forming a strong material that adopts the shape of the mold. The mycelium is therefore acting as a natural adhesive with a self-assemble capacity that makes mycelium composites unique [13]. The material is hence composed of two components, the mycelium network and the lignocellulosic material, known as substrate, which could be anything from coffee, tobacco, grains such as brown rice, wheat, rye, corn, to agricultural waste, such as hemp, sawdust, cotton, straw, and wood logs, see Figure 4 [14].

Mycelium has long been used in the medicinal industry to develop dietary supplements, anti-inflammatory, antimicrobial, insecticidal etc. Since the 1980s, mycelium has been used for mycoremediation, coined by the famous mycologist Paul Staments, this term concerns how the enzymes produced by fungi can be used to break down contaminants and restore the balance in the ecosystems [6].The development of mycelium composites started in the 1990s by Shigeru Yamanaka, who explored mycelium for the production of paper and building materials [15]. Since then, this material has been further explored for its potential and interesting properties.

Figure 4. Mycelium composites [16].

1.2 Problem formulation

1.2.1 Problem area

Environmental pollution coming from plastics and industrial agriculture are some of the biggest problems that humanity is facing nowadays. Global plastic production continues to increase and reached 380 million tonnes in 2015. Seas and oceans are recipients of up to 12 million tonnes of waste [17]. The agricultural sector accounts for 24% of global greenhouse gas emissions and almost 90% of global deforestation is the result of its expansion [18]. Therefore, alternatives to plastics are necessary in order to preserve life in the ecosystems and ensure a good future for the upcoming generations. Scientists are aware of this critical situation and in the last decades, researchers have focused their efforts on the development of new sustainable materials. Mycelium composites are one of them.

Research has been done seeking to explain how to produce this material while testing different species of fungus. Besides, tests have been conducted to analyze the mechanical, thermodynamics, acoustic and structural properties of the material [3], [15], [4]. However, since it is a research area far from being mature, information is unstructured in several aspects; The procedure to follow to fabricate this material is unstandardized, several studies used different steps involving parameters, such as temperature, time or moisture percentage, with different values; some of them also skips steps that are important in other ones; it is not clear enough which species are more suitable for the development of the materials since each study select just a few or work with only one. So far, only 36 species have been registered in patents for the development of mycelium-composites [4]. Just a tiny number in comparison with the 1.5 million species of fungi that are believed to exist in our planet [6]. Nowadays, only a few companies know the right parameters and techniques of cultivation to develop high-quality mycelium-composites for successful industrial applications. Moreover, several important details seem to be covered by industrial secrecy and are not published in any scientific papers [15].

Although it is important to continue studying the material properties, fungal species and industrial applications, no study has been done yet analysing what it does, what it expresses to us, what it elicits from us and what is makes us do [5]. How to design for experiences using this material hasn't been addressed and the effect that it may have on the user's perception of it. It is believed that mycelium composites can have a lot of potential yet to be discovered. Moreover, the material is presented as a sustainable solution that encourages users to take care of the environment. Therefore, a design for an industrial application that resembles shapes in nature, could fit the material and add more value to the project regarding product design.

The project at hand is an example of how to integrate art, design, and engineering. The engineering part of the project relies on the study of the material, its characteristics and experimentation with it. The design side of the project is reflected in the methodology that is followed, its human-centred approach, the methods used to understand the market and the user, to come up with concepts etc. The project has also a strong artistic part since the final product is considered an artistic expression and has the aim to transmit emotions. Moreover, decisions are highly influenced by the feedback that is received from the users but eventually is the student the one to decide which concepts better express his intended emotions.

1.2.2 Aim

The project aims to; present the existing knowledge regarding mycelium composites, their properties and industrial applications related to product design; to develop an acoustic insulation application where the intrinsic characteristics of the material are valued, there is a purpose of generating emotion and awareness of sustainability.

1.2.3 Research questions

1. What are the existing applications of mycelium composites in product design?
2. What are the limitations and opportunities of using mycelium in product design?
3. What is the user's emotional response when interacting with a bio-based product?

1.3 Delimitations

The project aims to cultivate fungus species to fabricate mycelium composites. For that, the cultures will be homemade without using equipment from a professional laboratory. That involves some risks of contamination from spores of other fungal species that are in suspension in the air or bacteria, which may slow down the cultivation process [14]. The equipment used is not professional, which may have a consequence in the final application. The techniques implemented are based on other scientific studies and the species cultivated have already been tested for creating mycelium composites in previous studies. The student that carries out this project is not a mycologist, so in-depth knowledge about fungal species and cultivation factors won't be presented in this study. Lately, since for developing mycelium composites it is only necessary to cultivate the white root-like structure known as mycelium, the study won't go into details about how to cultivate the fruiting bodies of the fungal species (known as mushrooms), even though the techniques and some considerations have a lot of similarities.

1.4 Disposition

The project is divided into 8 points which are:

1. Introduction. At this stage the background of the project is presented, why the material is important and what is the problematic situation addressed. Besides, this point covers the aim and research questions along with the delimitations of the project.
2. Theoretical background. This point presents all the theories behind the project that are going to support all the decisions and solutions that are developed. All the methods implemented are part of the different perspectives, approaches and methodologies presented in this point.

3. Method. The methods that are used for proceeding when coming up with solutions, understanding the user, the market, finding articles etc. are presented at this stage. This point is divided into the different stages of the Design Thinking Bootleg methodology which are Empathize, Define, Ideate, Prototype and Test, which established the order in which those methods are going to be implemented.
4. Approach and Implementation. Following the order of the stages of the Design Thinking Bootleg, the methods were applied at this point. This point presents the findings from the research that was done, how decisions were made, as well as the process followed to develop the final product.
5. Results. This point is focused on showing and explaining all the different aspects of the final solution.
6. Conclusion and discussion. At this point, reflections are made on the outcome of the project. What was done right, what could have been improved, what is the prospect of the material, if the product succeeded or not etc. Moreover, the research questions are answered one by one.
7. References. All the articles and webpages that have been used to gather information and write this document are referred to in this section.
8. Appendix. All the additional material that is still relevant, but that takes too much space, is presented at this point

2 Theoretical Background

2.1 Product Design

Product design could be defined as the process of developing products with a deep understanding of user needs and with the aim of solving their problems, making the final solution aesthetic, intuitive and functional. Product design also involves anticipating opportunities in the market and factors such as ergonomics or user experience (UX) [19]. To get a deeper understanding of the term, it is important to be familiarized with other disciplines such as art, industrial design, engineering design, product development or industrial design engineering and the relationship those terms have with product design.

2.1.1 Art vs. Design

Art could be defined as the expression of human creativity by applying a set of skills as a medium. It is a way of communication and it is subjective, what might be art for one may not be perceived as such by others. There are different forms of artistic representation but for what this project concerns, only visual arts are considered important. Some examples of visual arts are photography, painting, sculpture, drawing etc. [20].

Design consists of identifying a problem and finding a solution to it. Design is made with a purpose. The difference with art relies on the constraints involved in achieving that purpose. An artist may be moved just by expressing the desired feeling or emotion, regardless of the tools, methods or techniques used. On the contrary, regarding design, the process is defined, the tools, methods and techniques are an integral part of it and they are selected for solving the specific purpose. Therefore, design involves art, since it is used to communicate, considers aesthetics and tries to express feelings and emotions, but is much more restricted to a more detailed purpose that requires certain considerations. Craftmanship such as pottery or glasswork gets closer to design, but design is related to the industry, where time, cost or feasibility for example are considerations that plays an important role [21].

There are different types of design: graphic design, user experience design (UXDesign), web design etc. since a design could be anything from a textile application, to a web page, to name a few examples. This project is focused on the discipline of product design.

2.1.2 Product development

Product development refers to all the different phases involved in introducing a new product to the market; the conception of ideas, going through the manufacturing process, the distribution stage and lately considering the end of the product's life. In all those stages product development involves professionals from the disciplines of product design, industrial design and design engineering. Those disciplines are correlated to each other and interdependent to ensure the success of a product. Product development could be seen as the framework that involves all of them [21], [22].

2.1.3 Industrial Design

Industrial design is closely related to Product design since it considers both the aesthetics and functional aspects of products. However, there is a special emphasis on the integration of factors such as usability, manufacturing processes, market trends and branding. According to Monö, Industrial design consists of "the formulation of properties primarily concerning the usefulness and appearance of products" [23].

2.1.4 Engineering design

Engineering design refers to all the engineering disciplines involved in the development of a product. There is a focus on all the technical aspects and it involves the application of all the principles regarding maths, physics, material science etc. so products can perform well, are structurally safe, and have an efficient use of resources for example [21].

2.1.5 Industrial Design Engineering

Product Design, Industrial Design and Engineering design reveal the different perspectives regarding the development of a product. This division can make different opinions or prioritizations arise when coming up with a final solution, which sometimes can evolve into conflicts within the team. To unify the different disciplines and see the product from a holistic point of view, Industrial Design Engineering appeared, which states that for a successful product to be developed is key to consider both the engineer requirements and constraints and the aesthetic factors [21].

Don Norman in his book *The Design of Everyday Things* expresses this holistic view simply, "If everyday design were ruled by aesthetics, life might be more pleasing to the eye but less comfortable; if ruled by usability, it might be more comfortable but uglier. If cost or ease of manufacture dominated, products might not be attractive, functional, or durable. Clearly, each consideration has its place. Trouble occurs when one dominates all the others" [19].

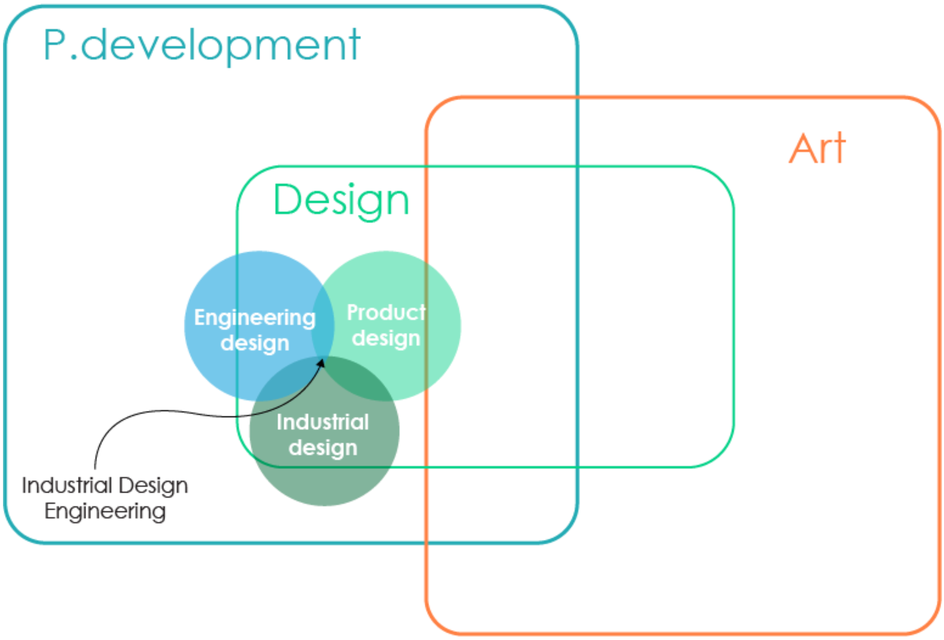


Fig. 5. Design disciplines and their relationship

The way how those different disciplines are integrated in the project was presented in 1.2.1 Problem area.

2.1.6 Design Science

Design has been influenced by the scientific method, which refers to the systematic approach to investigating phenomena and getting to reliable conclusions based on empirical evidence [24]. Consequently, the Design Science Methodology has emerged as an approach that combines elements of design theory and scientific inquiry to solve problems and gather data. Since Product Design is a human-centred discipline, methodologies inspired by the scientific method have been developed known as Design Thinking Methodologies [25]. Quoting once more Don Norman, "the increasing complexity of everyday objects necessitates a human-centred design process, one which is informed by a deep understanding of psychology and technology" [19].

2.1.7 Design Thinking

Design Thinking is a structured process with a human-centred approach to generating creative ideas. It is used to understand users and challenge assumptions, redefine problems and create innovative solutions. It is also a way of thinking and working as well as a collection of tools and methods [26].

Tim Brown, the executive chairman of IDEO, a well-known design firm and consultancy, defines Design Thinking as "a human-centred approach to innovation that draws from the designer's toolkit to integrate the needs of people, the possibilities of technology, and the requirements for business success" [27].

As mentioned in 2.1.1 Art vs. Design, design involves constraints to achieve a specific purpose and develop successful products. Regarding Design Thinking constraints can be organized into three main ones, which are feasibility, viability and desirability, see Fig. 6.

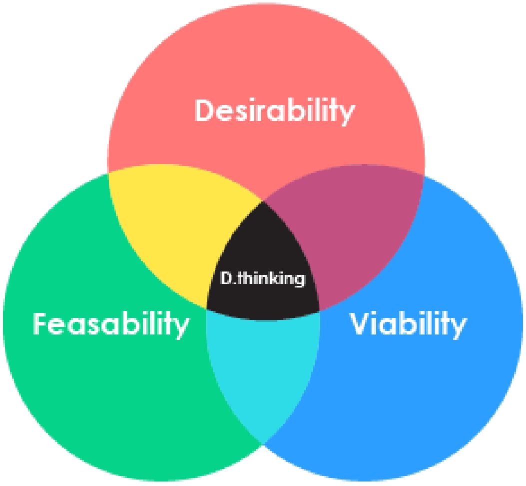


Fig. 6. The three constraints of Design Thinking. Based on IDEO [27].

In any given project it is common to focus more on one of those constraints, but ideally, the aim should be to balance those three by working on the intersecting area of them, where Design Thinking lies [28].

2.2 Design Thinking Bootleg

The conventional way to come up with solutions is based on a good definition of the problem. Albert Einstein said: "If I were given one hour to save the planet, I would spend 55 minutes defining the problem and 5 minutes resolving it". This approach to problem-solving may be good to discard those first solutions that come up just when the problem is presented. However, it can lead to conventional solutions, or the team can get stuck in the early stages of the process because they do not know how to handle the project or feel that all the solutions are already invented. Under this scenario is where Design Thinking comes up.

There are many ways to implement Design Thinking. It has been addressed by different international design schools, giving their personal view on the approach. Examples are The Delft Design School and the Institute of Design at Stanford University [29], [30].In this paper, the Design Thinking Bootleg Methodology from Stanford University is the one applied, since it provides useful methods to trigger innovative solutions and it is well structured and easy to understand, with a focus on the user. It is a set of tools and methods which constantly evolves [30]. It is about embracing simple mindset shifts and tackling problems from a new direction. Besides, it guides the members of the team through the whole process, keeping people on track and curbing the tendency to spend too long exploring or to impatiently skip ahead. It focuses more on the goal rather than the problem itself and it is especially useful when the problem is too open or difficult to understand [27].

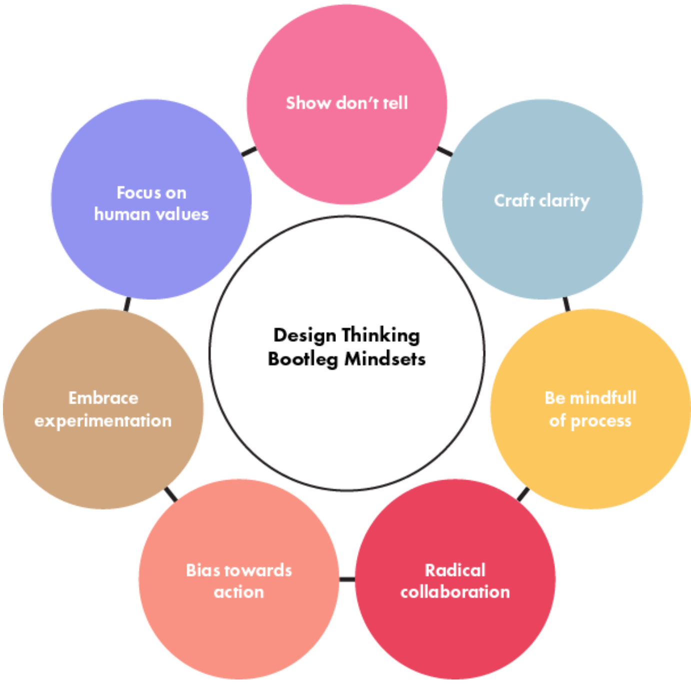


Fig. 7. Design Thinking Bootleg Mindsets. Diagram inspired by Design Mindsets presented by Standford d.school [30].

The Design Thinking Bootleg is structured in five "modes" identified as the components of Design Thinking. Those components are empathize, define, ideate, prototype and test [30].

2.2.1 Empathize

Empathy with the user is considered the foundation of a human-centred design process. To empathize is necessary to:

- Observe. View the user and their behaviour in the context of their lives.
- Engage. Interaction with and interview the users.
- Immerse. Experience what your user experiences.

Because rarely the problems the designer is trying to solve are his own, it's key to understand the user and their personal problems, what is important to them [30].

2.2.2 Define

The empathy findings are synthesized into user needs and insights. The main goals of the Define component are to develop a deep understanding of the user and the design space, and based on that, to come up with an actionable problem statement. This problem statement will be present throughout the whole design process, and it is focused on specific users, insights and needs [30].

2.2.3 Ideate

Ideate is the mode focused on idea generation. The goal of ideation is to explore a wide solution space, generating many ideas and diversity among those. It is a mode of "flaring" rather than "focus". The fundamental principle of ideation is to be cognizant of when the team is generating ideas and when they are evaluating ideas and mix the two only intentionally [30].

2.2.4 Prototype

Prototype consists of getting ideas and exploration out of the head and into the physical world. Prototypes are more successful when people can experience and interact with them. What the design team learn from those interactions can help drive deeper empathy, as well as shape successful solutions. It also helps to narrow down some ideas and to see which ones should be left behind. Besides, by showing visions, other teammates can get inspired, so the exploration of new ideas can come up [30].

2.2.5 Test

The testing mode consists of placing high-quality prototypes (close to how the actual product should look) in the appropriate context of the user's life. It's the chance to refine solutions, make them better and learn even more about the users. Testing can reveal issues with the actual concepts, which means going back to the drawing board. Therefore, the five modes of the Design Thinking Bootleg are not always sequential, it shouldn't be interpreted as a hierarchical or step-by-step process, the modes can often occur in parallel and repeat iteratively [30].

2.3 Material Driven Design

As mentioned before in 1.2.1 Problem area, the main engineering focus of the project relies on the investigation of the material at hand. Since the discipline of the master is Product

Design, it is important to address this from a design perspective. With that aim arise approaches like material-driven design.

A material-driven design approach is based on the idea that a material should elicit a meaningful user experience beyond its utility. It aims to facilitate design processes in which the material is the main driver [29]. According to E. Karan et al. [5], "this requires qualifying the material not only for what it is, for what it does, what it expresses to us, what it elicits from us and what it makes us do".

Material science is moving towards the development of new and more sustainable materials, therefore the materials' active role in user experience has gained more interest in the last couple of years. Now it is considered important to inform users about the material used, explained the reason behind it, and give it meaning in order to elicit emotions [5]. There exists a dualistic view, the material should satisfy the functional needs, but also the hedonic need of people. Therefore, material science has reached academics and professionals in design, seeking to develop materials achieving both experimental and functional goals. For the same reason, designers have also begun to study materials to "interpret", "understand" and "design" for experiences [5].

E. Karan et al. presents a method to facilitate designing for material experiences when there is a focus on a particular material. The method will be further explained in 3. Methods. Here it is presented its three main foundations:

- To design with a material as the main driver it is important to have a deep understanding of the material at hand. Its unique characteristics, how it behaves under different circumstances, its highlights, and drawbacks, as well as its competitors.

- As in any design process there is a need for a guide, action steps to be followed so designers work in a structured way. It should start with a thorough understanding of the material, then benchmarking to position the material in the market, concept creation and concept selection and final product development.

- When considering creating an "experience", the designer journeys go through research and understanding but it also involves experimenting with the material, so the theoretical knowledge obtained is also put into practice, giving the designer a clearer vision within a wider context [5].

Since there is an aim to create experiences with the material it is important to have a foundation on the Design for emotion perspective.

2.4 Design for Emotion

Design for Emotion is a design perspective that takes the emotional impact as the leading principle of the design process. Positive experiences trigger our curiosity and give us good memories and negative experiences protect us from repeating mistakes. According to A. van Boeijen et al. [29] "Designs which tap into the user's emotion are considered to do more than just respond to their stated needs and provide a greater level of user experience." According to E. Demir, the increased demand for products states that in the current market, it is no longer sufficient to design products just for their functionality or their intrinsic values, but for the experience they create, the emotions they evoke and their meaning. Emotions are considered one of the three integral elements of a design argument, the other two are its practical utility (technological element) and its character, which refers to its intrinsic value [31].

In the field of design and emotion, the concept of "experience" is elaborated based on two disciplines psychology and philosophy [31]. In the framework of psychology P. Desmet et al. proposed that experience is equivalent to affect, where three different levels are identified: i) the aesthetic level, generated by sensorial stimulation; ii) the meaning level, affect induce by the characteristics of the product; iii) the emotional level, P. Desmet et al. attributes labels to this emotional response, such as anger or fascination [32]. In the same way, D. Norman in his book *Emotional Design*, states that affection may arise also in three different levels, but with a focus on cognitive involvement concerning products. i) The visceral level refers to the immediate response, the first impression, such as a smile on the face or sense of pleasure when touching a smooth surface; ii) the behavioural level, which refers subconsciously to user's evaluation in their everyday use of the product, if they feel satisfied when achieving a task using it or the product helps them to achieve their goals; iii) the reflective level, after the first interactions with the design, users start to judge the product for its performance, benefits, meaning and value for the money [33].

The concept of "experience" is borrowed from the discipline of philosophy. J. Dewey explains that experiences are the process of "doings", interacting with the product and "undergoings", the user is transformed by the interactions with the product until both the object and user are mutually adapted through a feeling of harmony. Therefore, the aim is that the user ends up engaged in the experience not only through bodily sensations and direct perceptions but waking up the analytical mind and inferential thinking [34].

The emotional bonds that can be created between the product and the user are considered also an important concept apart from "emotion" and "experience" extracted from the disciplines of psychology and philosophy. It refers to the power of products to evoke meaningful moments throughout the course of a relationship, giving rise to positive experiences. For example, when the user has interacted on different occasions with the produce, he or she may develop a tendency to take care of the product and keep it as long as possible. These kinds of relationships are referred to as "bonds", and designers should aim to create them [31].

One main argument within the perspective of Design and Emotion is whether is possible to design experiences. The emotional response of a user to a product is also dependent on the situation, the context and the user's concerns and pre-established ideas. In other words, the users can differ from the designer's expected reactions. Hence, it is possible to define and design for underlying universal behavioural patterns and emotions, but there are always variables that are not dependent on the designer. Mc Carthy et al. [35] state that "it is not possible to design an experience but to design for an experience, which means shaping the product to maximize the possibility of evoking the intended experience".

2.4.1 Patterns analysis

Geometric patterns might have an impact on the emotional response of users when they visualize them. According to Y. Wang et al., "diagonal and angular patterns tend to be associated with threads, while rounded features and curved lines tend to be linked to pleasantness and happiness" [36]. They may also produce the development of subjective meaning. For instance, a sharp-v shape conveyed angry or disturbance, while a rounded shape was related to happiness and calm. This suggests that people can extract affective meaning from simple geometric shapes. Moreover, this emotional response may occur even at an unconscious level [36]. Abstract shapes are more complex, even though the individual features included in abstract shapes retain the symbolism from the simpler shapes, abstract shapes can present combinations of angular patterns and curved lines, making their meaning more difficult to grasp. It can also be defined by just a small detail in the form.

However, abstract shapes give designers more freedom to play as well. For instance, when using the top half of the shape as a circle and having the other half more squarish, that can exhibit the playful features of a circle and the more serious features of a square [37]. Hence, for designers it is about understanding how to communicate with the shapes they use, tailoring the forms to a particular audience or with the aim to evoke specific emotions. The same thing happens with patterns and the composition they create [38].

Organic patterns that resembled natural shapes in nature, seem to be inherently preferred over synthetic foams. In the field of architecture, nature-like patterns or organic patterns have been used and explored a lot, since it seems to improve mood, reduce stress, improve concentration and working memory performance, giving similar feelings as interacting with nature itself. It is believed that in the field of architecture, the design of our surroundings can have a significant impact on psychological states and well-being [39].

Organic shapes share many properties with circles as they are usually characterized by curving lines. Organic patterns are usually not symmetrical, they can look unorganized and unplanned, but they can also give a sense of freedom and lightness. Some of the traits that organic patterns can evoke are a sense of freedom, a connection to nature, a sense of flow, delicacy and unpredictability [40]. To visualize some examples of organic patterns, see Fig. 8.

(a) (b) (c)

Fig. 8. Organic patterns in nature. (a) Coral (b) Snake skin (c) Aloe vera. [41], [42], [43].

2.5 Design for Sustainability

Design for sustainability is a design perspective that aims for designing products that can have a positive impact both for society and the natural environment. Designers have the responsibility to pay attention to the work they do concerning the repercussion it has on the environment. There has always been a tendency to treat sustainability as a desired factor but not as a priority. Lately, due to the increase in social awareness about the importance of taking care of the planet, both for planetary health and for human prosperity, Design for Sustainability has started to be taken more as a requisite than a wish. There are several approaches presented in the Delft Design Guide [29], that can be followed to apply Design for Sustainability, which will be further developed in 3. Methods.

2.6 Biomimicry

Biomimicry comes from bios, which in Latin means life, and mimesis, meaning to imitate. A formal definition is given by R. Tocke in the Biomimicry Resource Handbook. "Biomimicry is learning from and then emulating forms, processes and ecosystems to create more sustainable designs". It is not about what we can extract from nature, but what we can learn from it, borrowing life's blueprints, biological recipes, and strategies for recycling matter and renewing environments. Therefore, Biomimicry offers a new methodology, a different perspective seen with a new pair of lenses and on top of that, a new humility [2].

The core idea is that nature has already solved many of the problems that we experience in today's modern society. Some examples of nature-inspired inventions are solar panels copied from leaves, steely fibres inspired in woven spider nets, internet sending signals like neurons in the brain, Velcro inspired by burdock which easily sticks to clothes etc. [44]. According to J. M, Benyus Biomimicry is based on three main principles: (1) Nature as a model. (2) Nature as a measure. Biomimicry can be used as an eco-standard to judge the "rightness" of our innovations, "what works, what is appropriate and what lasts". (3) Nature as a mentor. "The more our world looks and functions like this natural world, the more likely we are to be accepted in this home that is ours, but not ours alone". The methods used to apply Biomimicry in Design are developed in 3. Methods.

The material at hand is itself an example of Biomimicry since it takes advantage of the natural agglutinant properties of mycelium instead of using synthetic glues. It is not only a source of inspiration for its agglutinant properties but fungi are also considered to be "the brains of the soil". The mycelium network forms symbiotic relationships with plants and makes partnerships with other organisms, sharing nutrient signals and providing protection from parasites or filtering toxins [7]. The importance of fungi in nature is further developed in 2.2.3 The role of mushrooms in nature.

3 Method

3.1 Empathize

3.1.1 Material Driven Design Method

The three main foundations of the Material Driven Design approach and the reason behind implementing it were presented in 2.3 Material Driven Design. At this point, it is addressed how to apply it and, more specifically, which are the steps to follow. Each step guides the designer through a journey that begins with the material at hand to a material experience vision (from tangible to abstract) and from a material experience vision to a tangible product (from abstract back to tangible).

Step1. Understanding the material

The first step consists of understanding the material at hand, both technically and experimentally, and creating awareness of its unique role in comparison with other alternative materials.

Step 2. Creating Materials Experience Vision

The designer must express how he/she envisions the material role in contributing to creating a unique user experience when creating a product and its purpose. Designers should reflect on how the material is connecting to the user, to other products, to society and to planetary health.

Step 3. Manifesting Materials Experience Patterns

Designers at this stage reflect on the interrelationship between the created material experience vision and the characteristics of the material and the product. Since it can be difficult to relate a vision to formal qualities, the first approach consists of relating qualities of the material and product to “meanings”, such as high-tech, sustainable, feminine or masculine, to give a few examples.

Step 4. Creating Material/Product Concepts

The findings from the previous steps are implemented into the creation of concepts. In the case of new biomaterials, the designer should have a semi-develop material sample at hand, where there are a couple of aspects still open for development [5].

3.1.2 Literature review

As part of the Design Science Methodology explained in 2.1.6 Design Science, it is necessary to find information following a scientific and systematic approach. Design Research Methodology (DRM) concerns the way to do research regarding the disciplines of engineering design, industrial design and product development in general, according to K. Säfsten et al., [45]. A literature review is a method used in DRM for doing research and finding useful information. It presents the current state of knowledge in a scientific area. Existing literature is identified, read, and compiled. For that, it is necessary to have a plan. K. Säfsten et al., [45] offer a systematic way of conducting a literature review comprised in the following steps:

Formulate criteria for including and excluding literature.

(II) Identify suitable keywords.

(III) Select a database.

(IV) Select articles based on the formulated criteria.

The literature review will follow a snowballing approach, departing from a set of articles that were used in the bachelor's thesis "El micelio como material de fabricación y su papel en la reutilización de residuos agricolas" [46]. It will be mainly forward snowballing since it is key to finding how knowledge has evolved from an initially selected set of articles, but the backward approach will also be used. Apart from this strategy search strings will be also introduced in different databases with the keywords selected, see 4.1.1 Literature review.

3.1.3 Benchmarking

Benchmarking consists of positioning a product against its competitors. It is important for finding a market gap where the product could succeed, and identifying in which aspects the product could have a competitive advantage [47].

The competitor search will be focused on companies that develop insulation applications with a focus on either sustainability or that use shapes and patterns inspired by nature. To find them, a search on the internet will be conducted, since it is a fast and easy way to gather data. Companies on their webpages offer a lot of valuable information about who they are, their core values, what they do and how they do it. However, it is even more useful to complement that information with data obtained by personal contact with the companies. For that, visits to design fairs will be done, where companies present their products and are open to talking with the public and sharing information about them.

3.2 Define

3.2.1 Persona

Sometimes design teams get hung up on outlying (or non-essential) characteristics of a number of particular potential users, spending a lot of time at this stage and not clarifying what are the main user needs. The tool Persona focuses the attention on the most relevant characteristics of the users, going straight to the point, and creating a fictional character that represents the whole population group.

This tool usually covers the user's likes, hobbies, and passions, it also shows the job of the user and other factors such as frustrations, mood, aspirations etc. It is worth mentioning that this tool should be taken into account throughout the whole process. Designers, at some point in the process, often fall into the application of their own likes in terms of shapes, colours or materials, forgetting about the user. This user illustration should be hanging on the wall of the workspace, so the design team can always remember to see the evolving product from the user's point of view [29].

3.2.2 SWOT Analysis

SWOT meaning strengths, weaknesses, opportunities and threats, is the most popular marketing planning tool. It is based on an analysis of the product opportunities, its competitors and its market. Together with benchmarking, this tool helps designers to position their products on the market. After a SWOT analysis designers should be capable to develop a product that highlights its strengths, minimize its weaknesses, exploit emerging opportunities and avoid threats [29], [48].

3.2.3 Perceptual map

Competitive analysis is usually followed by a perceptual map, where key values that are considered important for the market are positioned in the four axes of a cross. Companies will be potion in the perceptual map according to how high they rate regarding the key market values. This will illustrate the market area that the project aims for in comparison with its competitors [29].

3.2.4 Product Journey mapping

A product mapping is a graphic representation of the product life cycle. It is a tool related to Design for Sustainability that provides a visualization of the journey that the product follows from the obtention of its raw materials, going through production and finishing with the waste it generates once it is discarded. Ideally, the product journey mapping of a product should aim to be circular, which means that the waste generated is used again for producing new products. This tool helps designers to consider all the different stages that the product goes through and to think about how to improve efficiency and effectiveness and how to minimize waste. It makes them answer important questions like; what happens after the use of a product? Can we use other alternatives to minimize waste? How can we reduce the final cost? Etc. [29].

3.2.5 Mood board

A mood board is a visual representation made from an assembly of different inspirational forms, colours and materials that creates a new whole. It is particularly common in Design Thinking methodologies and the Design for Emotion perspective. Making a mood board is an important visualization technique in the design process, suitable to present a particular atmosphere or context that designers want to relate to the new product. It usually comes right before the ideation stage of the design process [29].

3.2.6 Definition of the intended emotions

The definition of the intended emotions supports step three of the Material Driven Design Method. The definition of the intended emotions consists of envisioning the desired emotions that the designer wants to evoke in the user, by making a list for instance. Emotions play a significant role in the success of a product. Positive experiences trigger curiosity and desire whereas negative ones generate avoidance. Therefore, it is important to have in mind the emotions to transmit when designing making sure to generate positive feelings. For that, it is important to understand the user, which is why the tool Persona is also used, see 3.1.1 Persona, and to measure to what extent the desired emotions are evoked by the product, see 3.5.1 PrEmo [29].

3.2.7 Checklist for concept generation

This tool is taken from the Design Thinking Bootleg methodology. Once sufficient information is collected from the material and the user, data is synthesised creating a list of product requirements, setting boundaries and naming the aspects that the product should have to succeed. This tool can be also used later on to decide between different ideas. According to Standford Design School, this tool ensures that concepts are “valid, insightful, actionable, unique, narrow, meaningful, and exciting” [30].

3.2.8 Culture media

A culture medium is an environment where mycelium is grown, it has the necessary nutrients and conditions for it to grow healthy and as fast as possible. There are four important aspects to consider when preparing a culture medium, those are: nutrients, moisture content, temperature and access to oxygen. The most common nutrients used in mushroom cultures are nutritional yeast or flour, mixed with water to moisturize the media, to achieve the right temperature a seedling mat or a heater is the most accessible options and regarding ventilation or contact with oxygen, in the case of just growing mycelium, a cotton filter added in the mould is usually enough [14]. The mycelium can be obtained from the stem or the spores of a wild mushroom, or it can be obtained by different suppliers on the internet by buying a culture in a Petri dish or grain spawn most likely.

3.2.8.1 Petri dishes

Petri dishes are cylindrical recipients made of plastics with thin walls that are commonly used in microbiology to cultivate bacteria. They are transparent and their lid is not tightly closed, allowing some air exchange. The walls are usually covered with a filter that avoids any contamination to get into the media, the most common brand for those filters is Parafilm [49]. In a sterile environment, a liquid culture based on agar-agar algae is put inside the recipient covering its base. This liquid has been previously sterilised so it is hot when putting it into the Petri dish. Once it cools down, it solidifies and then is ready for the inoculation of mycelium. There are multiple recipes in the book written by P. McCoy, Radical Mycology [50], some examples are the ones presented in TABLE I.

TABLE I

AGAR MEDIA RECIPES

Malt extract agar	Dry, light malt – 10g
Malt yeast extract	Malt - 10mL, yeast – 1mL
Potato Dextrose Agar (PDA)	Boiled potatoes – 150g, dextrose – 7g
Malt extract with honey	Malt – 10g, honey – 16g

Some recipes for agar media from the book Radical Mycology by P. McCoy [50].

3.2.8.2 Liquid culture

The recipes used for this culture are similar to the ones used for agar media. The difference is that the liquid culture technique does not use the algae agar-agar. Therefore, the liquid does not solidify when it cools down and the mycelium grows in liquid. The advantage of this method is that is a better technique when thinking about transferring the mycelium from one medium to another. The recipient has a self-healing injection port for using a syringe. Once the mycelium has grown, it can be transported by injecting the syringe through the injection port and absorbing the liquid with mycelium, then the inoculation on the new media is carried out by dropping some of the liquid inside. This procedure allows a more homogenous propagation of the mycelium in the new media and, since the syringe is already sterile, it minimizes the chances of contamination. Moreover, it increases mycelium propagation because it can grow three-dimensionally by being in a liquid suspension, according to P. McCoy [50].

3.2.8.3 Grain spawn

Once the mycelium has grown in either two of the previously mentioned media, the culture is transferred to grain spawn. Grains form a cheap substrate rich in nutrients that allows mycelium to grow fast and form a dense network that can lately be transferred to wood, hemp or the final substrate that is going to be used for either growing mushrooms or producing mycelium composites. There are a lot of different types of grains that can be used, some examples are wheat, millet, birdseed, popcorn, millet etc. The most popular ones are brown rice and rye since they absorb a good amount of water which keeps the moisture content high for enough time for the mycelium to colonize the whole substrate

[50]. The grains need some previous preparation before they are used as grain spawn. They have to be left in water for 24 hours and cooked in boiling water for 5-10 minutes for them to absorb water and get the right consistency for the mycelium to take nutrients from them. Before the sterilization process, grains shouldn't be too hard nor too soft and should be easy to break up. The advantage of using grain spawn is that when transferring the culture to the final substrate, each grain becomes a new source for the mycelium to start colonizing the new substrate, so if the grains are properly mixed with the new substrate, a successful, fast and homogenous colonization will be ensured [14].

3.2.8.4 Substrate

The final medium is where mycelium is going to grow in its final stage for either growing mushrooms or building mycelium composites. There is a huge variety of options here, but for both applications, the most common substrates are based on hardwood or softwood. In the case of mycelium composites, it is usually hardwood the substrate selected. TABLE II shows some examples of wood that fit into those two categories. TABLE III shows other materials where mycelium can easily grow. It is important to mention that this final medium is usually mixed with some nutrients like nutritional yeast or flour, to increase the growth rate of the mycelium, since this medium lacks nutrients when compared to the previous ones.

TABLE II

HARDWOOD AND SOFTWOOD

Hardwood	**Softwood**
Mahogany	Pine
Oak	Cedar
Nogal	Douglas fir
Elm	Cypress
Birch	Spruce

[6]

TABLE III

ALTERNATIVES SUBSTRATES

Bamboo	Cotton
Coffee grains	Soy hulls
Cactus	Hemp
Coconut coir	Straw

[6]

3.1.2 Sterilization

Every culture media that has been mentioned before has to be submitted to a sterilization procedure, where all the contaminants that the media are killed before the inoculation with mycelium. This is important because the media might have invisible contaminants like bacteria or spores from other fungi that will compete against the mycelium for colonizing the culture. In the book Growing Gourmet and Medical Mushrooms, P. Stamets presents six vectors of contamination:

1. The cultivator

2. The air

3. The media

4. The tools

5. The inoculum

6. Mobile contamination units (MCU's) [14].

For each vector, there are different methods to prevent contamination. The different options will be briefly presented highlighting the ones that are going to be used in this project. For more detailed information is recommended to read chapter 10 of the book Growing Gourmet and Medical Mushrooms, by P. Stamets [14].

1. The cultivator refers to the person that is going to carry out the cultivation. If the hands or the clothes are not properly cleaned, they might be a potential source of contamination. A facial mask is recommended as well since contaminants can be spread by breath as well.

2. The air. According to P. Stamets "Air can be described as a sea of contaminants" [14]. To prevent this source of contamination, professional laboratories use HEPA filters that clean the air constantly. The most common alternative to this is to use a still air box, which is a plastic box, with holes for the hand, that has been disinfected before each work with commercial disinfectant sprays.

3. The media. As mentioned before the culture media has to be sterilised. For that, the most common method is to use a pressure cooker. The media is introduced inside a jar or polypropylene bags and then left inside a pressure cooker at 15psi with boiling water from 40 to 90 minutes, depending on the media. In the case of agar media or liquid culture, only 40 minutes will be necessary, for grain spawn or final substrates it has to be 90 minutes. In this case of not having a pressure cooker, a conventional cooker can provide good results as well, by putting the lid on and doubling the times for each case. The key variables in this procedure are heat and pressure, which will kill possible competitors.

4. The tools that are going to be used, such as knives, syringes, forceps etc. have to be disinfected. There are sterilizer chambers that work with UV lights that eliminate contaminants. A more accessible solution is to use alcohol and a burner.

5. The inoculum is the mycelium that is going to be transferred, whether it comes from a petri dish, from a wild mushroom or any other media, it can be contaminated. For that a quick transfer and address properly the previous vectors of contamination are key. There are also some professional techniques to purify mycelium that are not going to be addressed in this project. For more information see Chapter 10 of Growing Gourmet and Medical Mushrooms by P. Stamets [14].

6. Mobile contamination units (MCU's) are insects that usually carry with them multiple contaminants that, when entering the laboratory, are spread everywhere. Among insects, mites are the most complicated to handle, for their tiny size and preference for fungi.

In the book Mushroom Cultivator: A Practical Guide to Growing Mushrooms at Home, P. Stamets et al. [51], present some of the most common contaminants, in TABLE IV some of them are presented:

TABLE IV

COMMON CONTAMINANT SPECIES

Trichoderma	*Bacillus*	*Black bread mold*
Orange bread mold	*Cobweb mold*	*Penicillium*

[51]

3.1.3 Inoculation. Still air box.

The still air box was presented in the previous point. Here more details will be given about how they are used as some pictures as examples.

A still air box is a clean, transparent plastic container that has been sterilized using frequently a conventional cleaning stray for disinfection that can be found in any grocery store. It is a semi-sterile environment where fungal, viral or bacterial particles that are usually found in suspension in the air can not penetrate the box from above. Although it is not as effective as a professional flow hood with a HEPA filter, it effectively minimizes the chances of contamination. The design of the still air box is simple, it is a plastic box with two holes in one of its walls, close to the bottom. Some designs add plastic gloves for washing dishes to those holes. However, it is very complicated to manipulate Petri dishes and be precise with the operations when using those kinds of gloves. It is considered better to leave the holes alone, use latex gloves for the hands, not attached to the box, and use hand sanitiser for every use. If the hands are regularly sanitized along the process then latex gloves are not strictly necessary. Another good consideration is to place a towel that has previously been cleaned with a mixture of water and bleach sanitiser, on the bottom of the box. That will ensure that the working surface is clean [52].

3.1.4 Cultivation chamber

The function of a cultivation chamber is to keep the right conditions for growing mycelium as fast as possible. The relative humidity (R H) is already given by the culture media, but to get the right temperature a heater is the best option. An alternative to a heater is to use a seedling mat, which is conventionally used for seed germination when growing plants. Another important requirement for a cultivation chamber is to have some insulation on the walls and on the top to ensure that heat is kept inside at the right temperature. It is important to mention that those are the requisites for growing mycelium. If the aim is to cultivate the fruiting bodies (mushrooms) then air exchange, lighting and humidity control in the air become key parameters [53].

3.3 Ideate

3.3.1 Sketching

A sketch is a rapidly executed freehand drawing that is not usually intended as a finished work. A sketch may serve several purposes: it might record something that the artist sees, it might record or develop an idea for later use, or it might be used as a quick way of graphically demonstrating an image, idea or principle. Sketches can be done in any drawing medium, on paper, digital drawing pads, on a surface etc. [54].

3.3.2 CAD

Once the concept is defined and its dimensions and measures are established, a virtual prototype with accurate measures is always required. According to Siemens, [55] "3D CAD (3-dimensional computer-aided design) is a technology that engineers, product developers and designers use to create functional, virtual prototypes of three-dimensional objects". With 3D CAD is possible to make testing simulations, draw, share, review and modify designs easily. Since its early development in 1985, CAD has opened the doors to innovative products able to get into the market fast. Besides, it improves communication among the different departments of a company, especially between design engineers and manufacturers [55].

3.3.3 Rendering

3D models can be used to create photo-realistic images for use in sales and marketing materials, known as renders. There are softwares for 3D CAD modelling and rendering. Some of the most common ones for 2D and 3D modelling are AutoCAD, Inventor, SolidWorks, CATIA, Alias etc. and for rendering Keyshot, Blender, Cinema 4D, Maxwell etc. In this project, the software used were Alias, Keyshot and Maxwell. Additionally, to improve the renders and add more details, the software Photoshop can be used. As it is with CAD, it improves the communication between industrial designers and manufacturers [56].

3.3.4 Mould preparation

Moulds are usually made of transparent plastic so it is possible to see through them and see how the mycelium is growing. This will allow checking if any contamination appears, if all areas are properly moisturized and if the mycelium is growing homogeneously. It is important to make small holes in the mould so the mycelium can breathe [57].

3.4 Prototype

3.4.1 Prototyping

Traditionally prototyping is thought of as a way of testing functionality. But prototyping is used for many reasons:

- Empathy gaining. Prototyping is a tool to deepen your understanding of the design space and your user, even at the pre-solution phase of your project.
- Exploration. Build to think. Develop multiple solution options.
- Testing. Create prototypes (and develop the context) to test and refine solutions with users.
- Inspiration. Inspire others (teammates, clients, customers, investors) by showing your vision.
- Learning. If a picture is worth a thousand words, a prototype is worth a thousand pictures.
- Solve disagreements. Prototyping is a powerful tool that can eliminate ambiguity, assist in ideation, and reduce miscommunication.
- Start a conversation. A prototype can be a great way to have a different kind of conversation with users.
- Fail quickly and cheaply. Creating quick and dirty prototypes allows you to test ideas without investing a lot of time and money upfront.
- Manage the solution-building process. Identifying a variable to explore encourages you to break a large problem down into smaller, testable chunks.

Prototypes as sketches evolve throughout the process, the first ones are usually known as mockups, they are a way of testing the dimensions of the products and understanding how the concept works. Once the project is in the latest stages, prototypes can get much more realistic, getting closer to the real product [30].

3.4.2 Growing

The evolution of how the material evolves will be presented through pictures that will be taken every 5 days.

3.4.3 Drying

This method consists of drying the composites once it is fully grown in a conventional oven at 80°C for approximately 4 hours, depending on the size of the piece. This will remove almost all the water content inside the composite and give the material its final properties.

3.5 Test

3.5.1 PrEmo

PrEmo is a non-verbal self-report instrument that measures 14 emotions that are often elicited by Product Design. Of these 14 emotions, seven are pleasant and seven are unpleasant. So with this tool, responders can report the emotion that the concept evokes with the use of expressive cartoon animations. Each of the 14 measured emotions is portrayed by an animation using dynamic facial, bodily and vocal expressions, the users have to select the ones that they feel more identified with when interacting with the product. It helps both the user, to understand their feeling and how much they like or dislike the product and the designer who see if he/she has succeeded in evoking the desired emotions [29], [31].

3.5.2 Interviews

According to K. Säfsten et. al., "Research interviews are suitable as a technique for data collection when the researcher wants to gather information (in the form of perceptions and experiences) from one or more individuals regarding a phenomenon [45]. Structured interviews have a particular aim and there are usually some questions that have been previously prepared [45]. Individual interviews will be conducted to evaluate the concepts created where potential users are asked about the emotions they feel and which ones they find more related to the material. This feedback will later be used to decide among the different alternatives. In the case of the final prototype, the interviews will be done along with PrEmo, to help responders understand and clarify their emotions, questions supported by a rating scale and response alternatives. The two late tools mentioned are presented by K. Säfsten et. al., in the book *Research Methodology for Engineers and Other Problem-solvers* [45]. The story behind the product will be explained to the users and short questions will be asked to evaluate its success and get some feedback for future possible modifications.

4 Approach and Implementation

4.1 Empathize

4.1.1 Literature review.

According to the systematic method presented in 3.1.2 Literature review, based on the plan established by K. Säfsten et al., [45], these were the keywords chosen to find scientific articles, see TABLE V:

TABLE V

KEYWORDS AND SYNONYMS – MYCELIUM COMPOSITES AREA

Keywords	Synonyms
Mycelium	Hyphae
Composites	
Fungi	Mushroom
Lignocellulosic fibres	Plant fibres
Biomaterials	Bio-based
Biodegradability	
Mechanical properties	Physical properties
Insulation	
Foam	
Thermal properties	
Species	

To do that the following search string was introduced in the selected databases:

(mycelium* OR hyphae*) AND (composites*) AND (fungi* OR mushroom*) AND (lignocellulosic fibres* OR plant fibres*) AND (biomaterials* AND bio-based) AND (biodegradability*) AND (mechanical properties* OR physical properties*) AND (insulation*) AND (foam*) AND (thermal properties*) AND (species*)

Regarding the Design discipline, a search string was also done with the following keywords, see TABLE VI:

TABLE VI

KEYWORDS AND SYNONYMS – DESIGN AREA

Keywords	Synonyms
Design for emotion	Feelings, sensations
Design for sustainability	Green design
Material driven design	Material focus
Biophilia	Nature
Circular design	Circular economy
Recyclability	Reprocess

Search string:

("design for emotion*" OR feelings* OR sensations*) AND ("design for sustainability*" OR "green design*") AND ("material driven design*" OR "material focus*") AND (biophilia* OR nature*) AND ("circular design*" OR "circular economy*") AND (recyclability* OR reprocess*)

Selection of data bases:

– Primo
– Scopus
– Web of science
– Google scholar
– MDPI

Criteria for selecting articles:

– Only scientific articles, webpages and books written in English will be considered. Except for the author's previous work on the topic [46].
– Scientific articles on the topic of mycelium composites published before 2010 will be discarded.
– Articles with no previous citations will be discarded.

Articles found:

- First search string:

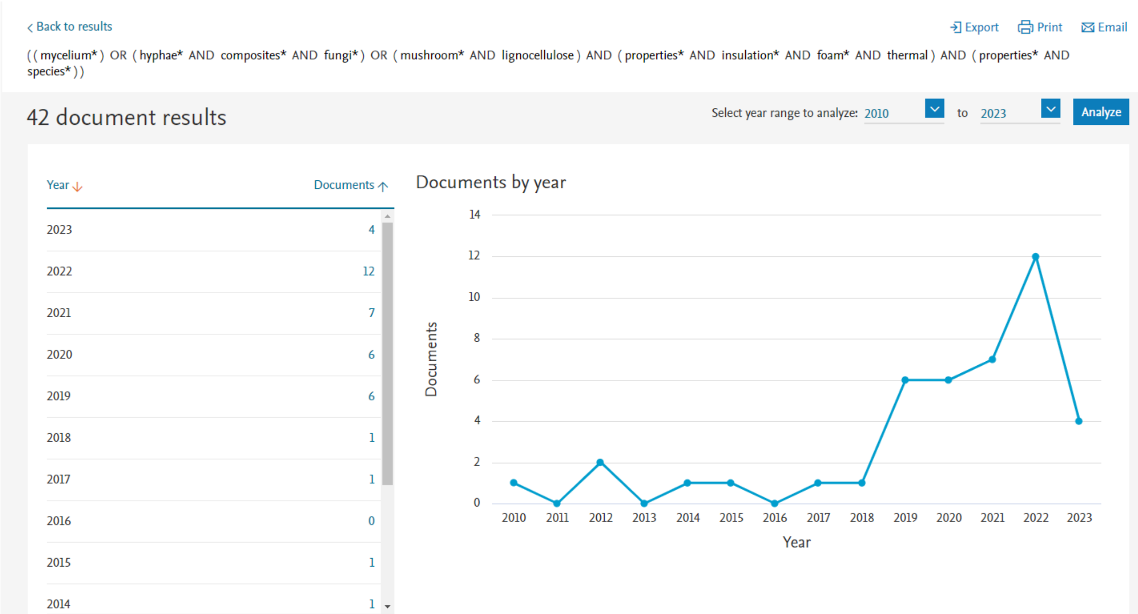


Figure 9. Data analysis from the 42 articles found in the first search string regarding mycelium composites in Scopus.

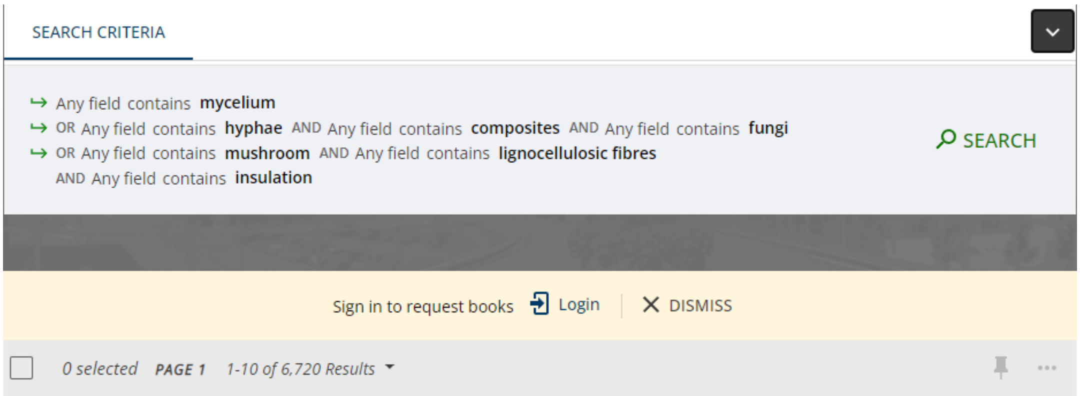


Figure 10. 6.720 results in Primo for the first search string regarding mycelium composites.

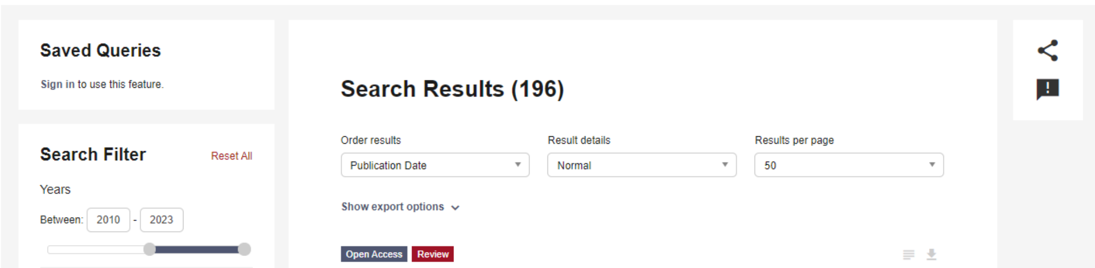


Figure 11. 196 results in MDPI database for the first search string regarding mycelium composites.

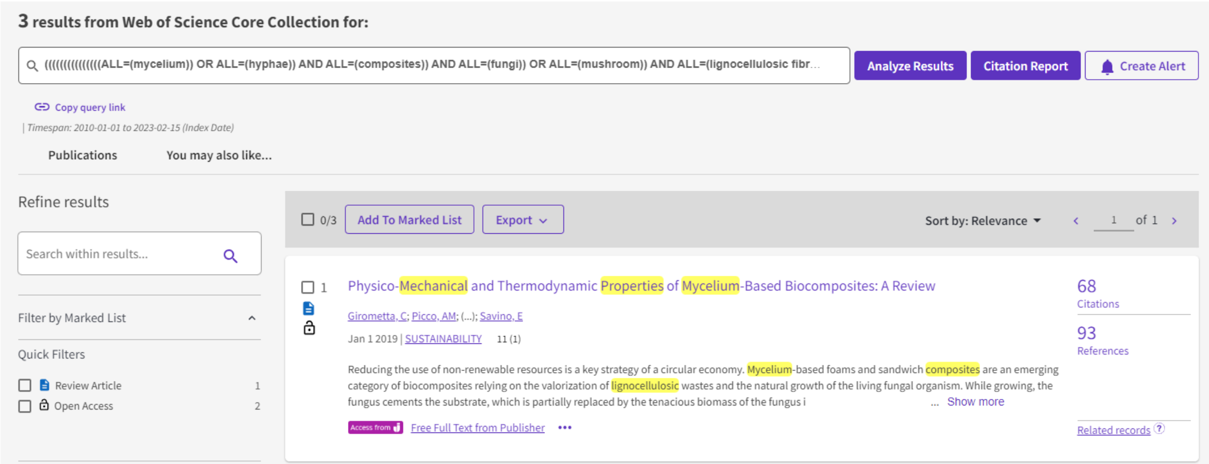


Figure 12. 3 results in Web of Science database for the first search string regarding mycelium composites.

Figure 13.110 results in Google scholar database for the first search string regarding mycelium composites.

TABLE VII

NUMBER OF DOCUMENTS FOUND IN THE SELECTED DATABASE USING THE FIRST SEARCH STRING

Scopus	42 documents found
Primo	6.720 documents found
MDPI	196 document found
Web of Science	3 documents found
Google Scholar	110 documents found

Just by reading the titles it was found that a lot of articles were not related to mycelium composites. Those were discarded and only the ones that fulfilled the criteria and where the title was appealing were further read.

It was mentioned that the search for articles was also complemented by a pre-set of articles that was used in “El micelio como material de fabricación y su papel en la reutilización de residuos agrícolas”[46] . See TABLE VIII for the titles of those articles and their related ones found by a forward snowballing approach.

TABLE VIII

PRE-SET OF ARTICLES AND THE ONES FOUND BY FORWARD SNOWBALLING

Title	Year
A comprehensive framework for the production of mycelium-based lignocellulosic composites.	2020
→ Recent advances in the construction of biocomposites based on fungal mycelia.*	2022
→ Mycelium bio-composites in industrial design and architecture: comparative review and experimental analysis.	2020
→ Mycelium-based composite: the future of sustainable biomaterial.	2022
→ Establishment of the basidiomycete Fomes fomentarius for the production of composite materials.	2022
→ Basics of building with mycelium based bio-composites: a review to built projects and related materials.	2022
→ The 3D printing of biomass-fungi composites: effects of waiting time after mixture preparation on mechanical properties, rheological properties, minimum extrusion pressure, and print quality of the prepared mixture.	2022
→3D printing of biomass-fungi composite material: effects of mixture composition on print quality.	2021
→Biomass waste materials through extrusion-based additive manufacturing: A systematic literature review.	2023
→ MY-CO SPACE: An artistic-scientific vision on how to build with fungi.	2022
Growing a circular economy with fungal biotechnology: A white paper.	2020
Mechanical physical and chemical characterization of mycelium-based composites with different types of lignocellulosic substrates.	2019
Physico-mechanical and thermodynamic properties of mycelium-based biocomposites: A review.	2019
→ Characterization of self-growing biomaterials made of fungal mycelium and various lignocellulose-containing ingredients.	2022
Life cycle assessment of fungal-based composite bricks.	2021
Packaging applications of fungal mycelium-based biodegradable composites.	2022

→Articles found by forward snowballing.

- Second search string

The same procedure was applied with the second search string regarding the design area. The following table brief the findings in each selected database. See TABLE IX.

TABLE IX

NUMBER OF DOCUMENTS FOUND IN THE SELECTED DATABASE USING THE FIRST SEARCH STRING

Scopus	2 documents found
Primo	12 documents found
MDPI	1 documents found
Web of Science	4 documents found
Google Scholar	3.200 documents found

In the same way as it was done with the first search string, articles were first selected by reading its title and then selected criteria were applied to them.

4.1.2 Material Driven Design

4.1.2.1 Properties of mycelium composites

The final properties of the composite depend on three main factors, the matrix (the fungal species), its spreading rate and capacity for degrading the organic matter, the feedstock (lignocellulosic substrate) and the compatibility between the fungi and their feedstock. Apart from that, the temperature and the moisture percentage during the culture, the drying process and the final density have a significant influence on the properties of the material [58].

The fungal species used to produce mycelium composites are usually the ones belonging to the group of *xerophilic fungi*. Those are primary decomposers, which means that have a great capacity to grow on a huge variety of lignocellulosic biomass and develop an infinite amount of hyphaes, only limited to the available space and nutrients in the medium. These fungi grow fast and create dense mycelium networks, which is the reason behind being selected for mycelium composites. According to E. Elsacker, in the year 2020, a total of 36 species of *xeropholic fungi* were registered in patents for the production of mycelium composites [4]. Now the number must be higher. Among those species the most common ones are: *Trametes versicolor, Ganoderma lucidum, Pleurotus ostreatus, Fomes fomentarus, Schizophyllum commune* and *Pleurotus djamor*, see Fig. 14 (a), 1 (b), 1 (c), 1 (d), 1 (e) and 1 (f).

(a) (b) (c)

(d) (e) (f)

Fig.1. Most common *xerophbolic fungi* used in mycelium composites. (a) *Trametes versicolor*. (b) *Ganoderma lucidum*. (c) *Pleurotus ostreatus*. (d) *Fomes fomentarus*. (e) *Schizophyllum commune*. (f) *Pleurotus djamor*.

Although the substrate selected, the matrix and the compatibility of those two aspects have a great influence on the properties of the material, it seems that there are some common properties presented in all mycelium composites. Those are:

- Low thermal conductivity

This property makes mycelium composites a good alternative to Polystyrene and Polyurethane for thermal insulation applications. The thermal conductivity of the composite is influenced by its density. The lower the density of the material, the lower its thermal conductivity and hence, the better the thermal insulation the composite provides.

The moisture rate inside the composite has also an influence on the thermal conductivity of the material. The lower the moisture rate, the better the thermal insulation. Mycelium composites are always dried once are fully colonized in order to stop the organism from continuous growth and to minimize the moisture content. However, a small percentage of moisture is always going to remain inside the composite according to M. Jones et al., *[59]*. The influence of this parameter is not that significant since an increase of 90% moisture will only increment the thermal conductivity by 15-20%, in a sample made out of hemp for instance [59].

- Acoustic insulation

Composites that present a higher density are good for acoustic insulation, representing a good alternative to Polyurethane foam and cork. The excellent acoustic absorption of mycelium composites is due to their porous, fibrous nature, which converts the mechanical motion of air molecules into low-grade heat, decreasing the sound wave amplitude and reducing sound accumulation and reflected noise. Mycelium composites can reduce 70-75% of the noise perceived at 1000Hz frequency (45.5-60 dBa) [59].

- Good mechanical behaviour under compression

A high density is also related to better mechanical properties. It is important to have hence, a high rate of substrate colonization, which depends on the nature of the species used and its compatibility with the selected substrate [59]. The type of fibres of the lignocellulosic biomass has a great influence, but even more important is the size and processing of those fibres. Pre-compress and chopped fibres with a size inferior to 5mm have proved to improve the mechanical properties of the material [58].

Mycelium composites are particularly good under compression. They exhibit excellent behaviour reaching values up to 0,73MPa for the Elastic moduli (*E*) and a tensile strength (σ) of 0.5MPa, with a density ranging from 60 to 300 $^{Kg}/_{m^3}$. The porosity of the material is inversely correlated to its resistance under compression stress [59]. According to J.A López Nava [60], the flexural strength of mycelium composites is significantly lower than polyurethane and polystyrene foams (6-63 folds), due to the porosity of the material.

- Fire resistance

The particle size and type of substrate seem to have a significant influence on the fire resistance capacity of the material. The mycelium itself doesn't seem to present this property. It is the substrate (lignocellulosic biomass) that provides this property. Substrates rich in natural phenolic polymers such as lignin produce silica (SiO_2), which can significantly improve thermal degradation, fire reaction and safety properties. For example, mycelium composites using rice hulls as a substrate have lower heat release rates than synthetic foams (107 $^{kW}/_{m2}$ vs. 503 $^{kW}/_{m2}$ in the case of extruded polystyrene). It is the white surface layer of the composites the one that provides its fire resistance properties [59].

- Low density

All mycelium composites have low density, between 60-130 $^{kg}/_{m3}$ in the case of using substrates coming from plant stems such as flax, straw or hay, and between 87-300 $^{kg}/_{m3}$ in the case of sawdust from hardwood or softwood. As mentioned before, density has a great influence on the final properties of the material. TABLE X shows a brief of the influence of density on the different properties of the material.

TABLE X

DENSITY INFLUENCE ON MYCELIUM COMPOSITES PROPERTIES

High density 60-130 $^{kg}/_{m3}$	High stiffness, high sound absorption, low water absorption.
Low density 87-300 $^{kg}/_{m3}$	Low stiffness, better flexural strength, low thermal conductivity, high water absorption.

- Disadvantages

Overall, exposure to moisture rapidly decreases the performance of mycelium composites in all aspects. Water absorption is the main disadvantage of mycelium composites, which restricts them to be used outdoors. Although mycelium is typically hydrophobic, it is the substrate used for the development of the composite the one that absorbs water. Again, the type of substrate is an important factor to be considered. Cotton burs, switchgrass, rice straw, corn stalks and sorghum stalks are semi-hydrophobic materials, being the best option if the water absorption capacity, is a major concern [11].

According to J.A López Nava [60], the flexural strength of mycelium composites is significantly lower than polyurethane and polystyrene foams (6-63 folds), due to the porosity of the material.

4.1.2.2 Treatments for improvement

- Improvement of the mechanical properties

Hot or cold press is the best method to increase the density of the material, this will suppose a reduction in its water absorption, better mechanical properties and an increase in its sound absorption capacity. In the last stage of the development process of mycelium composite, (*see 4.1.5 Development process*), the material is introduced inside an oven for three hours at 80 degrees. Either before or during the drying process, pressing the material will significantly increase its density. The difference between the cold press and the hot press is that the cold press is done before the drying step and the hot press is done while it is inside the oven [61]. Hot pressing shifts the performance of the material from foam-like to wood-like according to A. Ghazvinian et al., [11]. Researchers report that the particle size of the substrate has also a great influence on the density of the material. Smaller sizes of the particles will suppose a higher density of the composite, ideally lower than 5mm. However, the powder-like substrate is not convenient since there is not enough air in between the particles for proper colonization of the mycelium. Hence, generally, the larger size of the particles supposes a better growth rate, since the mycelium easily finds oxygen among the particles of the substrate, always considering good compatibility between substrate and fungal species. Depending on the application a higher density or faster colonization will be prioritized [11], [13], [58].

To increase mechanical performance, there are a couple of strategies that can be followed. Apart from, cold pressing and hot pressing for increasing the density of the material. Liquid culture inoculation instead of grain spawn, (see 3.2.9 Liquid culture), has reported higher compressive strength values in the final composites (0.07 MPa for liquid inoculation vs. 0.002 MPa for grain spawn inoculation). The difference is due to a better homogenization of the mycelial network throughout the substrate when using liquid culture and better chances for colonization within the centre area, which is typically less colonized due to a lack of oxygen [4].

By coating the material with an infusion of bio-resin, like soy resin, on the surface of the composite, the strength and stiffness of the material are significantly increased, improving its shear yield and ultimate stress [59]. Mycelium composites treated with soy resin performed a significant increase in their flexural strength, up to 30 MPa, situating mycelium composites between low-density polyethylene (14MPa) and ABS (75MPa). Another method to improve the mechanical properties of the material consists of hybridization with synthetic-butadiene rubber or natural reinforcements like cellulose nanofibrils. An addition of a 5vol% styrene-butadiene rubber could almost double the compressive strength of a composite made of *P. Ostreatus* and cotton seed hulls, going from 177 kPa to 343 kPa, according to M. Jones et al., [59]. However, the improvement in mechanical properties may be offset by additional costs in the processing and its effect on sustainability. Besides, it slightly delays the germination of mycelium. In the case, of nanocellulose reinforcement, just small quantities (2.5wt%) supposed an increased in the flexural strength, (from 1,5 MPa to 3.5 MPa) and Young modulus (from 220 MPa to 575 MPa). Higher quantities did not provide an improvement in mechanical performance. Therefore, this might be a better option for hybridization, since it doesn't compromise the sustainability of the material in terms of biodegradability, according to M. Jones et al., [59].

With the double objective of increasing the mechanical properties of the material and making it weatherproof, sandwich structures have been proposed. In this case, the mycelium composite is placed between two sheets of either metal, wood or plastic, covering the material and giving it a higher strength while protecting it from water. However, the increase in mechanical performance is not as significant as it is in hybridization or resin infusion. Besides, these methods also compromise sustainability and production costs [59]. For instance, Wong et al. [62] reported that a sandwich structure of mycelium composite covered by two laminates of aluminium sheets didn't experience better compression strength than the composite on its own.

- Water-proof treatment

As mentioned before, lower densities of the material suppose higher water absorption rates. Therefore, a method to minimize this aspect consists of increasing the material's density by cold or hot pressing. Another method consists of coating the material with bio-based solutions such us polyfurfuryl alcohol resin (PFA) [59], shellac (a natural polymer) or edible films made of carrageenan, chitosan and xanthan. Water-insoluble proteins extracted from agricultural waste, such as corn zein and wheat gluten, or fish myofibrillar have also been used by the textile industry [4]. I.Irbe et al. reported that in terms of water absorption, the composite made of the fungal species Agaricus bisporus (champignon) grown on rapeseed cakes reported strong hydrophobic properties and could be used for moisture-resistance products [61].

- Fire resistance

The addition of glass fines improves the fire resistance properties of mycelium composites by increasing its silica content. According to M. Jones et al. [59] "Mycelium composites incorporating 50wt% glass fines has much longer times to flashover (311-370 s) than synthetic materials, such as extruded polystyrene insulation foam (XPS) (61 s) and particleboard (173 s)".

- Termiticides

Common termiticides like vetiver oil, guayule resin, cedar oil and borax have successfully been used by S. Bajwa in mycelium composites boards made out of hemp and kenaf using *D.confragosa*, *T.versicolor* and *G.Lucidum* [63].

4.1.2.3 Applications of Mycelium composites

Among the different industrial applications of mycelium-composites, the ones with more research and development are:

- Insulation

Acoustic and thermal insulation, together with packaging, might be the most industrialized application of mycelium companies. There are a lot of companies that produce insulation panels. The biggest one is MOGU, the Italian company that produces acoustic panels. Another example is BIOHM, based in London which produces both acoustic panels and panels for thermal insulation [64]. See Fig. 15 for an example of an insulation panel.

According to the knowledge presented before the main difference between acoustic and thermal insulation is the density of the composite. For acoustic insulation, a high density is needed, whereas for thermal insulation, a lower density is preferred. In the case, of acoustic insulation, is not recommended to hot or cold press the material since, even though, it will increase its density, it might reduce the thickness of the panel too much, compromising its sound absorption capacity. For thermal insulation, since a low density is preferred, there is no need for a hot or cold press.

The most common substrates used for sustainable insulation applications in general are hemp, flax and straw. In the case of thermal insulation flax and straw will fit better since they will provide a lower density and a high growth rate. In the case of acoustic insulation, hemp might be the most popular option since its particle shape and size will provide a higher density and better mechanical properties [59], [58], [61].

In terms of fungal species, *P. Ostreatus*, *G. Lucidum* and *T. Versicolor* are the ones that have been studied the most. However, companies might be using other strains and they keep that information in industrial secret. Besides, it is not clear which of those three species might be more suitable for acoustic or thermal insulation. Other species that have been used for insulation applications are *P.Sanguineus* and *L.Velutinus* [61].

Fig. 15. Insulation panel [15].

- Furniture

The use of mycelium composites has attracted the attention of architects and designers for building chairs, benches, tables, stools, lamps, plant pots etc. Some examples are the chair and stool made by Erik Klarenbeek, the project Mycosella by Natalia Piórecka or Mycelium + Timber by Ninela Ivanova and the work done by Philip Ross, see Fig. 16.

These applications take advantage of the strength that mycelium composites present under compression. The compression strength as mentioned in 2.1.1. Properties is higher for those composites made from hard wood or soft wood sawdust. More specifically, hard wood is the best option, with a particle size lower than 5 mm.

Again, the most common species are *P. Ostreatus*, *G. Lucidum* and *T. Versicolor*. Mycelium composites made of *T. Versicolor* have demonstrated higher values of tensile strength and Elastic modulus when submitted to compression, whereas *P. Ostreatus* and *G. Lucidum* composites, for the same substrate, experienced better flexural strength according to M.Jones et al [59] and E. Elsacker [4].

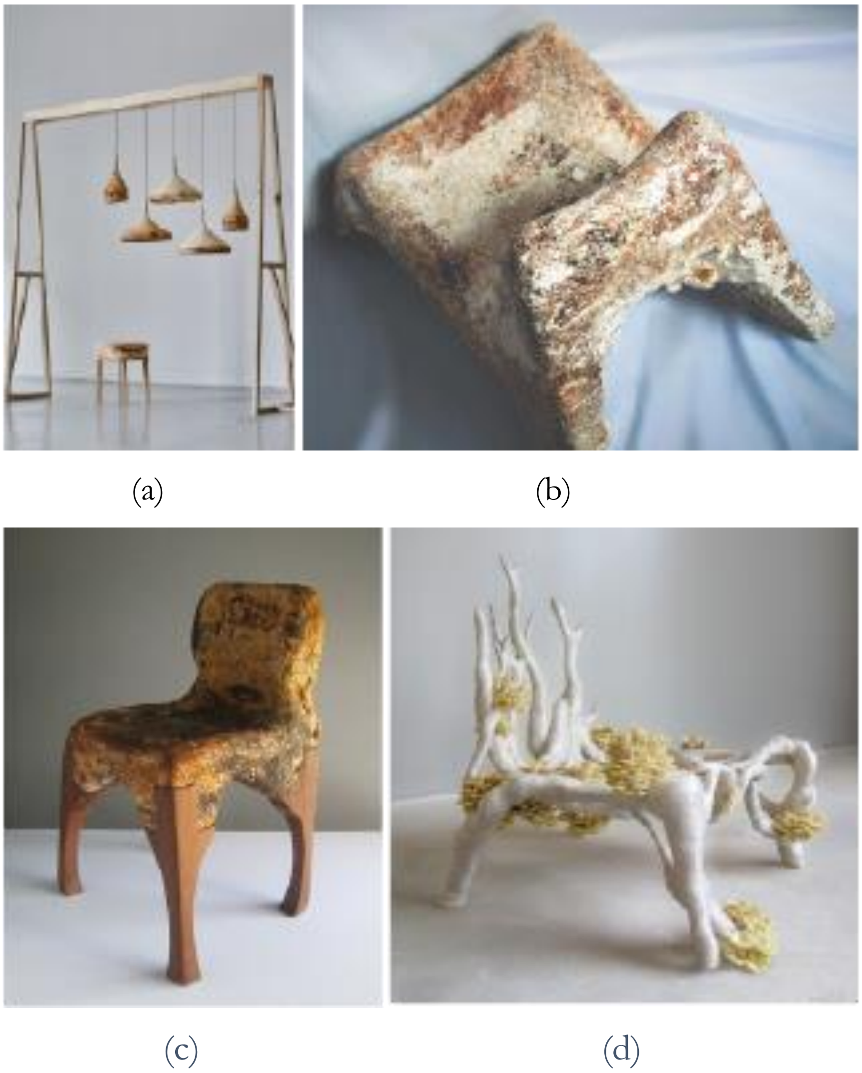


Fig. 16. Mycelium furniture. (a) Mycelium + Timber. (b) MYCOsella, (c) The Yamanaka chair by Phill Ross (d) Mycelium chair by Eric Klarenbeek. [65], [66], [67], [68].

- Packaging

Packaging is one of the most interesting applications of mycelium composites since the packaging is thought to be thrown away right after the client receives the product. The advantage that mycelium composite present compared to its competitors is that it is a biodegradable material, that can be thrown straight into the organic waste or into the soil, without requiring any recycling process. Moreover, dead mycelium in soils represents a decomposition hotspot and a habitat for the microbial community. According to V. Brabcová et al [69], "the decomposition of mycelia clearly represents an important process for nutrient cycling in forest soils". Another advantage regarding packaging applications is that mycelium composites are lightweight materials.

Ecovative is the most famous company in the world regarding mycelium composites. It started in 2007 in Green Island, USA, by producing packaging applications [70]. They have made packaging for known companies such as IKEA and DELL [71], [72]. Right now, they produce foam for insulation, food, shoes, skin care products and leather. Another company that is focused on mycelium packaging is Magical Mushroom Company, based in the UK, Fig. 17, [73].

For packaging applications, hemp and sawdust seem to be the best options regarding substrates [74], [15], [59]. Again, it is not clear enough which is the best mycelium strain for packaging since it is kept by industrial secret, but *P. Ostreatus*, *G. Lucidum* and *T. Versicolor* might be the best options [59], [4].

(a)

(b)

Fig. 17. Mycelium packaging, (a) Ecovative +IKEA (b) Magical mushroom company packaging [73], [72].

- Construction industry

Architects and designers have seen the potential of mycelium composites in building structures made of mycelium bricks for their excellent behaviour under compression. Those structures are usually supported by steel bars. Early developments of these structures were made by Philip Ross, one of the pioneers who began working with this material in the early 90s and founder of the company Mycoworks [75], [76], which as Ecovative, also produces a big range of products out of mycelium (see Figure X). A good example of a big structure made of mycelium bricks is the Hi-fi tower by David Benjamin. The Hi-fi was coated by a natural oil penetration to make the bricks weather-proof [4], see Fig. 18.

(a) (b)

Fig. 18. Mycelium structures. (a) Structure by Phill Ross, (b) The Hi-fi Tower by David Benjamin [75], [77].

For the construction industry, sawdust from hardwood is the most suitable option as a substrate since it is the one that the best mechanical properties provide. If compression strength is key T. Versicolor might be the best mycelium strain option, if some flexural strength is necessary as well, then bricks made of *P. Ostreatus* or *G. Lucidum* are a better choice [4]. Again, this is according to the species that have been studied the most. Other species like *S. commune* or *F. fomentarius* has also shown high values of tensile strength under compression efforts [15], [4].

- Textile

There are a lot of companies focused on leather-like textile applications using mycelium. Mycoworks by Philip Ross, produce a patent technology known as Fine Mycelium out of *G. Lucidum*. They presume to be able to control design parameters such as softness, drape, thickness, shape, texture, flexibility, strength and density. "Fine Mycelium engineers mycelium cells as they grow to create three-dimensional structures that are densely entwined and inherently strong" [78]. To produce mycelium leather is necessary to use pure mycelium (mycelium in the aerial state), which is the foam-like structure that forms on the surface of the substrate when the mycelium is in contact with oxygen. To obtain pure mycelium it is necessary to control the moisture content in the air and the temperature. It is not clear what are the exact parameters to increase the development of these mycelium structures, but it is known that some species have more tendency than others. *G. Lucidum* (also known as Reishi) seems to have that tendency and that is why it is widely used for textile applications. Once this aerial mycelium is obtained, the samples are pressed and coated [78], [4]. The fruiting body of the fungi *P. ellipsoideus* has also being used for textile applications [4].

Some other companies that are also focused on mycelium leather are Bolt Threads, form California, USA, with their product Mylo, which has been used in collaboration with Adidas in the sneakers Sam Smith [79], Mycotech Lab from Indonesia [80], Neffa from the Netherlands [81], Le Qara from Perú [82] and the previously mentioned Ecovative [70], see Fig. 19.

Fig. 19. Mycelium textile applications. (a) Mylo, (b) Neffa t-shirt. (c) Mycotech Lab, (d) Le Qara [83], [84], [85], [82].

TABLE XI

APPLICATIONS OF MYCELIUM OF MYCELIUM COMPOSITES AND THEIR RELATED PROPERTIES

Application	**Mycelium composite properties**
Insulation	Fire resistance, low density, acoustic absorption, low thermal conductivity
Furniture	Compression resistance
Packaging	Lightweight
Bricks	Compression resistance
Clothes	Pure mycelium

4.1.2.4 Process for developing mycelium composites.

It is important to understand the general protocol of how to develop mycelium composites. Research papers follow different procedures and apply different parameters, since those conditions usually depend on the mushroom species and the preferences of the researchers of using one method or another, see 3. Methods. However, it is possible to present an overall approach since some steps seem to be repeated in all the studies [15], [58], [59].

1. The mycelium is initially grown in either Petri dishes in an agar medium, liquid culture or directly in grain from a mushroom sample. These methods have been developed in 3. Methods. The mycelium might come from the spore of a mushroom, from the stem of it or from cloning another sample. The first medium where mycelium is grown must be previously sterilized, to avoid any other organism to grow along with mycelium. For that, pasteurization is the most common method. It consists of putting the medium inside a jar, closing it up and putting it inside a pressure cooker with boiling water. The time for pasteurization is usually between 45 and 90 minutes. Once this step has been done, all microorganisms that could be living in the medium are gone, and the medium is ready to be inoculated with mycelium.

2. After 1 week or less, the mycelium has colonized the whole initial medium and it is ready to be transferred to the substrate selected for the composite. This second medium is going to play a key role regarding the final properties of the material. The substrate doesn't usually have as many nutrients as the first medium, hence, some bran like flour or nutritional yeast is added to enrich the substrate. Besides, it needs a high moisture content and for that, it is humidified with water. Again, once the substrate is ready, it must be sterilized. In the case of the pasteurization method, this time it takes no less than 90 minutes.

3. The sterilized substrate is hand-packed in a sterilized mould already designed with the desired shape for the composite. The top part of the mould is covered, so any contaminants get inside it, and it usually has a hole with a filter, since it is important for the mycelium to get some air exchange.

4. The mycelium will grow in a controlled environment for 1 or 2 weeks, depending on the substrate and the size of the mould. This stage is divided into two phases; The first one consists of growing the mycelium inside the mould; The second one is about taking the composite out of the mould once it is covered in white. However, the surfaces that are close to the walls of the mould could be further colonized and therefore, the material is grown for a couple of days more outside the mould, so those outer layers have now contact with the oxygen, increasing the mycelium density in those areas.

5. The last step consists of heating the material until the moisture is eliminated from the inside. This step is the one that will give the stiffness to the material. The heat treatment is done inside an oven at 80°C for 4 hours. Overall, that seems to be a configuration that works. However, there is no consensus about the time the

material should be heated or for how long, it varies among different studies. It should be until the material feels dry.

6. Coating and post-processing can be applied to the material depending on the final application in order to enhance some of the properties [4], [58].

The following figure illustrate a schema of the whole process, see Fig. 20.

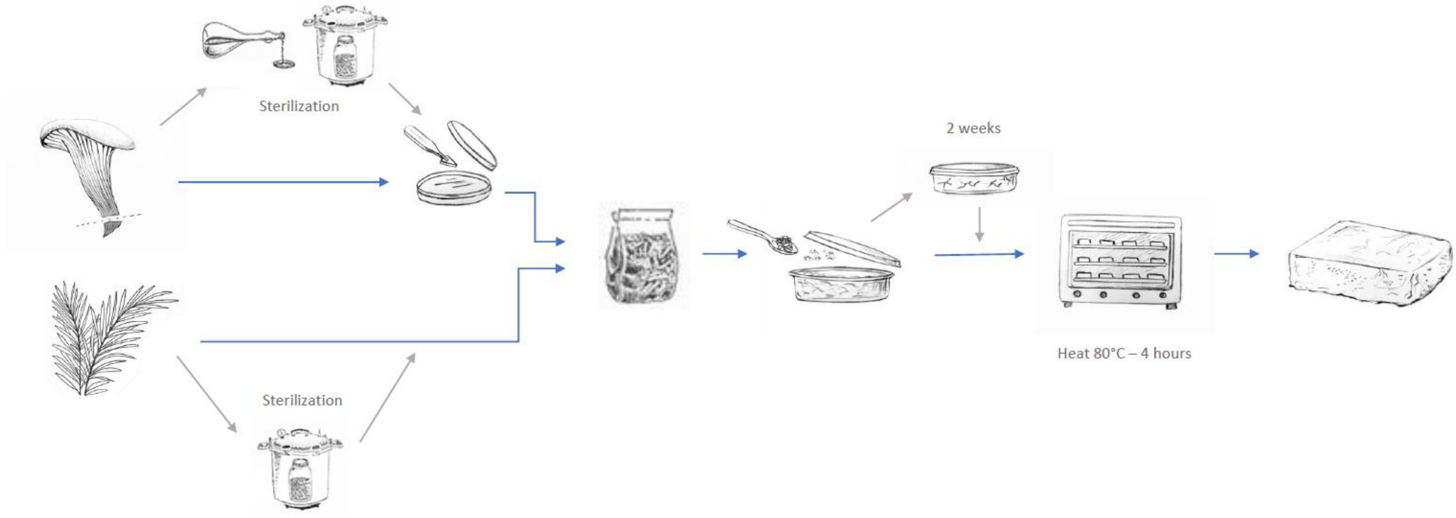


Fig. 20. Process for developing mycelium composites.

4.1.2.5 Latest advancements in mycelium composites

- 3D printing

The most widely used technique for building the material is based on cultivating the material inside a mould so the composite ends up taking its shape. The problem with this technique is that there is not that much freedom in terms of shapes, so far, the geometric complexity is limited to simple shapes. Therefore, late research focuses on developing mycelium composites suitable for additive manufacturing. Early in 2013, the designer Erik Klarenbeek 3D printed a chair for the Dutch Design Week (see Figure X), he did it by 3D printing a fine outer layer of bioplastic, that the mycelium will lately degrade, and an inner base using a straw powder-based filament, water and mycelium [11], [86]. Similarly, and more recently, Cheng et al. presented a technique where they 3D print cellulose pulp previously inoculated with mycelium and an outer layer that supports the material to grow until it has enough stiffness to be supported on its own [87]. Blast Studio, based in the UK, is an example of a company that is working with mycelium in additive manufacturing using filaments made out of coffee cups. Their design is also about optimizing the growth of mycelium, generating shapes that keep the moisture content [88], see Fig. 21. Students from Lund University have recently worked on protocols to scale up production with mycelium companies, using 3D printing technology. Their design mimicked the way termites build the mounds [89] [88]. Graz University of Technology also developed a project with students mixing clay and mycelium to create an extrudable filament called Mycera [90].

There are still important issues with 3D printing mycelium composites: the quality of the printed is very low compared with the results done with plastic filaments, the material clogs during the extrusion, the mycelium doesn't colonize the structure properly and contamination may appear during the growing stage. The company Ecovative [70] has also been working on this technology and has concluded that by adding psyllium husk powder the printability of the mixture is improved as well as its workability. Apparently, the fungi is able to survive the printing process and grow [74]. Colmo et al, developed a mixture adding xanthan gum, guar gum, wet hay and glycerol previously inoculated with *P. Ostreatus*, with the aim to avoid the need of sterilization [91].

Fig. 21. 3D printed structure by Blast Studio [88].

- Optimizing the cultivation process

A big challenge with mycelium composites is the time, energy and cost that it supposes the sterilization process of the substrate. The latest research has been done on seeking to avoid this step. For that, there are different suggestions. The addition of herbal remedies such as cinnamon-bark oil, thyme oil, oregano oil, and lemongrass oil has proven good results when avoiding contamination, instead of doing pasteurization. Another alternative is to use fungal species able to grow clean on non-sterilized substrates, species like *C. Lacerate* seem to be able to grow clean on non-sterilized substrates according to Shao, G-B et al., [92].

- Modify genes to inhibit fruiting bodies formation.

Mycelium presents a self-healing capacity with lots of potential. When mycelium is still alive, it is only limited from producing hyphae by the amount of nutrients in the substrate (until the substrate is fully degraded) and the space. Hence, when two growing composites created from the same strain are put together the mycelium will create strong bonds between both parts. In the same way, if mycelium suffers cracks on its surface or one is cut, the mycelium will cover that area again within just a few days. Again, this capacity only exists when the composites are not submitted to the drying process. It is used as well in 3D printing since this possibility makes it not necessary to have big 3D printing machines to create big pieces. Instead, it is possible to create smaller pieces and take advantage of the self-healing capacity to assemble them. The risk involved in not drying the material is that the composite on one side might start to produce fruiting bodies (mushrooms), which will then produce spores that probably colonize other parts of the environment. On the other hand, the properties of the material will be much worse, compromising also its life span. However, since this self-healing property seems to attract researchers, late research has been done on modifying the molecular mechanisms of the fungal species in order to inhibit fruiting body formation. The strain *S. Commune* was a prove of that genetic modification, also showing 3-fold faster growth than conventional species [4].

- CNC

Also, to maximize the self-healing properties of mycelium, CNC machining technology has been implemented seeking to develop more complex shapes for mycelium composites. A base block with a simple shape is fabricated and once it is fully colonized with mycelium (or at least partially so it has some stiffness), it is cut with the desired shape using saw cutting. The new surfaces will be colonized within a few days, see Fig. 22. The risks involved are that the pre-shape might not resist the cutting stress from the machine or that the piece could be contaminated during the cutting process [93].

Fig. 22. CNC on mycelium composites. [93]

- Maximizing the homogenization within the composite

As previously mentioned, the mycelium struggles to colonize the interior parts of the piece and creates more dense networks on the surface. This is due to a lack of oxygen in the centre of the piece. This influences the properties of the composites and to tackle it, research has been done on the addition of algae that produce oxygen in that centre part, successfully reporting a higher degree of colonization in the area [93].

4.1.2.6 Acoustic Insulation

For the product to be feasible and viable, not only desirable, see 2.1.7 Design Thinking, it is important to understand key acoustic insulation concepts when designing an acoustic solution. The final product must be able to absorb sound and for that, considerations regarding design and the material have to be done. This point digs into the engineering side of the project explaining how acoustic insulation works.

Sound insulation specializes in reducing the transfer of noise. Sound insulation prevents the transfer of airborne sounds like voices, airplanes or traffic or impact noises such as footsteps [94]. Acoustic applications are especially popular in music studios intending to improve the sound quality and absorb sound, so it doesn't bother the neighbours. Sound insulation expresses how well an element can hinder sound from travelling through it. This capacity is usually expressed by the Noise Reduction Coefficient (NRC), which represents how much sound a material can absorb. For instance, if a material has an NRC of 0.30, it means that the material is capable of absorbing 30% of the acoustic energy and reflecting 70% [95].

Two main aspects influence the NRC of an acoustic element: the thickness of the acoustic foam and its texture (shapes on the surface). Depending on the frequency that is desired to absorb those parameters will vary. Frequencies are divided into low frequency (below 500 Hz) and high frequency (between 8 and 20 kHz). A bass drum, thunder, and a man's deep voice are examples of low-frequency sounds, and a high whistle, a scream or a child's voice are examples of high-frequency sounds. It is important not to confuse it with intensity which refers to how loud or soft it sounds [96].

The main factor that influences the absorption performance is the thickness of the element. Thinner acoustic foams will absorb high and mid-spectrum sound waves whereas thicker foams absorb mid and low frequencies. Bass traps for instance are super thick foam pieces, usually above 10cm thick, designed to absorb the low frequencies of bass. Acoustic foams with a thickness of around 7 cm have proved to have the overall best acoustic performance, absorbing high, mid and low frequencies. [97].

The most common shapes used in acoustic panels are the following ones:

- Flat, with a smooth surface: as there is more foam per square meter, it is better suited for low-frequency sound applications.

- Wedge: this is common for its aesthetics, although the sound absorption could be uneven since it depends on the direction of the sound.

- Eggcrate: its shape is versatile and is one of the most cost-effective solutions.

- Pyramid: it is better than the wedge pattern in terms of performance, but it can still have directional issues. Therefore, it is more convenient for small spaces.

- Strip: it is a simple yet effective shape for low-frequency sound absorptions.

- Metro: with a complex design, it spreads the sound waves, scattering the reflections around the room and softening the waves [97], see Fig. 23.

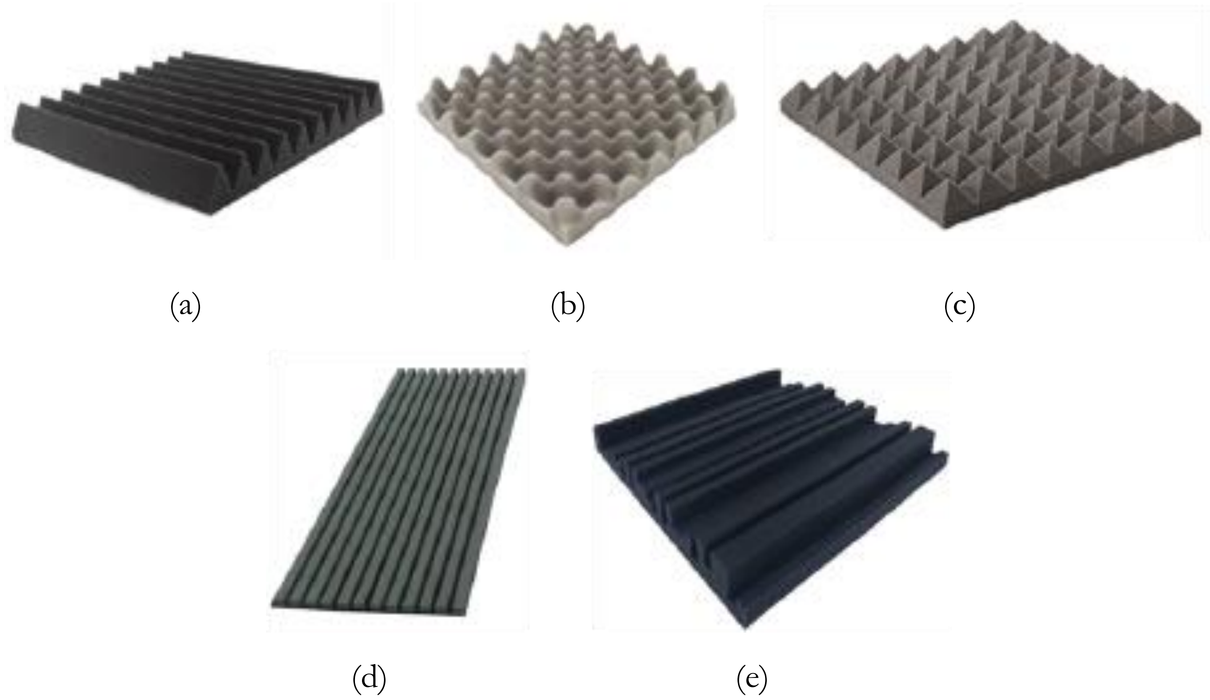


Fig. 23. Most common patterns used in acoustic panes. (a) wedge, (b) eggcrate, (c) pyramid, (d) strip, (e) metro.

TABLE XII

BRIEF. PATTERNS CHARACTERISTICS RELATED TO SOUND ABSORPTION

Pattern	**Characteristics**
Flat	Low frequency
Wedge	Depends on the sound direction
Eggcrate	Best cost-effective solution
Pyramid	Convenient for small places
Strip	Low frequency
Metro	Scatter reflections

[97]

The porous nature of the material is a common characteristic of all insulation panels. According to P.S. Liu the porous body of the material acts in two ways when interacting with the sound wave: 1) “the porous body absorbs sound wave energy to terminate the reflection and transferal of the sound” 2) “the porous body eliminates resonance and decreases noise”. When the sound strikes the cell wall of a pore, it makes the air within to compressed, causing hesitation and dissipating the energy of the wave [98].

4.1.2.7 Benchmarking

The benchmarking was focused on companies that develop sustainable acoustic applications that compete against synthetic foams such as Polyurethane and Polystyrene. The benchmarking was mainly done by visiting companies at Design Fairs and by searching on the internet. The fairs that were visited for this purpose were The Stockholm Design Week and The Workspace Design Show in London.

- MOGU

MOGU is mainly focused on acoustic applications, providing also some solutions regarding flooring. The Italian company believes that it is possible to build a future where we don't only work together with nature, but also where we learn from nature. Nature already provides multiple solutions to modern society's problems that humankind is not even aware of. They try to bring Nature closer to people's homes with a vision of interior design that embraces Nature's radical character [99].

Their mycelium-based acoustic panels provide a Noise-Reduction Coefficient of 0.4-0.53, being able to compete against synthetic alternatives with a NRC of 0.644, according to E. Elsacker [4]. See Fig. 24 illustrating some examples of their acoustic panels.

Fig. 24. Mycelium acoustic panels by MOGU [99].

- BIOHM

BIOHM is a multi-award-winning research and development biomanufacturing company. Based in London, UK, the company not only focuses on mycelium composites but also on a sustainable material they call Orb made of orange peel. So far, they have produced lamps with organic shapes using Orb and regarding mycelium composites, they have developed insulation panels. They claim to provide an acoustic performance that absorbs at least 75% of the sound at 1000 Hz (the typical frequency of road traffic noise). The company was contacted at the Workspace Design Show in London, where they revealed that their insulation applications use hemp as a substrate. However, they were not allowed to reveal which fungal strain they are implementing on that. For Orb, they use completely organic binders that allow the product to be 100% biodegradable.

They share some of the same values that MOGU has as they state to "allow nature to lead innovation, to revolutionize construction and create a healthier, more sustainable, built-environment" [64], see Fig. 25 for examples.

(a) (b)

Fig. 25. (a) BIOHM stand at the Workspace Design Show. (b) Acoustic panel by BIOHM.

- BAUX

Based in Stockholm, the company was founded in 2013 by Johan Ronnestam, Fredrik Franzon and the founding members of the design studio Form Us With Love. BAUX was born with the mission of creating better working conditions for people worldwide. They presume to be pioneers in sustainable materials regarding acoustics. Being nature their source of inspiration, they create acoustical solutions that, apart from being functional and aesthetic, contribute to creating a better future for the planet. They have a set of rules that they follow when selecting materials:

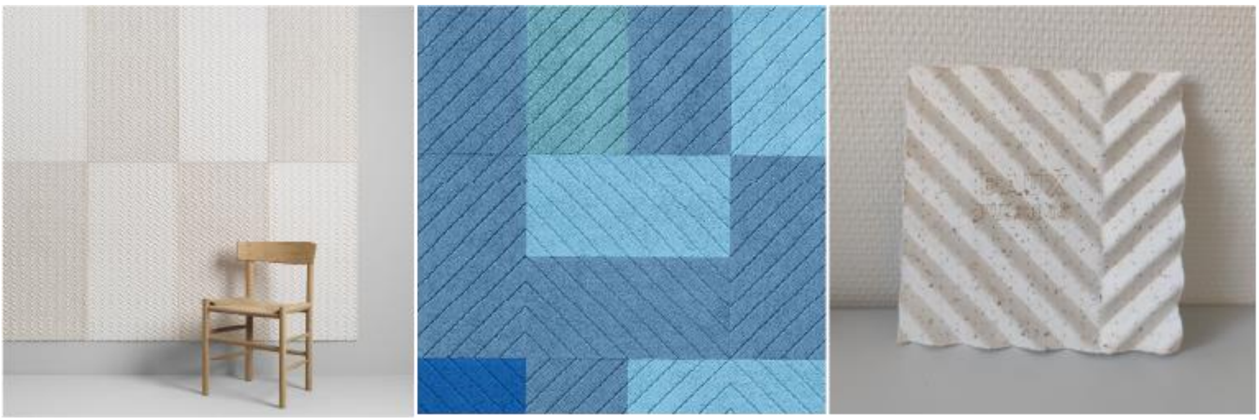
- "It should be possible to trace the material back to its source origin".

- "There should be zero risk of recycled materials containing dangerous content".

- "Materials should have a low amount of volatile organic compounds (VOC)".

- "It should be possible to recycle and/or reuse the material" [100]

For acoustics, they offer three different ranges of products: Acoustic Wood Wool, Acoustic Pulp, and Acoustic Felt – Recycled PET. The first one is made of wood fibres which offer excellent insulation, heat retention and sound absorption, as a binder they use cement, providing strength, moisture resistance and fire protection, lately to mix both components they use water [101]. The acoustic pulp range is 100% bio-based and is a combination of cellulose from sustainable harvested Swedish and FSC (Forest Stewardship Council) controlled fir and pine trees, water, potato starch and citrus fruits for strength and wax for fire protection. In this range of products, they achieve colour by using different percentages of wheat bran since adding paint would have comprised its bio-based character [102]. Recently, their Acoustic Felt range closed the loop on PET waste. It takes unwanted plastic from landfills which are processed and turned into PET flakes. They melt down recycled plastic and convert it into fibres that are later used for their acoustic panels [103]. See Fig. 26 for examples of their range of products.



(a) (b) (c)

Fig. 26. (a) Acoustic pulp BAUX panel, (b) Recycled PET acoustic panel, (c) BAUX sample got from BAUX in The Stockholm Design Fair 2023 [100].

The irregular 3D-shaped surfaces that BAUX panels have breaks up reflections of the sound spreading them into different directions, hence improving the acoustic insulation capability. BAUX acoustic panels have an NRC of 0.35 according to the information provided in the BAUX catalogue given in the Stockholm Design Week.

- VANK

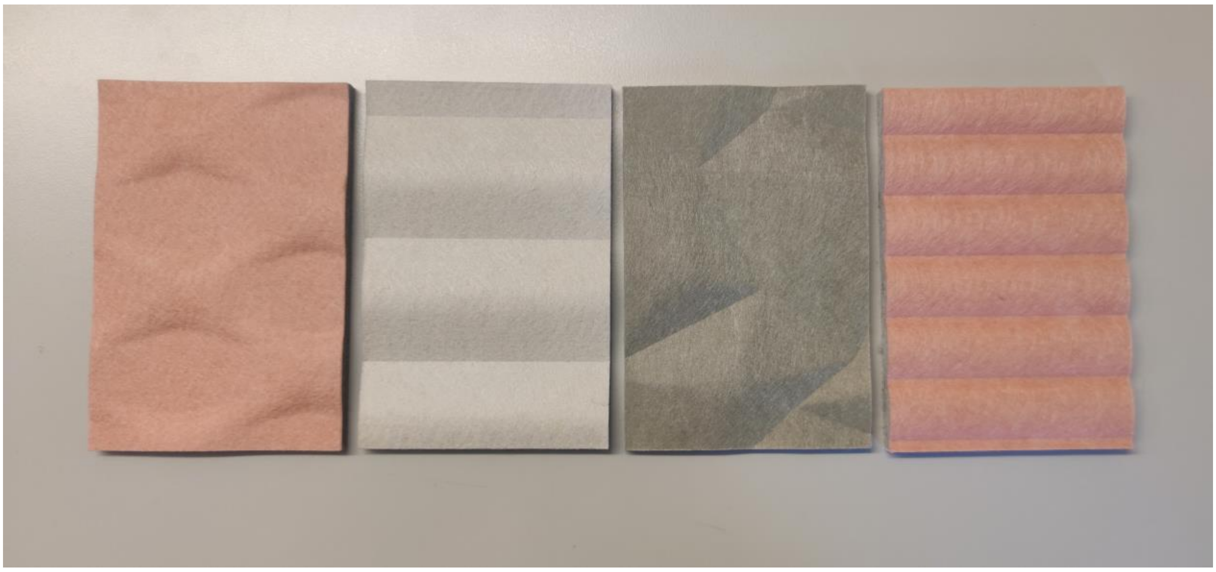
VANK is a multi-award-winning Polish company that uses bio-composites based on fibrous plants to create acoustic pods, acoustic panels, office cabinets and furniture. They are a team of architects, engineers and artisans that strive to use the minimum number of raw materials to reduce their environmental impact. For example, their PEEL chairs use wood from veneer leftovers and the frames are made with recycled aluminium. They also reuse the waste from other companies as is in the case of their RING chairs, where the cushions are filled with shredded foam sourced from post-industrial material. For their acoustic solutions, as BAUX does, they use recycled PET from plastic bottles, as well as bio-composites based on flax and hemp fibres. Their acoustic panels have an organic texture, geometric patterns and a colour scheme that bring harmony to the workspace. They believe that by surrounding people with beautiful things they can improve their quality of life [104], [105]. See Fig. 27, to visualize some of their acoustic solutions. The company was contacted in the Workspace Design Show in London.

Fig. 27. VANK acoustic panels [105].

- Woven Image

Established in 1987 in Sydney, Woven Image is an international interior finishes company with sustainability and design at its core. Their product portfolio consists of acoustic finishes such as EchoPanel®, suitable for wall, ceiling, and space-dividing applications in interior spaces such as workspaces, schools, or hospitals, see Figure 28. EchoPanel®, patented and launched by Woven Image, is made using 60% recycled PET, it has a 10-year life expectancy, after which the material is still 100% recyclable. They claim that by 2030 they will be able to reduce their greenhouse gas emissions by 50% whilst maintaining a positive social impact [106]. The company was also met in the Workspace Design Show in London.

(a) (b)



(c)

Figure 28. (a), (b) Woven Image acoustic panels, (c) Woven Image samples got from Workspace Design Show in London 2023 [106].

- Okko

“Okko is an international interior company specialized in creating and developing sustainable and innovative acoustic solutions that fuse form and function” [107]. They create innovative solutions in public places such as museums, auditoriums, restaurants, libraries etc. They claim to use sustainable and eco-friendly materials always working with the highest quality sound absorbers. They present the collection Acoustic Art by Nature, a collection with organic shapes inspired by nature made from natural or recycled materials with a negative carbon print. Among the sustainable and organic materials that they use, they highlight hemp and peat fibres. Their acoustic solutions are characterized by being modern and innovative with the aim of creating healthy and improved sound environments. See Figure 29, for some examples.

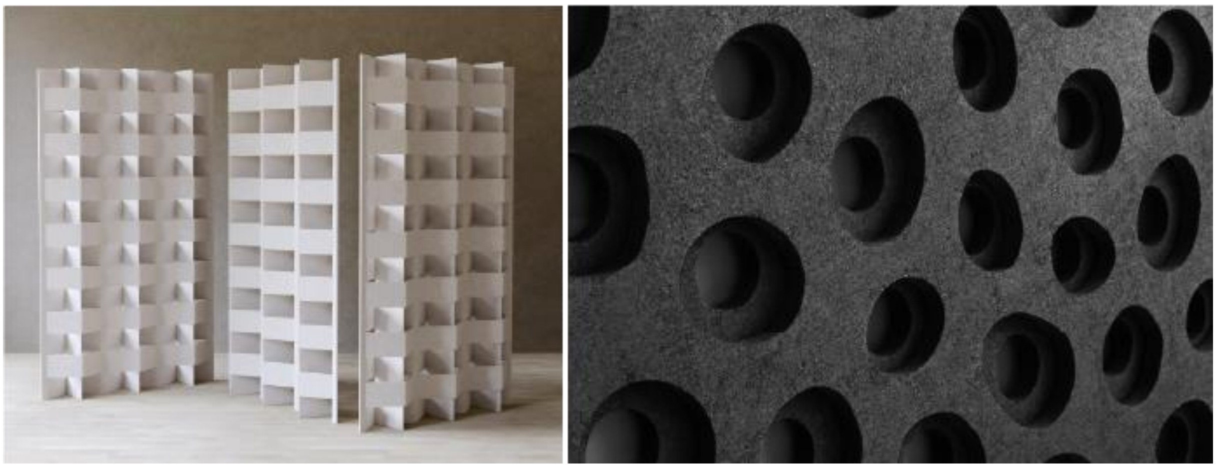


Figure 29. Okko acoustic panels.

4.2 Define

4.2.1 Persona

Three fictional characters were created to identify potential users and to consider their likes when designing and throughout the whole Design Thinking process, see Fig. 30.

Name
Emma Gustafsson

Definition
Woman who likes art and technology

Work
Artist

Quote
"I love art and exploring new sustainable materials for my creations".

Goals
"To find a piece of art to decorate my workshop and serves as a source of inspiration".

Demographic

- Residence: Stockholm
- From: Sweden
- Age: 30

Motivations
- Nature
- Creativity
- Sustainability

Frustrations
- Mass production of plastics
- Lack of support to creative alternatives

(a)

Name
Erik Jonasson

Definition
Musician who is building his home music studio

Work
Musician and guide in national parks.

Quote
"I like to spread the message of the importance of taking care of our planet".

Goals
Find a sustainable acoustic solution for my music studio.

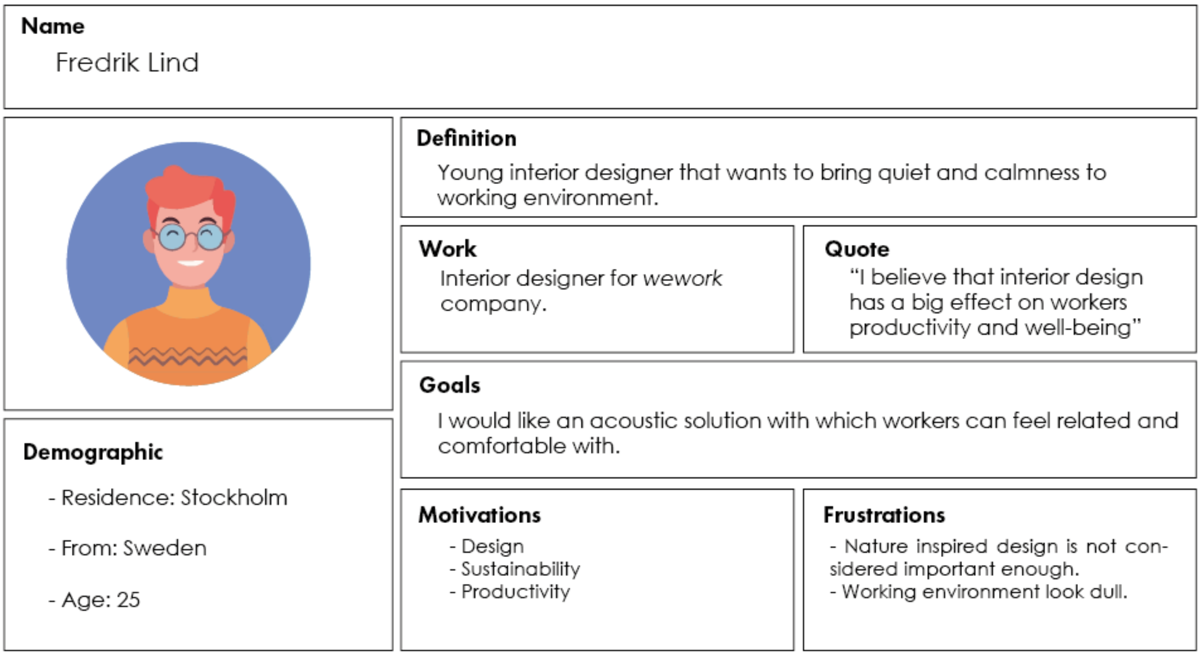
Demographic

- Residence: Umeå
- From: Sweden
- Age: 36

Motivations
- Biology
- Sustainability
- Forest protection

Frustrations
- People don't care about sustainability.
- Acoustic solutions pollute the environment

(b)



(c)

Fig. 30. (a) Persona Emma (b) Persona Erik (c) Persona Fredrik.

4.2.2 SWOT

Strengths and weaknesses represent the internal factors of the material at hand. Strengths refer to what separates the material from its competitors and weaknesses to what could be improved or the points where the competitors are stronger. Opportunities and threats represent external factors. Opportunities refer to external circumstances that give the material a competitive advantage whereas threats are the ones that minimize it.

The competitive environment for the SWOT analysis was acoustic panels with sustainability at their core. See Fig. 31 to visualize the SWOT analysis done.

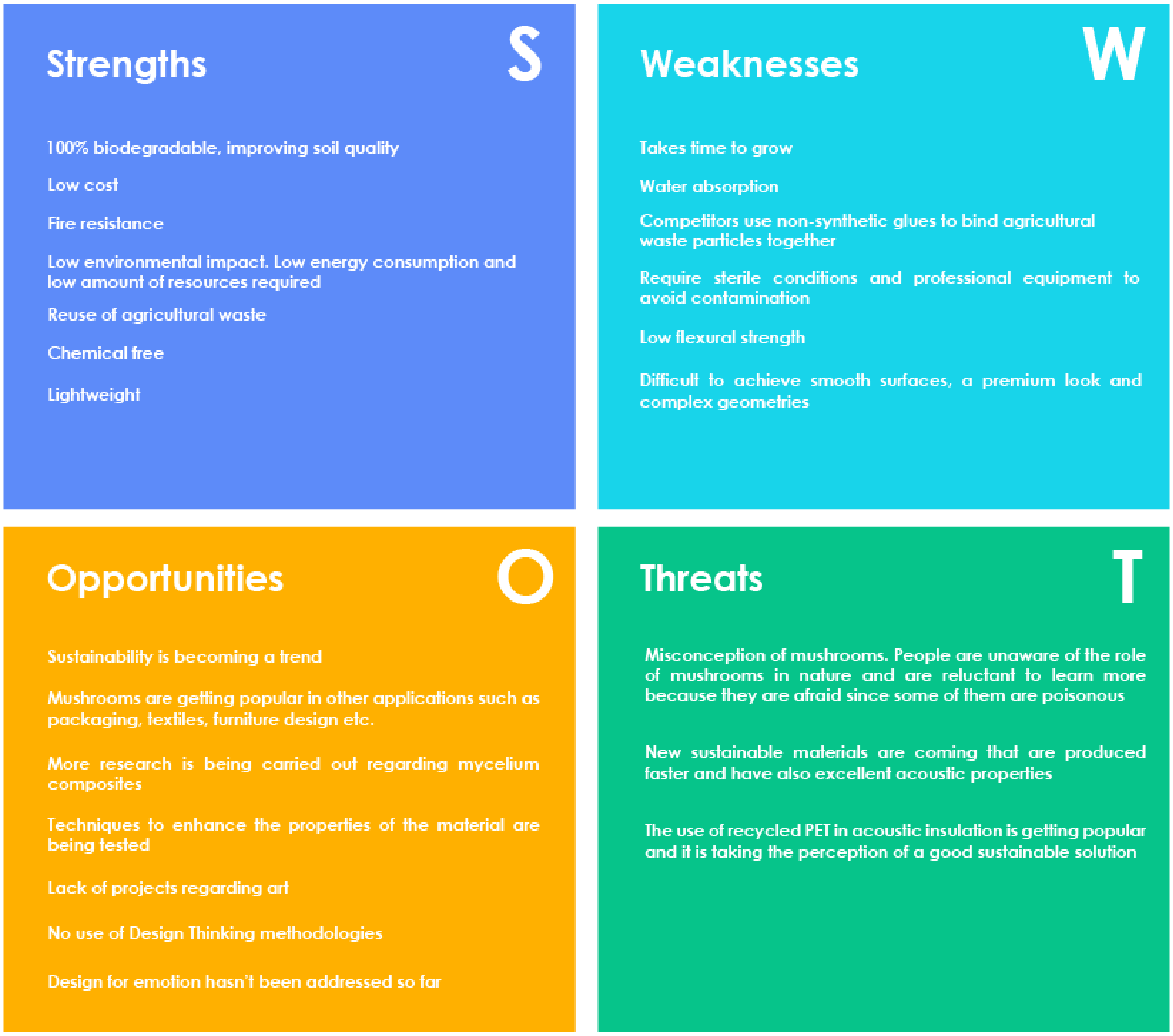
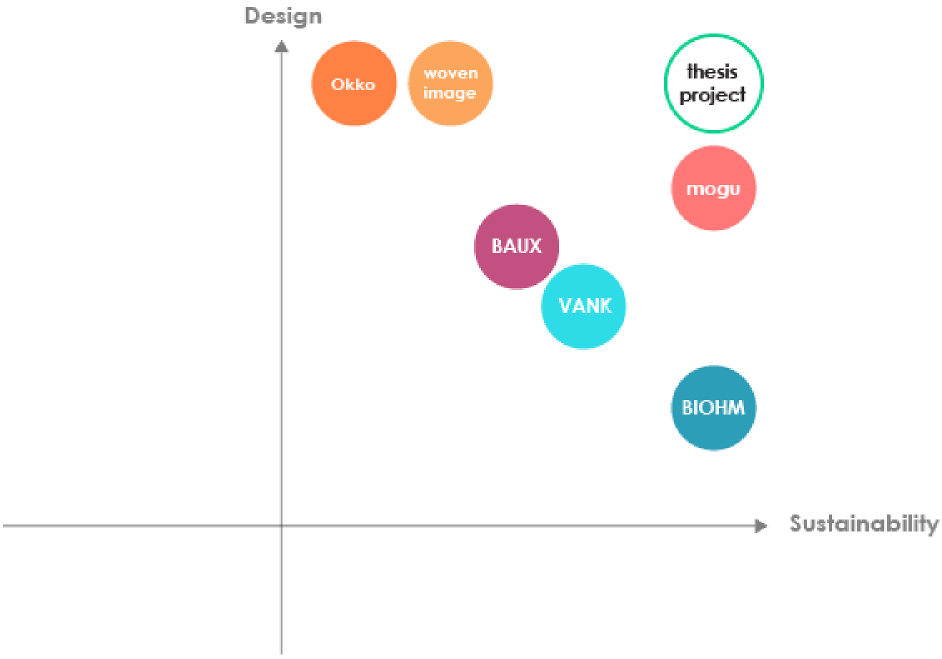


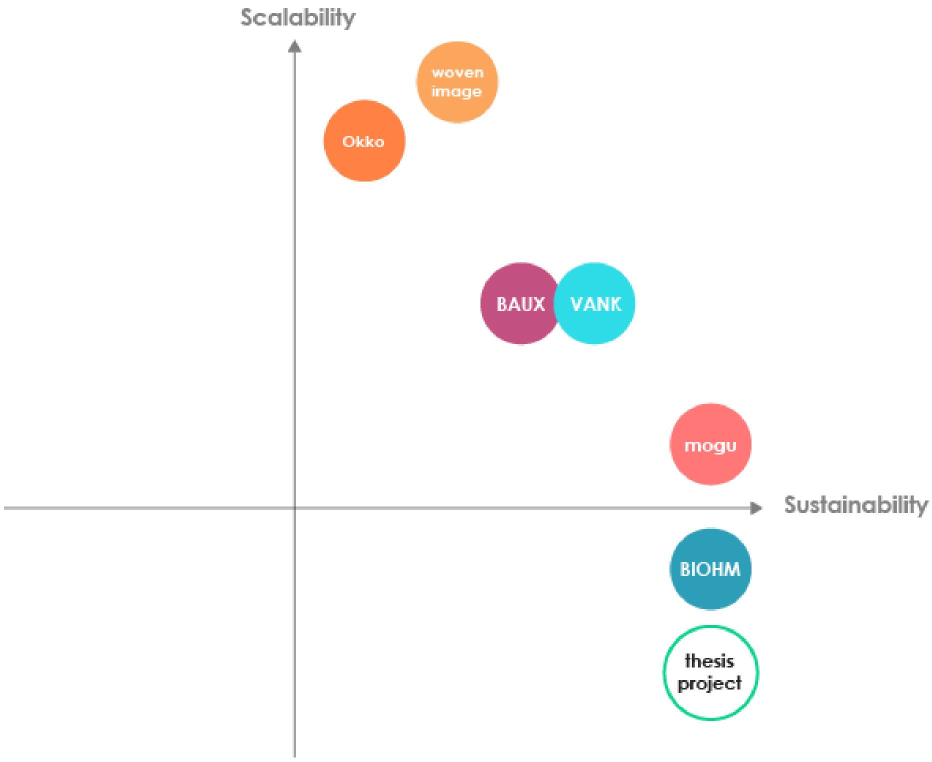
Fig. 31. SWOT Analysis. Strengths, weaknesses, opportunities and threats.

4.2.3 Perceptual map

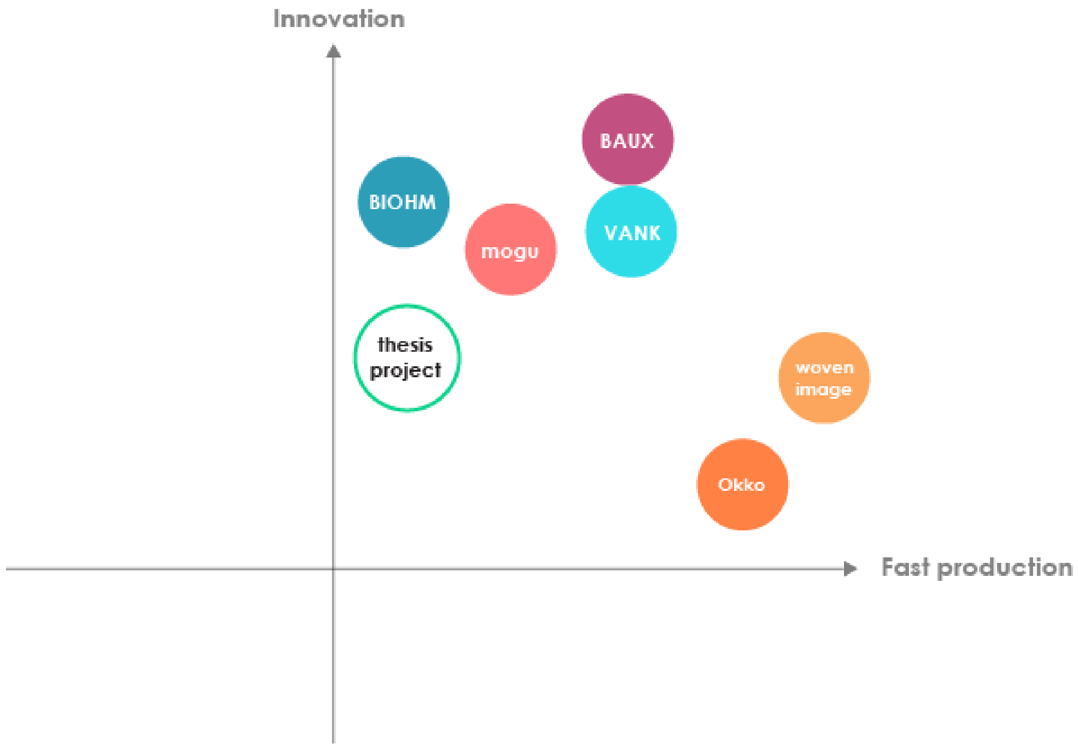
Three perceptual maps were done to position the project against its competitors. Companies were evaluated regarding two attributes at a time for each perceptual map. See Fig. 32(a), 25(b) and 25(c).


Design
Okko
woven image
thesis project
mogu
BAUX
VANK
BIOHM
Sustainability

(a)


Scalability
woven image
Okko
BAUX
VANK
mogu
Sustainability
BIOHM
thesis project

(b)



(c)

Fig. 32. Perceptual maps. (a) Design vs. Sustainability, (b) Scalability vs. Sustainability, (c) Innovation vs. Fast production.

In the analysis made in Fig. 32(a), Woven Image and Okko provide a high variety in terms of shapes and patterns in their acoustic solutions, therefore, they are rated higher in that category. However, even though woven image offers some solutions using recycled plastic, they are not considered as sustainable as the other companies presented. Since the project uses mycelium composites and also makes an effort to add value through design, it is ranked very high between those two attributes. However, for Fig. 32(b), the project is ranked as high as mogu and BIOHM regarding sustainability, but, since it is developed with low-tech techniques and resources, it is very difficult to escalate to mass production. Because Woven Image is a big international company with a successful trajectory, is ranked as the highest regarding scalability. In the last perceptual map, see Fig. 32(c), the project is considered innovative for the approach that follows to work with the material and for its design. However, other companies also work with mycelium and agricultural waste, and those companies, also innovate when referring to the use of new sustainable materials, so companies like BAUX or BIOHM are considered the most innovative ones. Once more, regarding industrial production Okko and Woven Image are ranked the highest for their fast production.

4.2.4 Product Journey Mapping

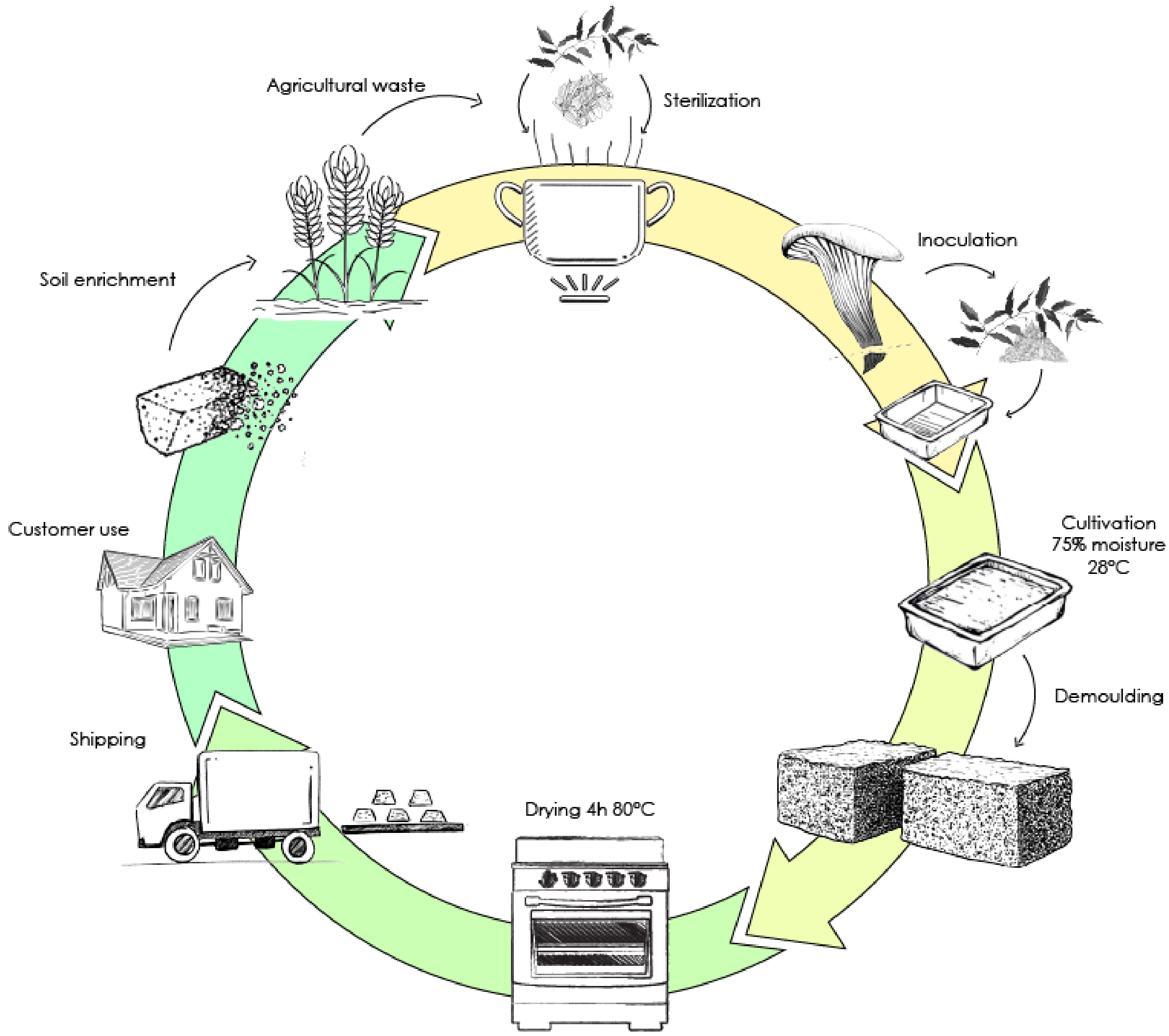


Fig. 33. Product Journey Map of mycelium composites. Inspired by the diagram presented by C. Girometta et.al [15].

The first half of the diagram is explained in detail in 4.1.2.4 Process for developing mycelium composites. Once the composite is taken out of the oven it is ready for shipping. Sometimes, depending on the application, the composite can be submitted to one of the techniques mentioned in 4.1.2.2 Treatments for improvement, to improve its mechanical properties or to make it water-proof. But, in general, the drying process will give the material the right properties needed for the applications presented in 4.1.2.3 Applications of mycelium composites. Since the material is lightweight, the air pollution involved in transportation is not considered a major concern. The material then arrives at the houses of the clients, the offices or the construction industry that is going to use them, and it can last, with good maintenance, approximately 20 years, according to P. Ross [108], [109]. After its lifespan, the material can be thrown away straight into the soil or given back to the agricultural industry where can be used to enrich the soil, according to V. Brabcová [69]. This will enhance the health of the new crops that can later be used to create more mycelium composites, starting the process all over again. Mycelium composites are fully biodegradable always under the condition that no synthetic glues or coatings have been added to the material at any stage of the process [15].

4.2.5 Moodboard

According to the knowledge presented in 2.4.1 Patterns analysis, it is believed that people can extract affective meaning from simple geometric shapes. Organic patterns seem to improve mood and reduce stress, giving a similar feeling to when humans are surrendered by nature. Therefore, and since the material at hand comes from mushrooms, the moodboard was done taking inspiration from the organic shapes and patterns that mushrooms present in nature. So in a sense, the concepts can be related to them, or at least inspired by mushrooms, with the aim of evoking similar emotions in the user. See Fig. *34*.

Fig. 34. Moodboard.

4.2.6 Definition of the intended emotions

Three emotions were aimed to be transmitted with the concepts. Those were calmness, flow and growth.

- Calmness

Calmness is supposed to be transmitted by the organic shapes and patterns that are implemented in the concepts. In any given environment the perception of the product should transmit calm, improve focus and reduce stress.

- Flow

Flow state is the state in which someone is fully engaged with an activity and is not aware of any other distractions and stimuli that come. It is also related to freedom and things not going in a linear direction, rather arbitrary, imperfect, organic and perfect in their own way, just as they come [110]. It is desired that the concepts trigger people's imagination when observing them, and that thoughts arise, taking them to past experiences or future scenarios. Users might relate the shapes with personal things they know, things from the past or they might build other alternatives or configurations for the concepts. Ideally, it should arise a "It looks like…" or "You could have done…", or just silence. Silence is good as well, it means thoughts are flowing in the user's mind, without disturbance, without limitations, full of freedom.

- Growth

Patterns might be restricted by the outer shape of the insulation panels, but users might imagine how those patterns continue, and how they evolve. In that way users are also contributing to the design of the product, it is happening in their minds. It would be great if the concepts can grow as well, helping the users to take those ideas out of their minds, making them try different configurations, and making the experience a bit more playful. Besides, the mycelium itself never stops growing in the forest, spreading its threads underneath the soil thousands of meters, and the process of cultivating the material is a process of seeing how it grows and evolves as a living organism.

4.2.7 Checklist for concept generation

The concepts should consider the following criteria:

- Organic shapes.
- Shapes that the users can feel related with.
- Shapes inspired by nature, mushrooms in particular.
- Allow more than one possible configuration.
- Enhance acoustic insulation.
- Tell a story.
- Trigger the intended emotions in the user.

4.2.8 Culture media

The culture process starts with a petri dish of the species *Trametes versicolour* that was obtained by the supplier Kinoko cultures [111]in 2021 and kept in the fridge until October 2022. The culture was transferred to a brown rice grain media inside a jar, where mycelium grew for a couple of months. The mycelium colonized the media in two weeks, being ready for another transfer at that stage. However, this first culture was not aimed to be used for this project at first. It wasn't until the thesis project was accepted that the possibility to use this culture arose. Lately, this culture was used to develop the final prototype of the project. When the project was approved by the end of January 2023, a small sample of this culture was extracted to grow the mycelium in liquid culture. The advantages of using liquid culture when developing mycelium composites were presented in 3.2.8 Culture media. The main reason for this is that liquid culture will allow a better propagation of the mycelium in its future substrates.

Fig. 35. *Trametes versicolour* (Turkey tail) in Petri dish. February 2021.

Fig. 36. *Trametes versicolour* brown rice culture. 17 October 2022.

Fig. 37. *Trametes versicolour* on liquid culture. 4 February 2023.

4.2.9 Sterilization

To sterilize both the grain culture and the liquid culture the pasteurization process explained in 4.1.2.4 Process for developing mycelium composites was applied. The difference is that it wasn't possible to use a pressure cooker. Instead, a conventional cooker was used. This is not always recommended, a pressure cooker will always ensure more chances of success, but if a conventional pressure cooker is the only option available, then the best way is to double the pasteurization. In this case, for the liquid culture the pasteurization time instead of being 45 minutes, was 90 minutes, and for the grain culture, instead of 90 minutes, it was 3 hours. As shown in Fig. 36 and Fig. 37. no contamination appeared and the mycelium grew successfully.

The tools for the later transfer of those cultures to the final prototype and previous samples were sterilized by using ethanol 96°, some clean tissue and fire.

4.2.10 Inoculation. Still air box.

Since professional laboratory equipment was not under disposition, the still air box method was used for working under sterile conditions. As explained in 3.1.3 Inoculation. Still air box, a transparent plastic container was bought and two holes for the hands were made in one of its walls, close to its bottom. The holes were made using a drill in the workshop of JTH (Engineering school) of Jönköping University. To make the inner environment sterile, prior to each operation, the box was thoroughly cleaned using disinfectant spray. See Fig. 38 showing the still air box.

Fig. 38. Still air box.

4.2.11 Cultivation chamber

To build the cultivation chamber, a transparent box with the same dimensions as the still air box was used. The walls of the chamber were covered with expanded polystyrene panels to give it some thermal insulation. At the bottom, a seedling mat with a temperature controller was placed and to avoid direct contact between the seedling mat and the cultures, a towel was put on the top of the mat. The box was kept closed during each culture in a dried place and to give it even more insulation, its exterior was covered with a duvet. See Fig. 39.

Fig. 39. Cultivation chamber.

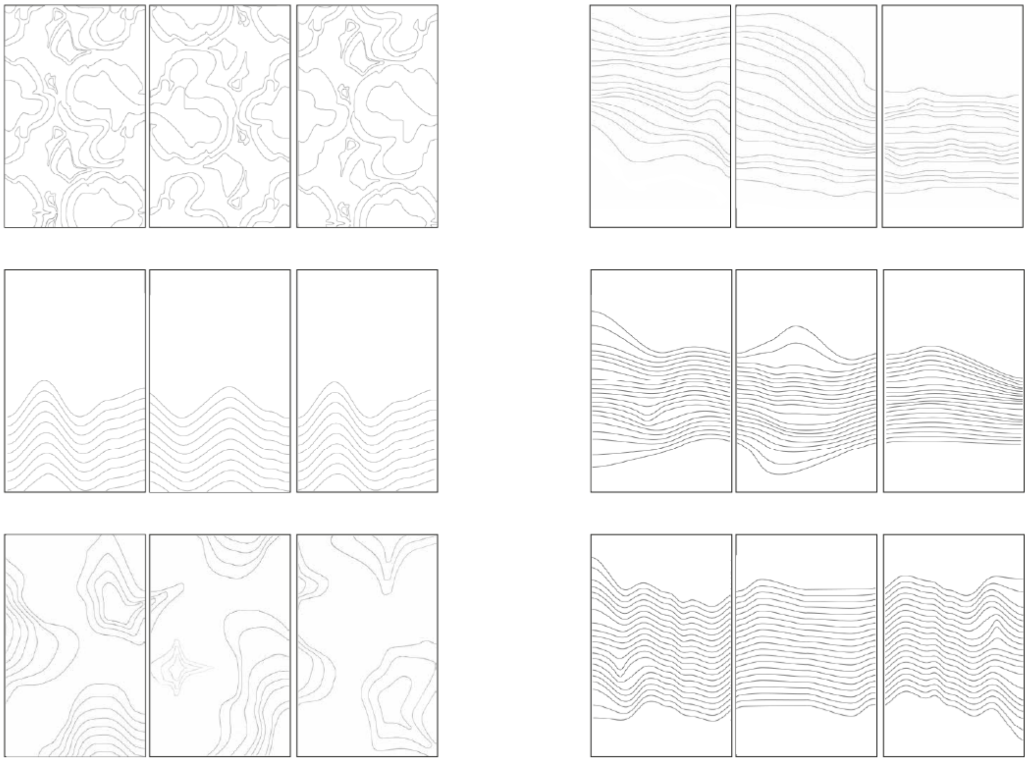
4.2.12 Composite selection

As was presented in 4.1.2.1 Properties of mycelium composites and 4.1.2.3 Applications of mycelium composites, the key requirement for getting the best acoustic insulation is to have a high density. The fungus *Trametes Versicolor* has shown in multiple cases a high density and a fast growth rate regarding mycelium composites. Among the different substrate options, hemp has been used in multiple acoustic insulations, like the acoustic of VANK, the Polish company presented in 4.1.2.7 Benchmarking, and the company BIOHM, presented in the same point.

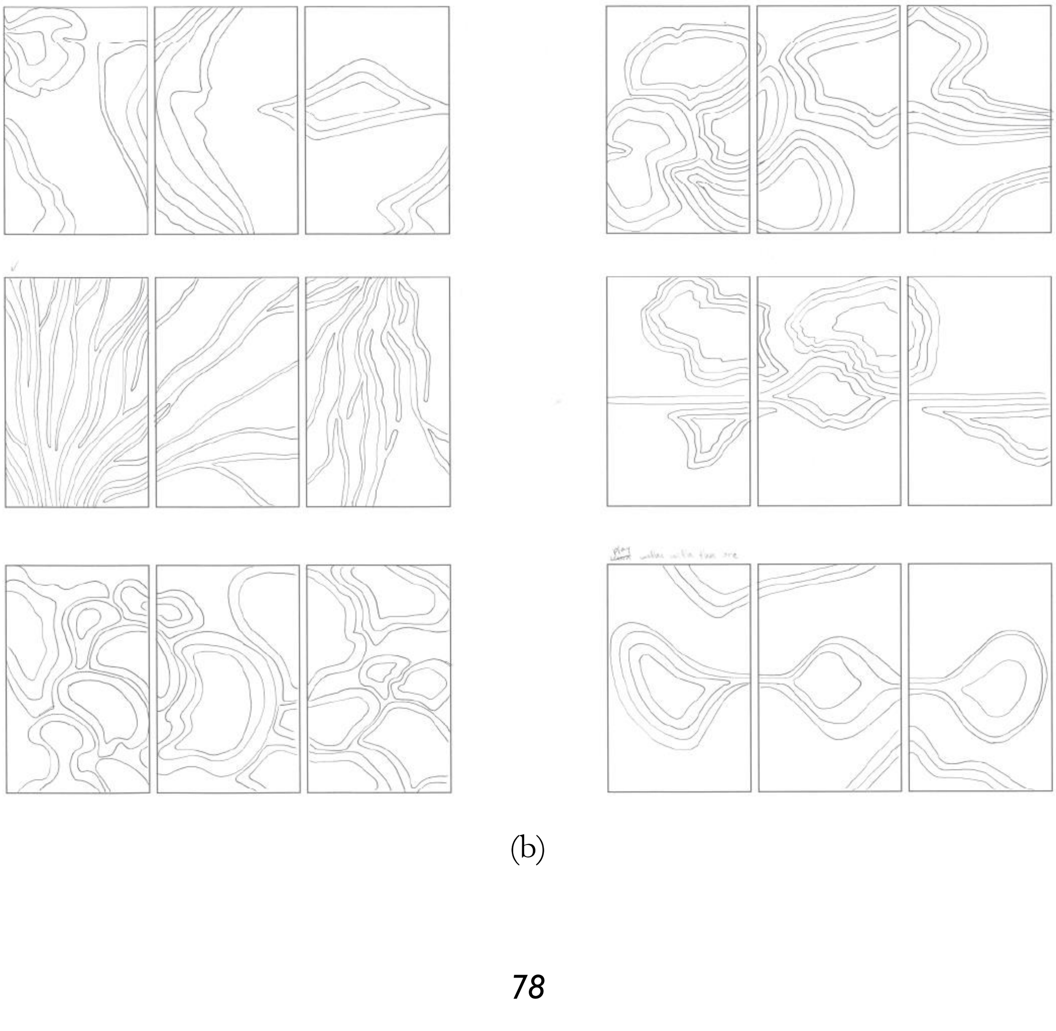
4.3 Ideate

4.3.1 First ideation

Having the moodboard and the checklist for concept generation at hand, the first sketches were mainly focused on imitating the shapes of mushrooms in nature, trying to evoke the intended emotions of calmness, flow and growth.



(a)



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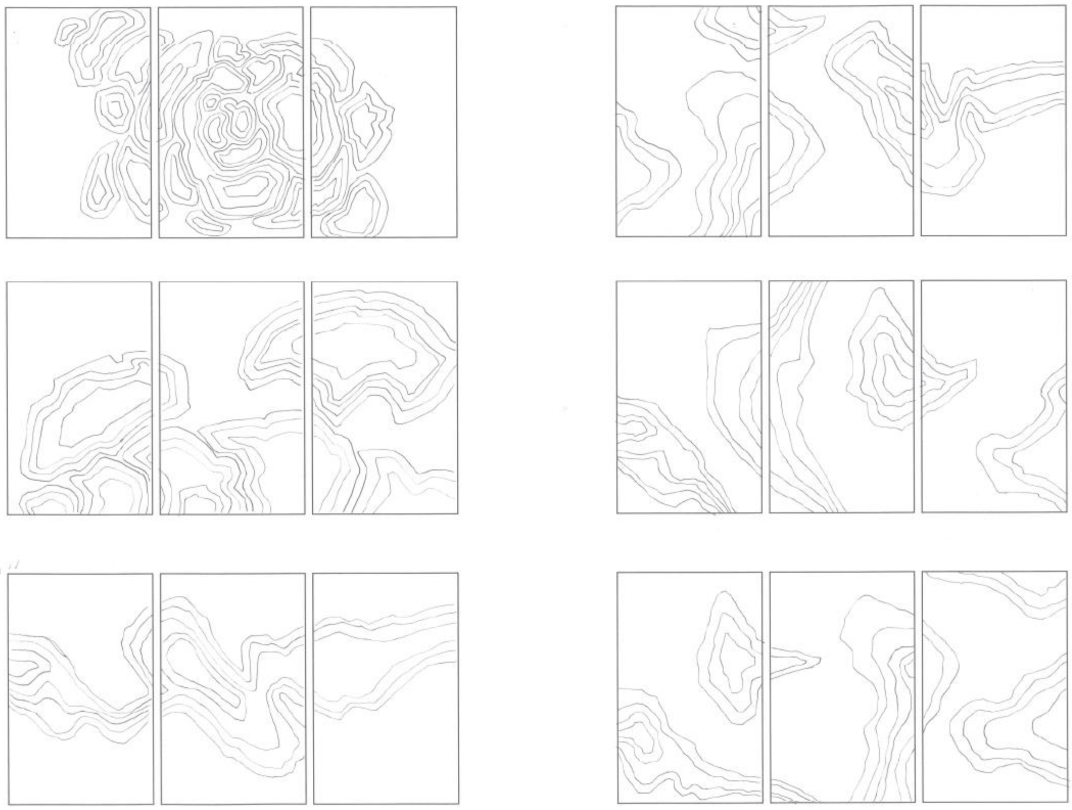

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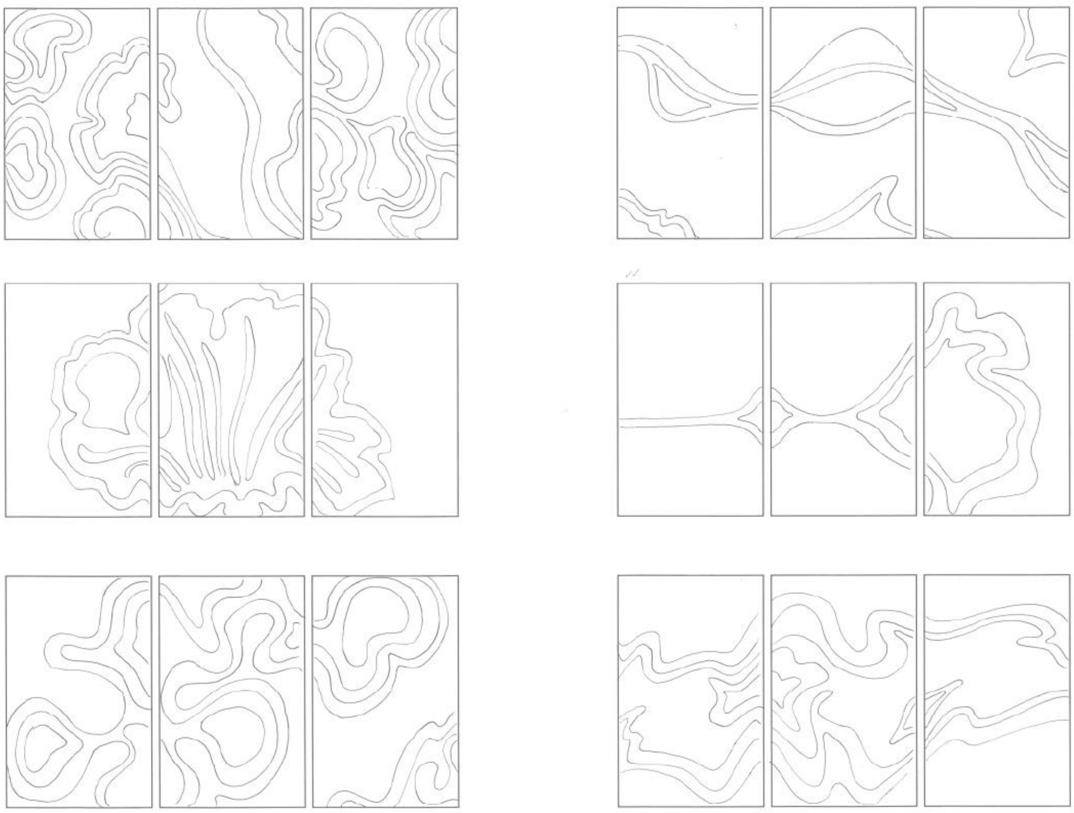

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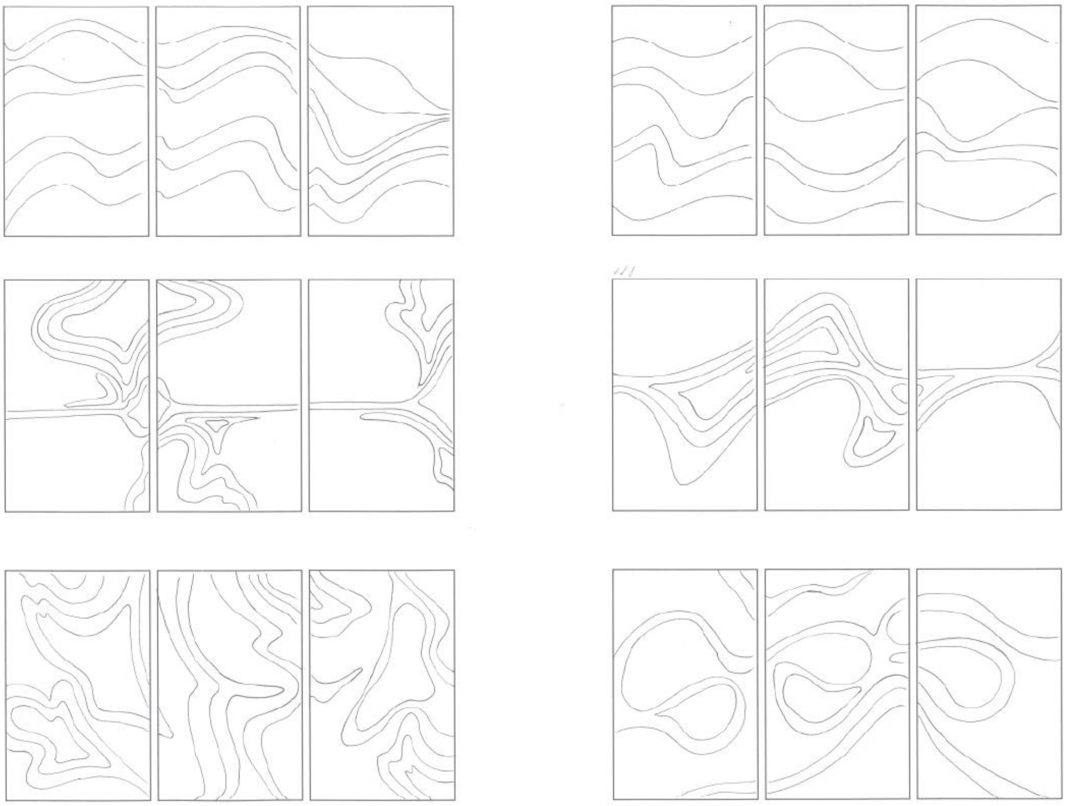

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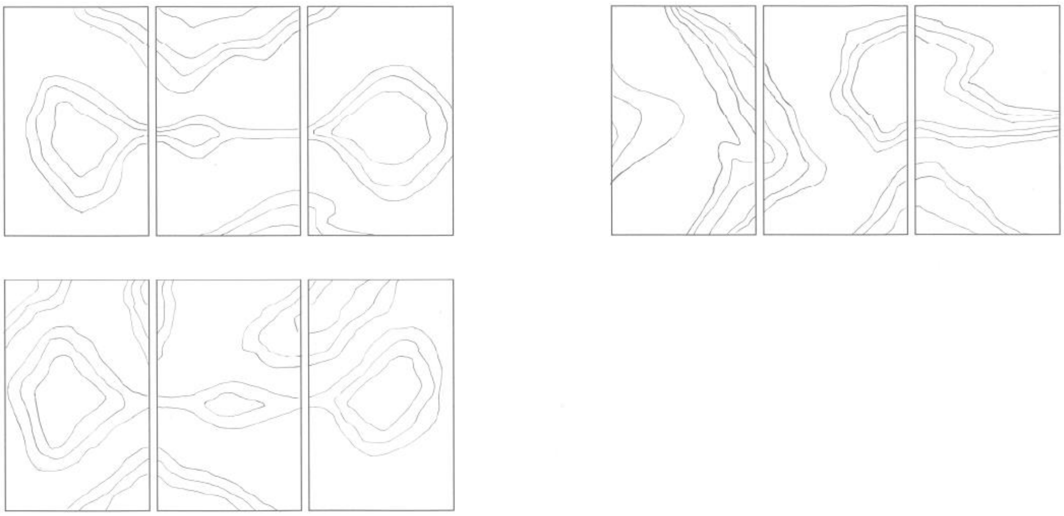


(f)

Fig. 40. First ideation sketches.

Having informal interviews with other students from the university, asking them about the relationship they see between the concepts and nature and the emotions they experienced while looking at them, three concepts were selected for further development. The concepts are supposed to work in different layers, their shapes have different heights and that can not be perceived by a 2D sketch. This was one of the feedback gathered from that first interaction with people, "it is difficult to grasp the different layers just by looking at the sketches". Therefore, simple prototypes in cardboard were made with the three concepts selected. See Fig. 41(a), 39 (b) and 39 (c), to visualize them.

(a)

(b)

(c)

Fig. 41. (a) Concept 1 from the first ideation phase. (b) Concept 2 from the first ideation phase. (c) Concept 3 from the first ideation phase.

4.3.2 Second ideation phase

After presenting the concepts to teachers and students, a lot of feedback was gotten. The following points were considered important for the second ideation phase:

- Explore different shapes for the frame. Using shapes that could allow different combinations.
- Find something that the user can feel related to, something that can be easily identified.
- Find a design that is not restricted to a certain number of panels. The user should feel free to design how many panels to buy, without compromising the aesthetics of the product, each panel should work on its own.

Taking those additional points into consideration, the tool Persona, the checklist for concept generation, the moodboard and the intended emotions, the following concepts were created.

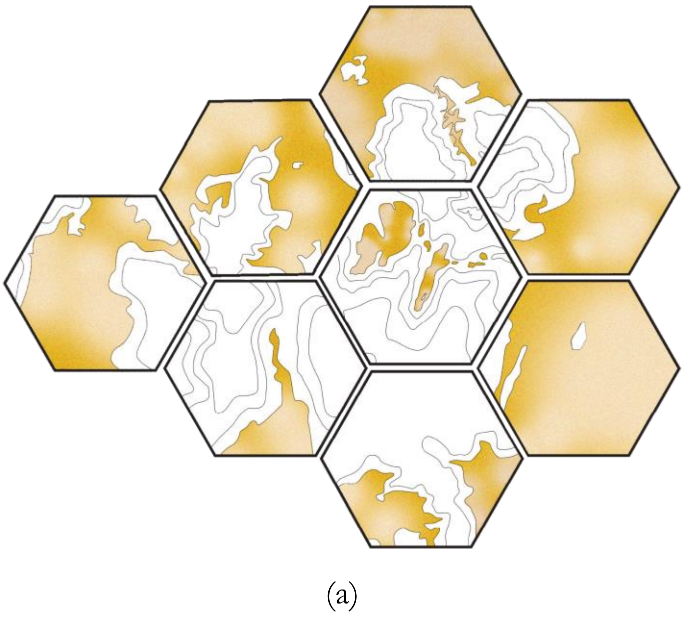
- Concept 1

(a)

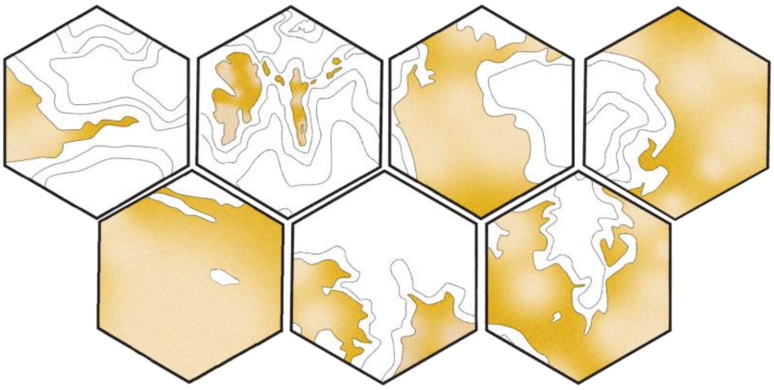
(b)

Fig. 42. Concept 1 from the second ideation phase.

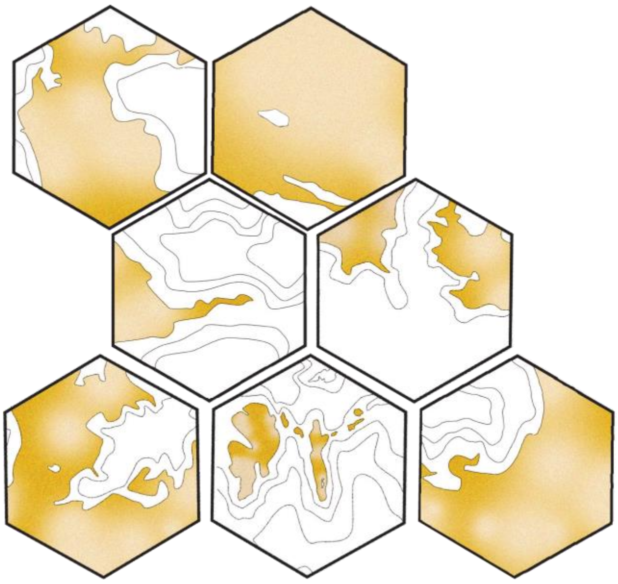
This concept represents the south of Scandinavia. It shows the south of Sweden, the south of Norway and Denmark. The idea behind this is that the user can recognize the shapes in the concept. At the same time, it is seen how the different shapes are also organic resembling mushroom patterns. It works as the previous concepts, showing different layers that give some volume to the concept and help to improve sound absorption. The user doesn't need to buy the whole map, maybe he/she comes from Denmark and decides to buy only the two panels of Denmark or maybe the user lives in Jönköping and wants to buy the panel where the lakes Vättern and Vänern are. Another alternative is that the user can buy some panels and create random configurations, creating a completely new map, experimenting and playing with the different shapes. Fig. 43. Shows, some more possibilities regarding this concept.



(a)



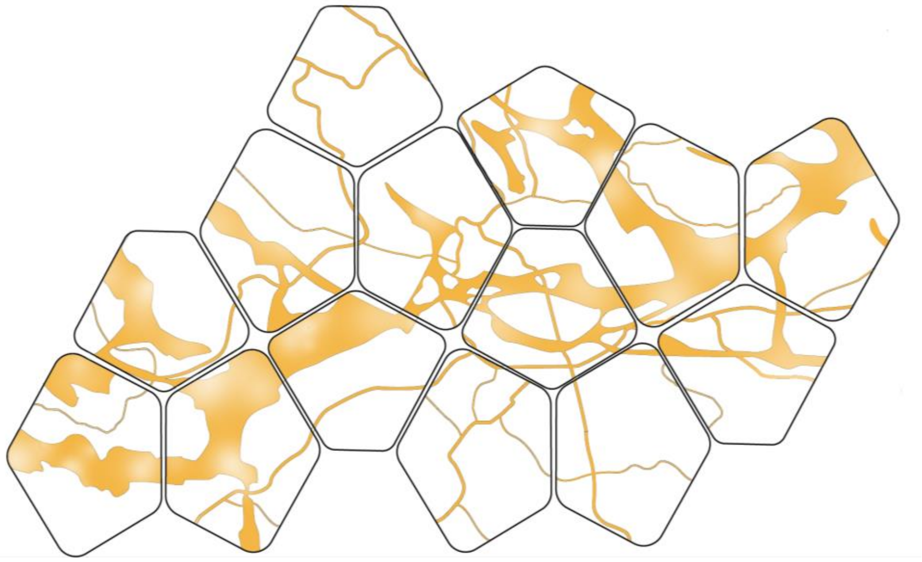
(b)



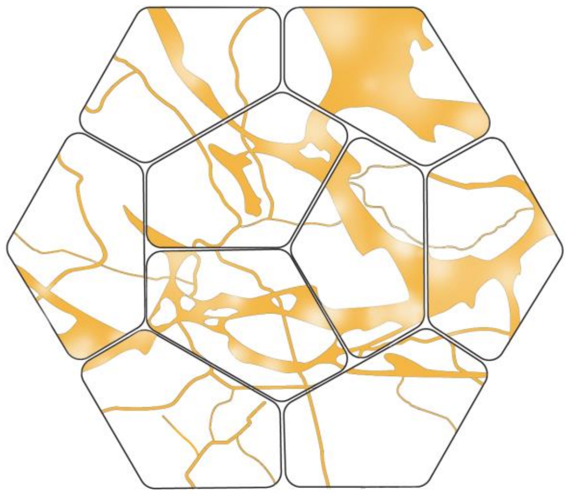
(c)

Fig. 43. Exploration of different configurations for concept 1 in the second ideation phase.

- Concept 2



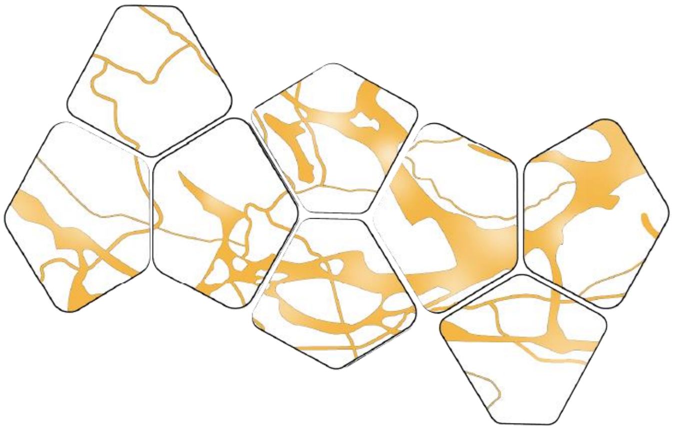
(a)



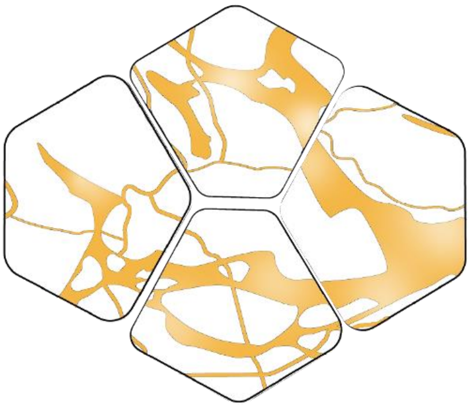
(b)

Fig. 44. Concept 2 from the second ideation phase.

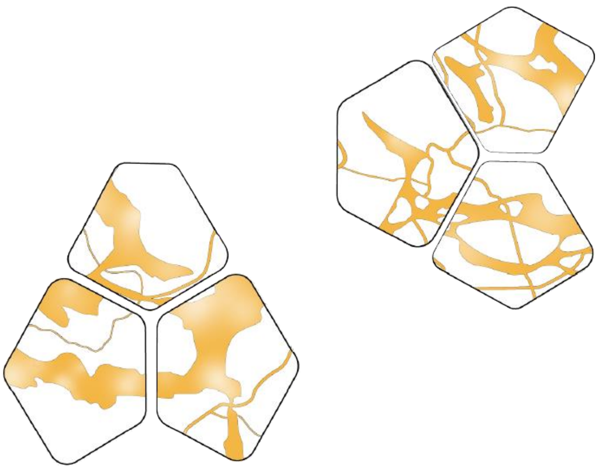
Concept 2 also represents a map. In this case, it shows the city of Stockholm. The main difference lies in the train lines that have been grabbed on the shapes of the archipelago. The idea behind this is to illustrate how the train lines and overall how the different areas of a city are connected, resemble the same patterns that the mycelium network has. In Fig. 3. shown in 1.1.1 Role of mushrooms in nature, the similarities between a city seen from above, the mycelium network and other similar patterns found in nature were illustrated. Besides, this concept aims to tell a story behind it. It planned to explain the importance that mushrooms have in nature and how the mycelium network connects trees to each other and nurtures different living organisms, which was explained in 1.1.1 Role of mushrooms in nature. It aims to create awareness for the user and change the view they might have of mushrooms. At the same time, the user can feel connected to the product if Stockholm is recognized and the user has feelings attached to the city. As in concept 1, the shapes of the archipelago are organic and can be linked to nature, bringing with them some of its positive feelings. Again, the user doesn't need to buy the whole map, they can decide to buy only certain areas of the city or individual panels they feel a connection with. Some alternative configurations of this concept are shown in Fig.



(a)



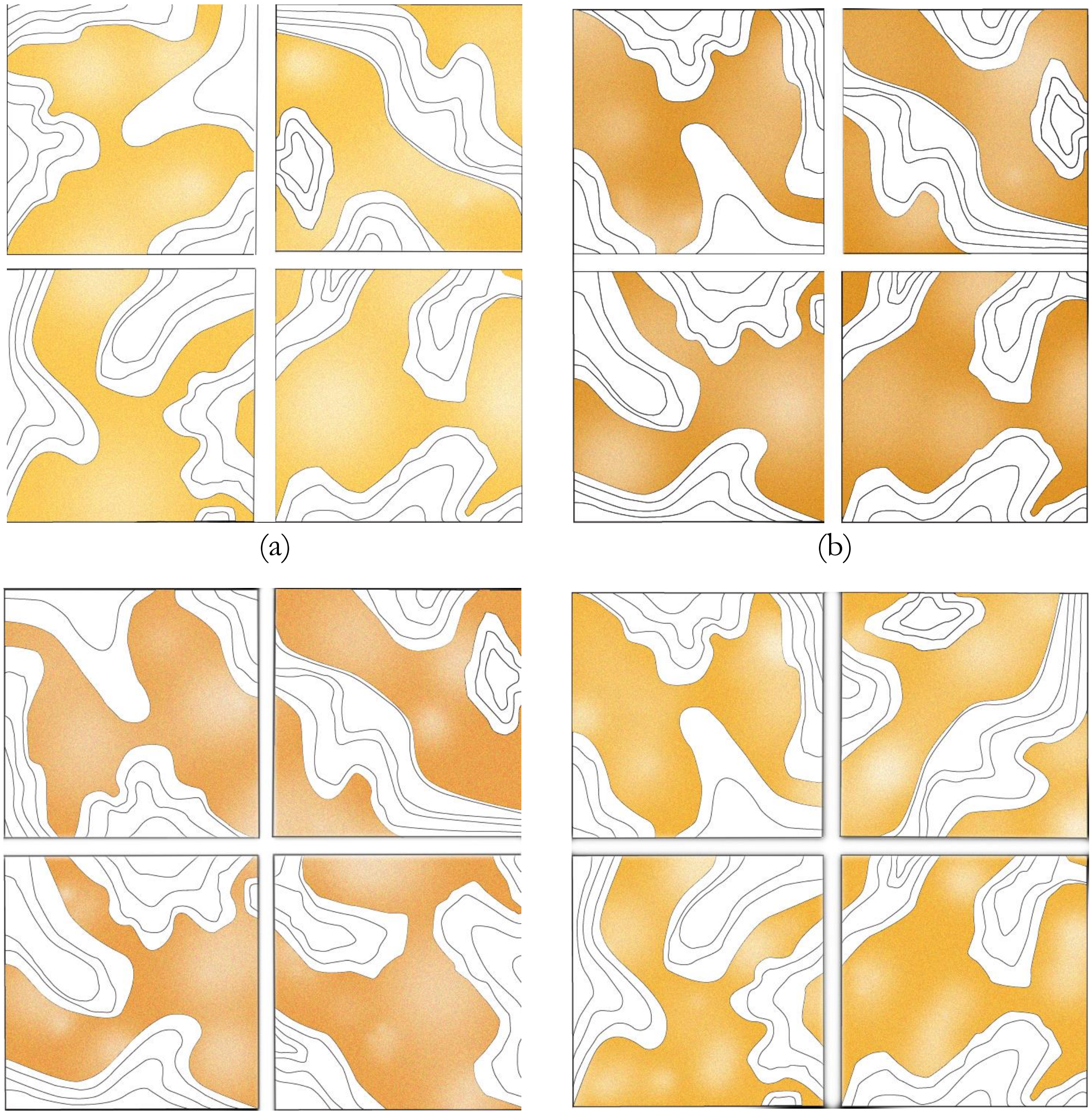
(b)



(c)

Figure 45. Exploration of different configurations for concept 1 in the second ideation phase.

- Concept 3



(a) (b)

(c) (d)

Fig. 46. Concept 2 from the second ideation phase.

This concept follows the same idea as the concepts presented in the first ideation phase. The shapes are inspired by mushrooms and they are supposed to have different heights as well. Some shapes are designed in a way that they connect with others from other panels, in that way the user can explore different configurations creating his/her own piece of art, developing the user's creativity. Four different possible configurations are presented in Fig. 46. Concept 2 from the second ideation phase. Once again, the user can decide if he/she only wants one, two, three or four. If the user decides to buy even more, saying 4 times each panel for example, then something bigger can be created, exploring now much more possibilities, see Fig. 47. Exploration of using multiple panels for concept 3 in the second ideation phase.

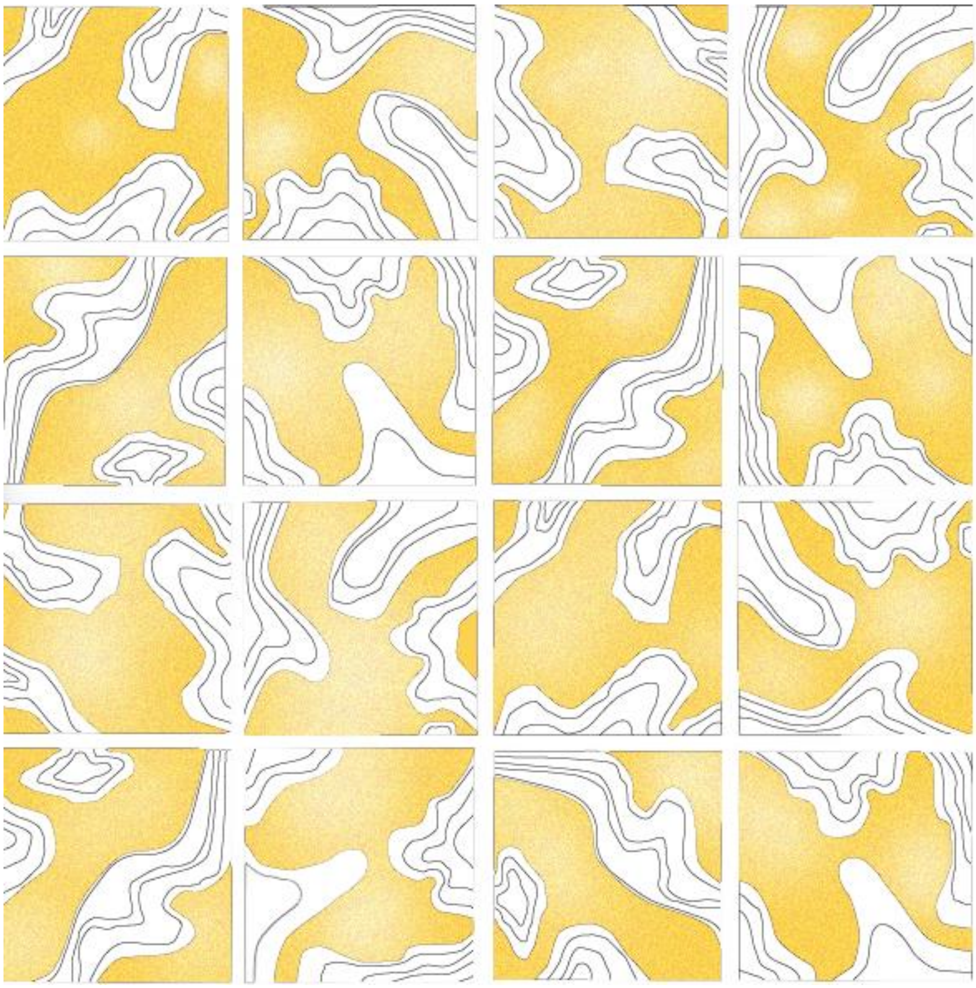
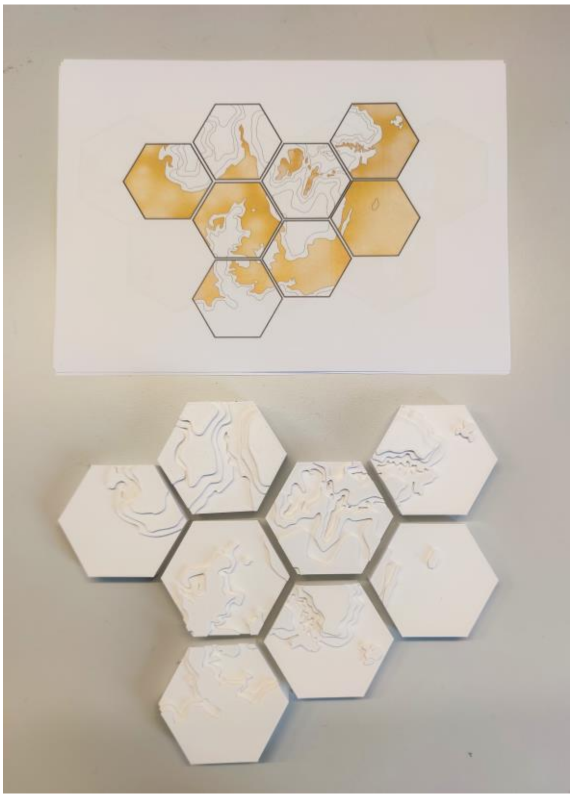
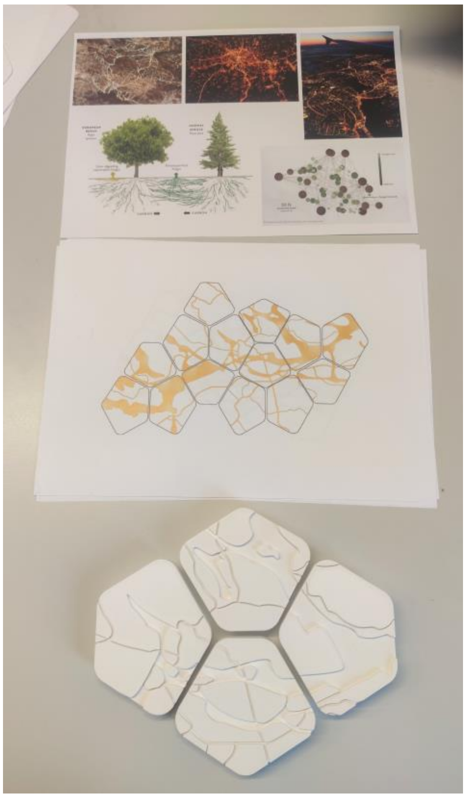


Fig. 47. Exploration of using multiple panels for concept 3 in the second ideation phase.

As it was done with the first ideation phase, it was necessary to visualize the concepts in 3D. For that, the concepts were developed in CAD using the software Solidworks, for later being 3D printed using the printer Prusa mini+ in PLA filament. The 3D printed prototypes were scaled 1:4 and then were shown to a higher variety of users than was done for the first ideation phase. The prototypes were shown together with some illustrations that supported the explanation of the ideas behind each of them and the whole concept behind the project.



(a)



(b)

(c)

Fig. 48. (a) Prototype 1 and illustration of different configurations. (b) Prototype 2, illustration of different configurations and images to support the story behind the concept. (c) Prototype 3, illustration of different configurations and moodboard showing mushroom patterns.

Those three concepts were shown to a total of 14 potential users. After the explanation of each concept, the users got some time to play with the shapes and the different configurations. They were asked the following questions:

- Which concept feels more related to nature to you?
- With which concept do you feel more connected? Why?
- Which concept makes you feel a sense of calmness, growth or flow?

(a)

(b)

Fig. 49. (a) Presentation of the three concepts for user test. (b) User test in Språk café in Stadsbibliotek, Jönköping.

See TABLE XIII to see a brief of the user's selection.

TABLE XIII

USER CONCEPT SELECTION

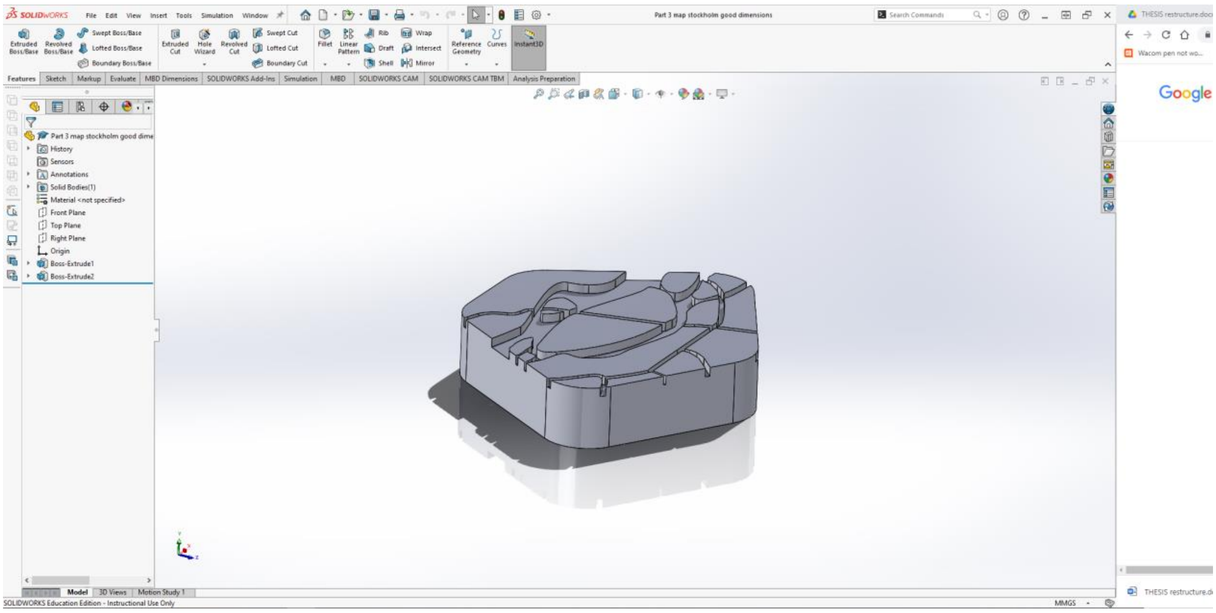
User	Concept selected
User 1 (Lightning design teacher)	C2
User 2 (Product designer from India)	C1
User 3 (Swedish product designer)	C2
User 4 (Swedish product designer)	C2
User 5 (Swedish product designer)	C2
User 6 (Swedish product designer)	C2
User 7 (Greek product designer)	C2
User 8 (Swedish teacher)	C1
User 9 (Spanish industrial designer)	C2
User 10 (Språk café)	C1
User 11 (Språk café)	C1
User 12 (Språk café)	C3
User 13 (Språk café)	C1
User 14 (Språk café)	C1
Total C1	6
Total C2	7
Total C3	1

After the user testing, it was decided to move forward with concept 2 taking it to the prototype stage of the Design Thinking Bootleg.

4.4 Prototype

4.4.1 Prototyping

As explained in 4.1.2.4 Process for developing mycelium composites, the general process to work with the material is to build a mould where to grow the material with the desired shape for the product. Therefore, the main aspect of building a prototype revolves around the development of the mould. For that 3D printing was the technology selected. To work with 3D printing is necessary to have a CAD model, see 3.3.2 CAD. The CAD model of the different parts of Concept 2 was done using the software Solidworks. These solid models were necessary for building the CAD model of the mould and later were used for the rendering of photorealistic images. See Fig. 50 to visualize the CAD model in Solidworks.



(a)

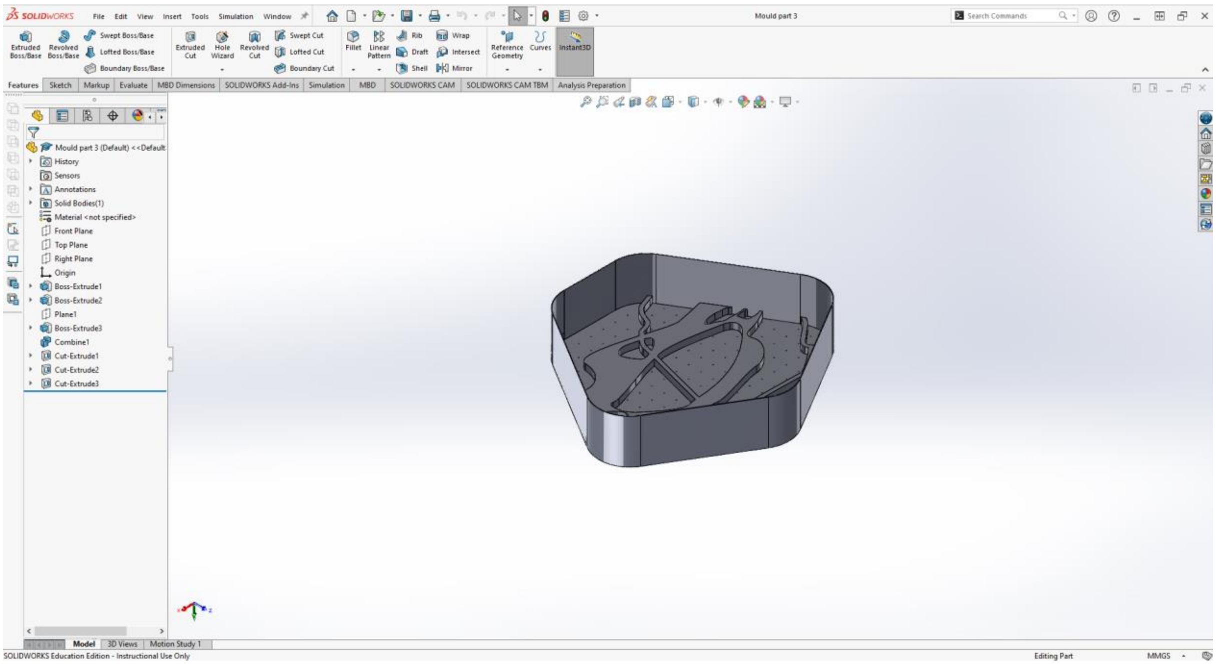


Fig. 50. (a) CAD model in Solidworks of one of the parts for concept 2. (b) CAD model Solidworks of one of the moulds for concept 2.

To do the organic shapes on the surface of the different parts, the software Illustrator was used. With this software, it is faster to draw paths and complex shapes. Once the sketches were digitally done, they were exported to .dxf format. Solidworks recognizes the .dxf format as a sketch that later can be extruded.

Once all the 14 different moulds were done in CAD, they were imported into the software Prusa for 3D printing. The moulds were printed in the Prusa MINI+ [112], the extrusion temperature was set to 210°C and the filament used was transparent PLA with a thickness of 1.75mm from the brand Verbatim [113]. See Fig. 51 to see a picture of the 3D printing process going on.

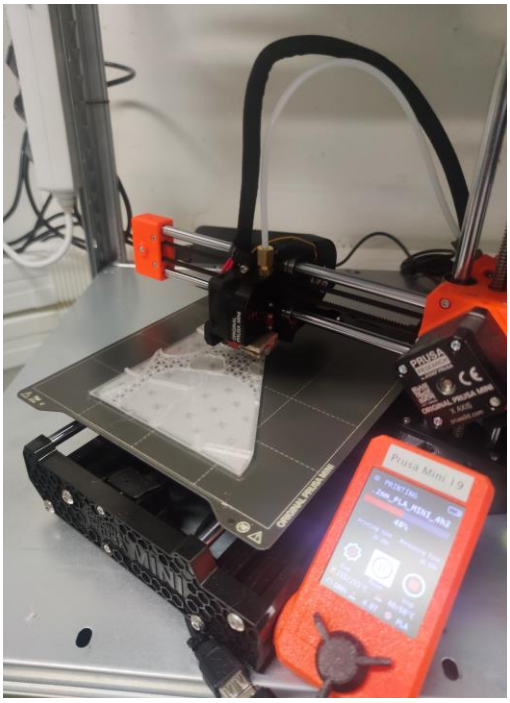
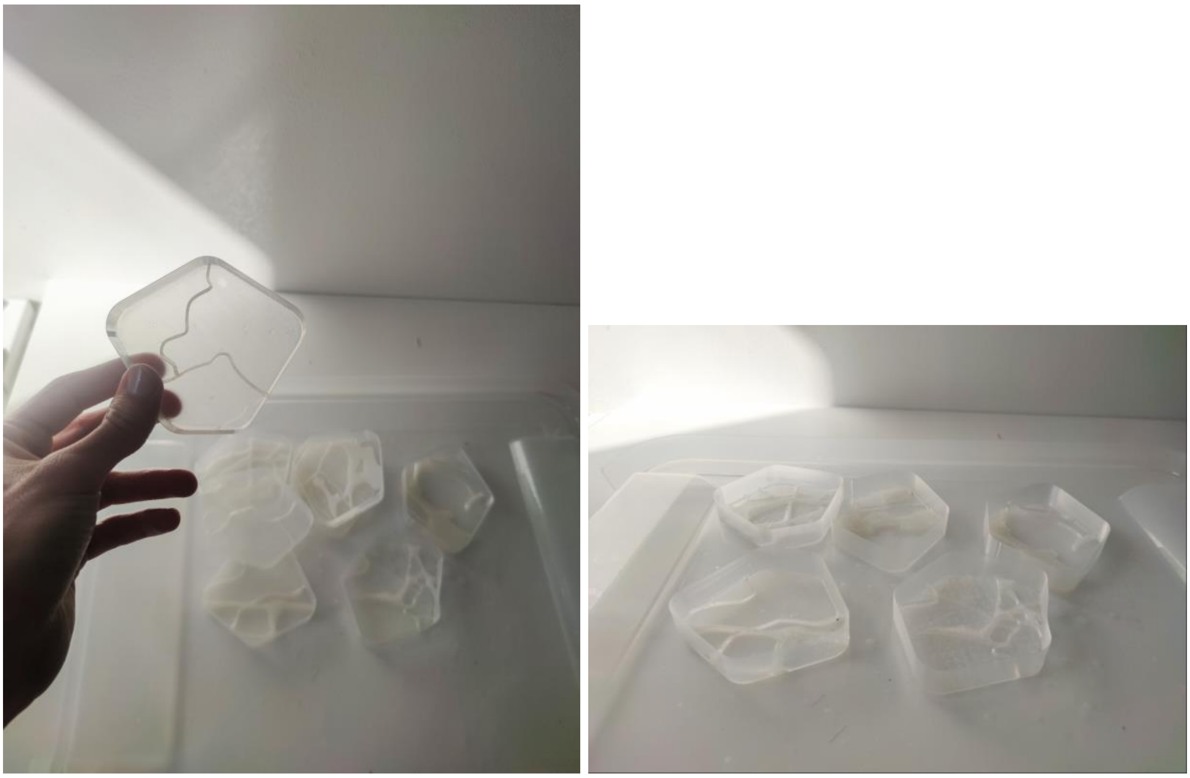


Fig. 51. Prusa MINI+ 3D printing one of the parts of concept 2.

The original size of the mould was on a scale of 1/2 and each mould was divided into 4 parts as seen in Fig. 51. However, there were some problems when cultivating mycelium in those moulds since the conditions were not ideal and some problems arose. For more details read the information and see the pictures in 8. Appendix. The final moulds were on a scale of 1/4, see Fig. 52 to visualize them.



(a) (b)

Fig. 52. 3D printed moulds in transparent PLA.

Once the moulds were 3D printed, it was the moment to prepare the substrate for the inoculation. As previously mentioned in 4.2.12. Composite selection, the substrate selected was hemp. 30L of hemp for domestic animal bedding was bought online through the online shop Zooplus [114], see Fig. 53.

Fig. 53. 30L of hemp.

The substrate was sterilized following the pasteurization method presented in 4.2.9. Sterilization. To measure how much was needed, a mould was taken as an instrument to measure. It was filled with hemp 14 times. Before submitting the substrate to the sterilization process, it was necessary to add some nutrients and water to it, to keep the moisture content above 70%rH (relative humidity) [4]. The recipe followed was given by the instruction manual given by the company Grow.bio [115]. 700mL of water was mixed with 3 tablespoons (tbsp) of flour, approximately 45mL. The blend was added to the substrate until there was humidified. The key to knowing the right amount of water in the substrate is to take some and squeeze it until just two or three drops fall. If more drops come out of the substrate when squeezed it means that there is too much moisture inside the substrate [116]. The recipient where the substrate is kept during the sterilization process must have a melting point high enough to resist the heat of the pasteurization. For that, two polypropylene bags were used as seen in Fig. 54 (c).

(a) (b)

(c) (d)

Fig. 54. (a) Hemp previous to the addition of bran. (b) Hemp after the addition of bran (c) Polypropylene bags with the hemp inside. (d) Bags inside the conventional cooker ready for pasteurization.

The pasteurization was done with boiling water and the lid on for 3 hours. Important to mention that a metallic mesh was positioned below the bags so they weren't in direct contact with the cooker base, which might be too hot. After the pasteurization, the hemp was ready to be used as substrate.

The inoculation of the moulds with mycelium *T.versicolour* was done following the method explained in 3.1.3. Inoculation. Still air box. The still air box used is shown in Fig. *38*. Still air box. Under sterile conditions, the bags were opened with scissors that were previously sterilised with alcohol and a lighter. The moulds shown in Fig. *52*, were filled with the substrate and the grain spawn shown in Fig. 36, using a spoon previously sterilized. Additionally, for better homogenization, some liquid culture, see Fig. 36, was added to the mix. Fig. 55, shows a picture taken during the inoculation process. It is important to mention, that alcohol was sprayed constantly inside the still air box, and hands were sanitized with hand sanitiser after filling every mould, to ensure sterile conditions.

Fig. 55. Inoculation of the moulds with *T.versicolour* and hemp.

Once the moulds were filled with the material, they were covered with plastic film and tiny holes were made in it to allow the mycelium to breathe. Then they were kept inside the cultivation chamber presented in 4.2.11. Cultivation chamber, see Fig. 39, at 27°C. For 16 days. After that period, the composites were ready to be unmoulded. They were left 2 days, outside the mould and inside a plastic bag with small holes to allow the mycelium to grow in those areas that had less oxygen contact. The composites fully colonized by mycelium can be seen in Fig. 58.

4.4.2 Growing

Fig. 56. Day 0. 8th May.

Fig. 57. Day 6. 14th May.

Fig. 58. Day 16. 23rd May.

4.4.3 Drying

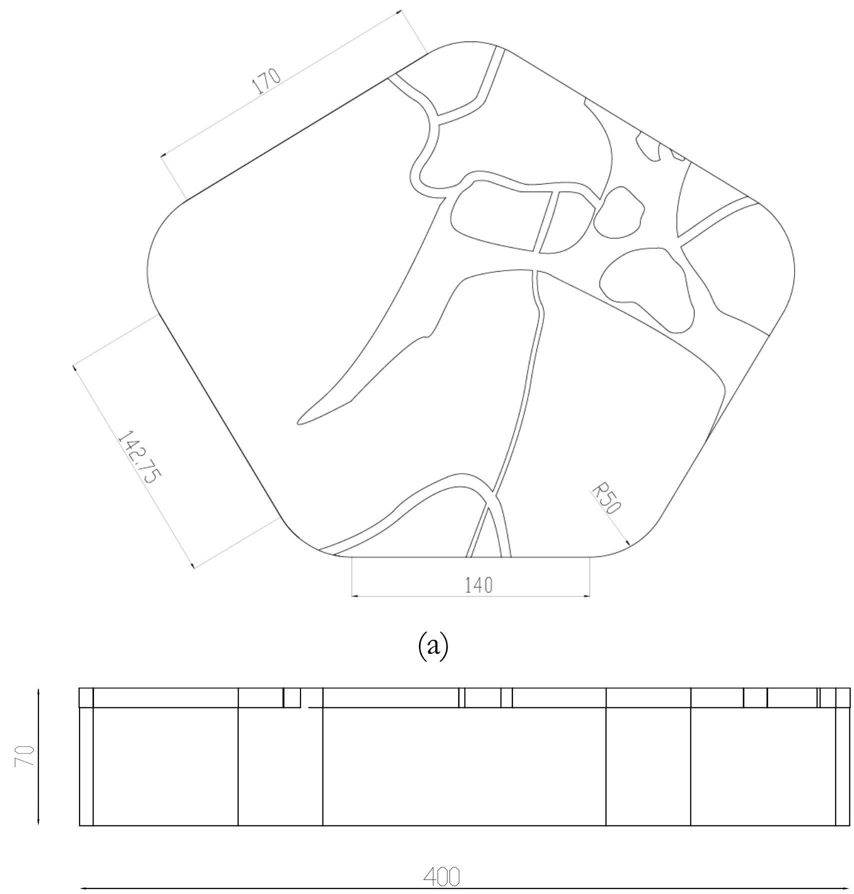
As explained in 3.4.3. Drying, the drying of the composite to evaporate the moisture inside and give it its final properties was done inside a conventional oven at 80°C for 4 hours. After the first 2 hours, the composites were flipped to make sure that all the faces were exposed to the heat. See Fig. 59.

Fig. 59. Pieces inside the oven.

5 Results

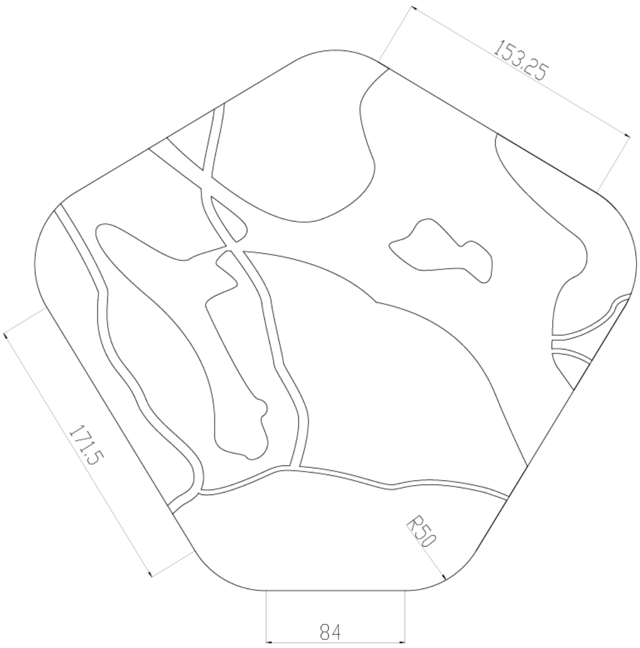
5.1 Product Description

The final product is formed by 14 panels for acoustic insulation. The shape of the panels is a pentagon with round corners. There are two types of pentagons with the following dimensions, see Fig. 60 and Fig. 61 The product is formed by 8 panels for type 1 and 6 panels for type 2.



(b)

Fig. 60. Panel type 1. Measurements in mm. (a) Top view. (b) Front view.



(a)

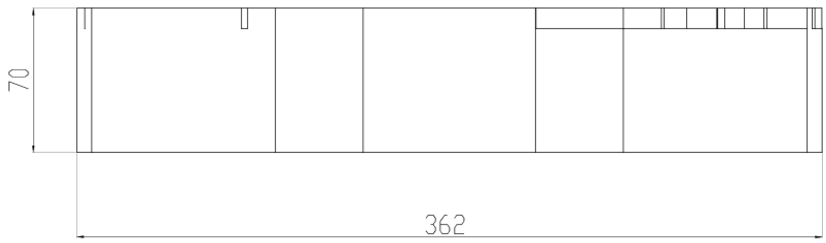
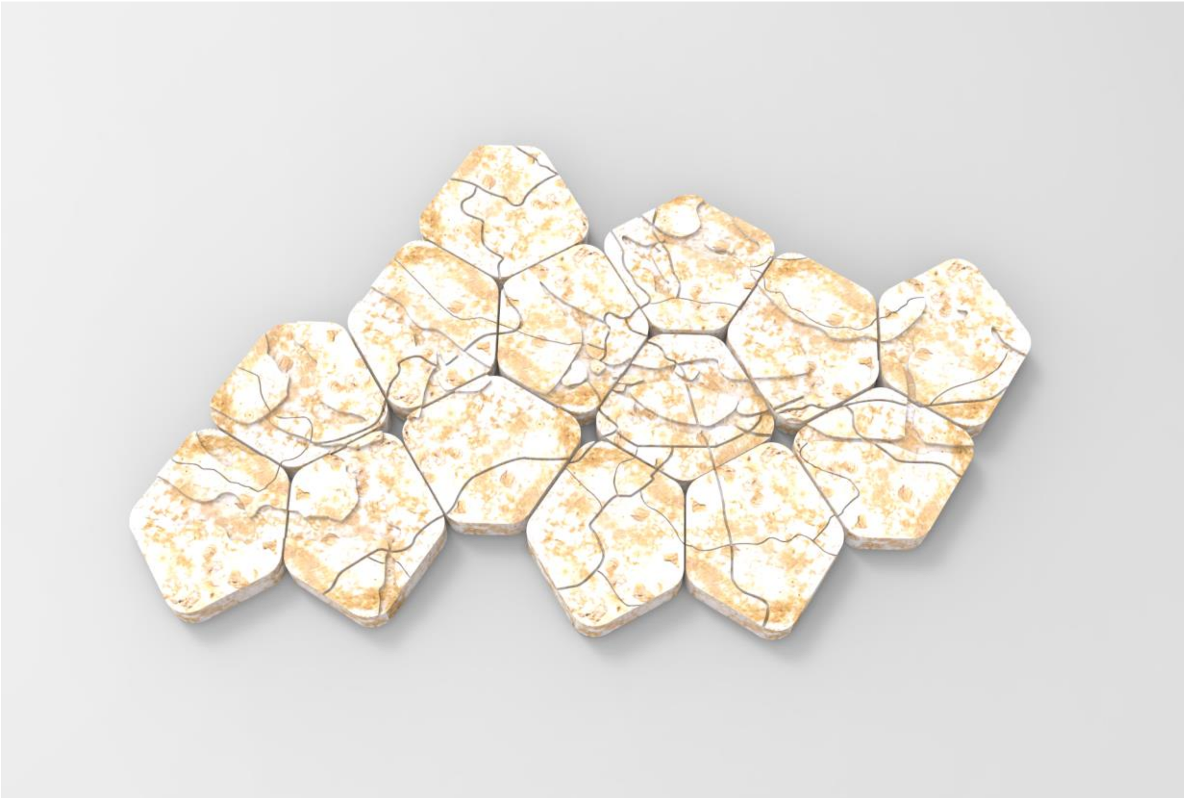


Fig. 61. Panel type 2. Measurements in mm. (a) Top view. (b) Front view.

The composition of acoustic panels is represented by a ¼ scale prototype, which has been developed growing the material at hand, and photorealistic images known as renders. Pictures of the prototype are shown in Fig. 62. The renders position the material in different real environments where it could fit. See Fig. 63(a), 57(b), 57(c), 57(d), and 57(e), to visualize the material in environments such as an office, a music studio, a hotel room, a restaurant etc.

Fig. 62. Prototype

One of the pieces was substituted for a 3D printed piece since the original one made out of mycelium was destroyed when removed from the mould.

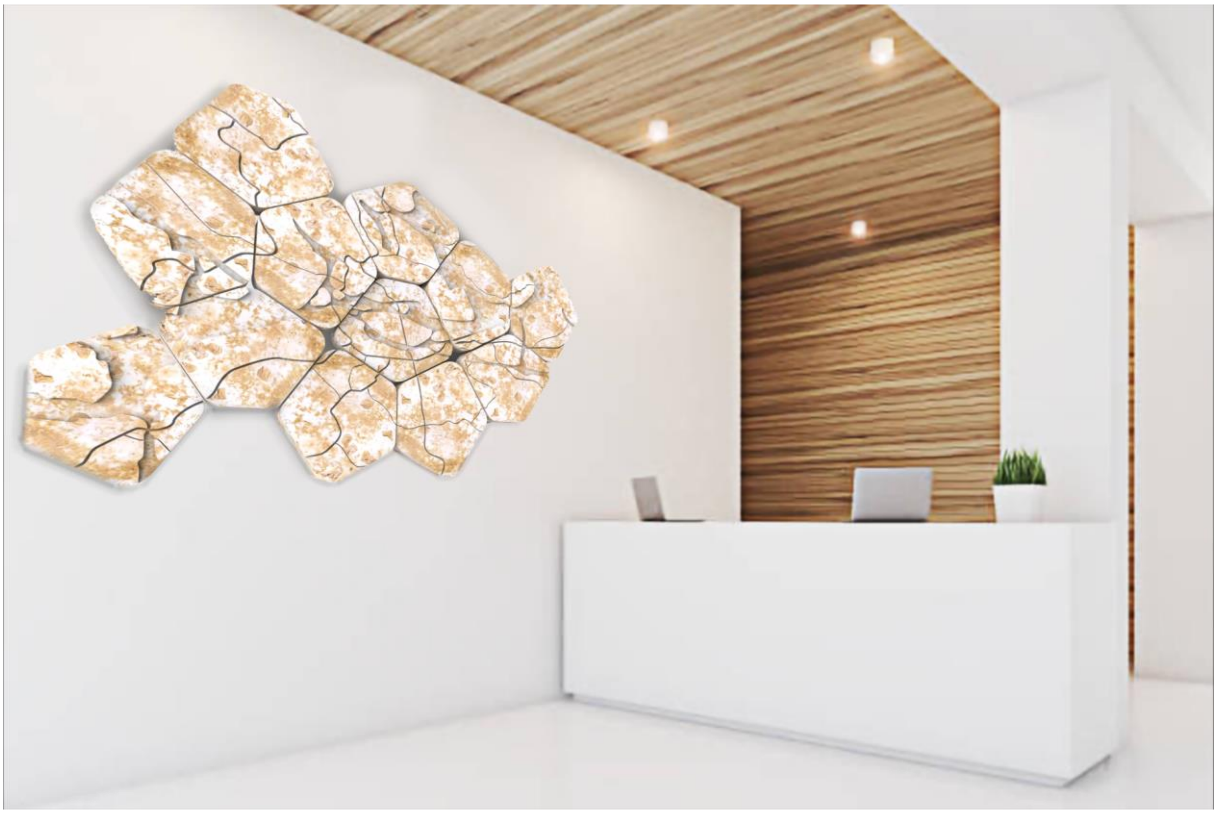


(a)

(b)

(c)

(d)



(e)

Fig. 63. (a) Render front view. (b) Render side view. (c) Home environment render. (d) Hotel room environment render. (e) Reception environment render.

The final solution aims to make a connection between the material at hand and the user by generating positive emotions, with the intent to touch their feelings. For that, there are a couple of aspects of the product that are there for a reason. Regarding Don Norman's three levels of design [33], presented in 2.4. Design for Emotion, the first aspect that makes users respond refers to the visceral level. At this level, the texture, shape and colour of the product, attract the user's attention. The surface of the product presents some rugosity and in some parts, the user will be able to feel the grains of hemp inside. The shape of each panel is organic and users may establish a connection between them and elements in nature or with the whole composition. Some people may resemble them as honeycombs, turtle shells or snake scales. The colour may also arise some questions since the panels are not fully white, some parts are more yellowish due to the nature of the material, the access it had to oxygen when growing and the drying process. After that first interaction with the material, at the behavioural level, the user starts wondering about the material, its purpose, its utility, and its properties. At this point an explanation either by text, illustrations or verbal communication is required. The user might recognize at this level that the patterns on each panel's top surface form the map of Stockholm when creating the composition. The user also learns that the product is an acoustic panel and that it is also a competitive alternative to synthetic solutions. Then he/she gets some knowledge about the properties of the material and how the product is made. Lately, the user starts to reflect on the benefits of the product, its performance, meaning and value. At this reflective level of interaction is when the user should be introduced to the story behind the product, in order to create a bond between him/her, the product and the material. Here the user learns about the importance of mushrooms in nature, their relationship with the forest ecosystem and planetary health, appealing to the user's feelings in that way.

5.2 Product's story

The shapes of the different islands of the Stockholm archipelago show how nature's organic shapes manifest themselves in different dimensions, from small mushroom caps in the forest to big extensions of land. There can be found similarities between mushroom patterns and Stockholm's islands. On the islands of the map, it has been drawn the train lines to illustrate how similar they are to the mycelial network. With this idea, it is explained how similar the way cities are structured to the way nature works, see Fig. 3. Remembering the user that humans are still part of nature and that nature has already invented solutions to some of the problems that modern society faces nowadays, like the development of an efficient way to distribute resources. Mushroom mycelium has the ability to connect to plants and trees' roots establishing a symbiotic relationship where both species mutually benefit by exchanging nutrients. The spreading capacity of mycelium allows it to be connected to multiple trees at the same time, creating a network similar to the internet, where there is not only an exchange of nutrients, but also an of information among trees and plants by electric signals. According to P. Stamets, almost 80% of all plants establish this symbiotic relationship with fungi, "Mushrooms are forest guardians. A forest cannot be defined without its fungi because they govern the transition between life and death and the building of soils, all the while fueling numerous life cycles" [6]. More detailed information is presented in 1.1.1. Role of mushrooms in nature.

With this story, some awareness about the importance of demystifying the role of mushrooms in nature and spreading the knowledge behind the product will hopefully be created. Moreover, it is expected that this knowledge shared will add some emotional value to the product, making it more attractive to the user.

5.3 Aesthetic analysis

According to the knowledge presented in 2.4.1. Patterns analysis, the organic shapes used in the product are supposed to improve mood, reduce stress, and improve concentration and working memory performance. Besides, with the design of the product, the user should be related to the intended emotions of Calmness, Flow and Growth, as was established in 3.2.6. Definition of the intended emotions. The accuracy of those statements is tested with users in 5.5. Test.

The texture of the product is far to compete with the smooth surface that some acoustic panels made of synthetic foams can present. The texture is rather rough. However, thanks to the smooth surface of the mould, it is possible to get flat surfaces and some tiny geometrical patterns due to the mesh of the 3D printed mould. Overall, the material doesn't offer a premium look compared to plastics. Besides the organic shapes of the archipelago islands are not perfectly defined and some have been slightly distorted when unmoulding the product since the mycelium usually sticks to the mould walls.

The colour of the product under a first impression doesn't present any particularities, it is perceived as rather dull and monotone. But with a closer look is curious to see how the mycelium by its nature creates yellowish patterns. It would be interesting to explore the reasons behind those patterns and how the growing conditions affect them. To be able to control that in the future opens a lot of possibilities for designing with the material.

5.4 Sound absorption

As presented in 4.1.2.6 Acoustic Insulation, it was necessary to take some considerations to maximize the sound absorption capacity of the final solution. For its design, the main factor was the thickness of the panels, and regarding the material, hemp and the fungi T.versicolour were selected as explained in 4.2.12. Composite selection.

When compared to the different types of acoustic panels that can be found in the market, the solution could be compared to the Strip solution shown in Fig. 23, with absorbs sound in the low-frequency range. Nevertheless, the thickness of the panel is 7mm which provides the overall best acoustic performance for high, mid and low frequencies, as presented in 4.1.2.6. Acoustic Insulation, [97]. Although the prototype won't be submitted to a sound absorption test, the substrate and the species have been selected to maximize the acoustic performance of the product, seeking high density and fast growth rate. As it was presented in 4.1.2.1. Properties of mycelium composites, the fibrous nature of the material which decreases the sound waves amplitude and reduces the sound accumulation and reflected noise, provide great acoustic performance with any given mycelium composite [59]. Regarding the one fabricated for this project, it is estimated that NRC (Noise Reduction Coefficient) is around 0.2-0.3, having in mind that the product has been developed with the equipment and the resources that were at hand.

5.5 Test

Personal interviews were carried out supported by three tools, the tool PrEmo to help users identify how they feel about the product, a rating scale to see to which degree the product is successful and to measure the overall performance of the product when interacting with the user, and response alternatives to one question. After the test, a discussion with the user was carried out, gathering additional comments, reflections or answering some questions they had. See Fig. 64, Fig. 65 and Fig. 66 showing PrEmo tool, response alternatives and 5 questions supported by a rating scale, respectively.

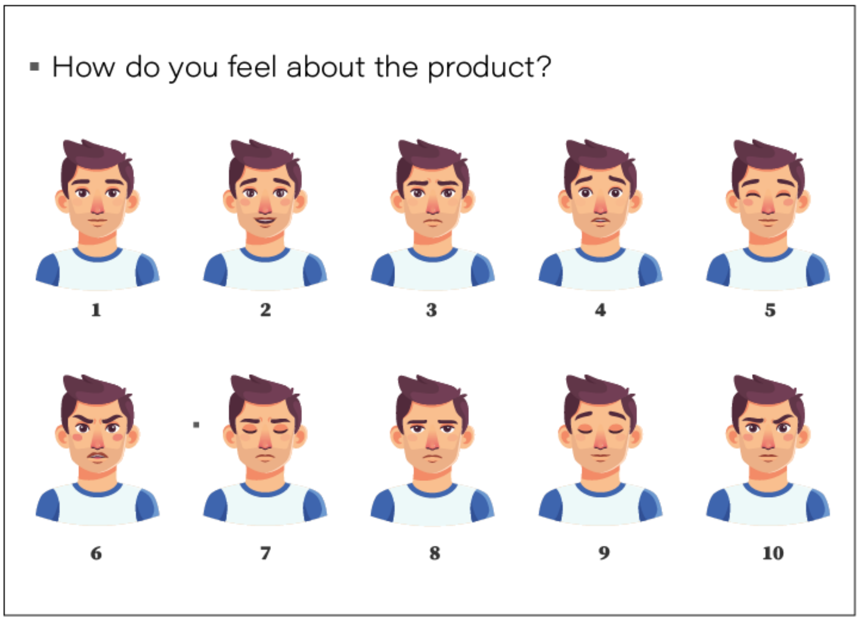


Fig. 64. PrEmo, 10 different emotions. Animation got from feepik.com under student license.

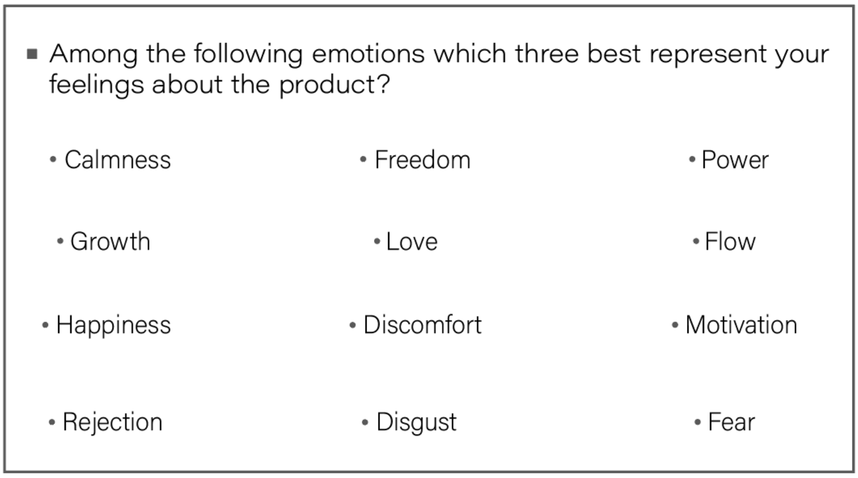


Fig. 65. Response alternatives. 12 options for the question "Among the following emotions which three best represent your feelings about the product?".

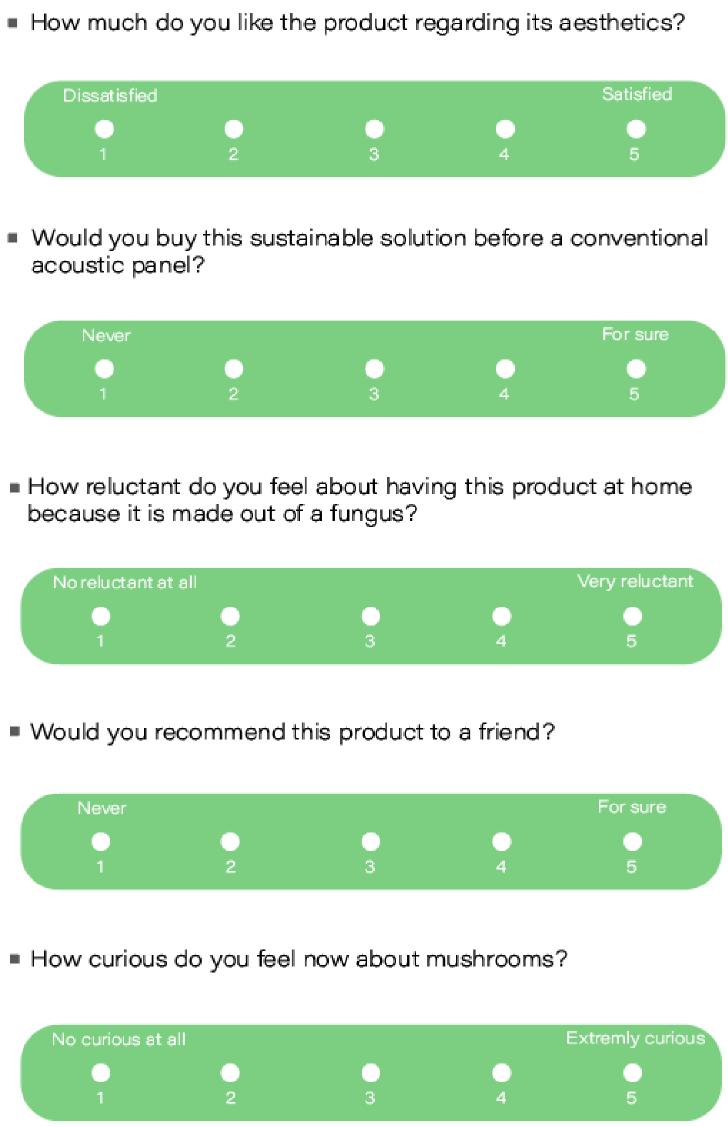


Fig. 66. 5 different questions related to the product performance supported by rating scales from 1 to 5.

The three tools mentioned that supported the personal interviews were presented as a questionnaire that can be seen by scanning the following QR code, which was shown in the fair Xjobbmässan that took place the first of June at Jönköping University. See

Fig. 67. QR for the questionnaire.

5.6 Packaging

Fig. 68. Packaging.

More pictures of the packaging can be seen in Appendix 12. - Appendix 14.

5.7 Brochure

Fig. 69. Brochure.

All the pages of the brochure are shown in Appendix 15. Page 1 of the brochure. Appendix 30. *Page 16 of the brochure.*

5.8 Poster

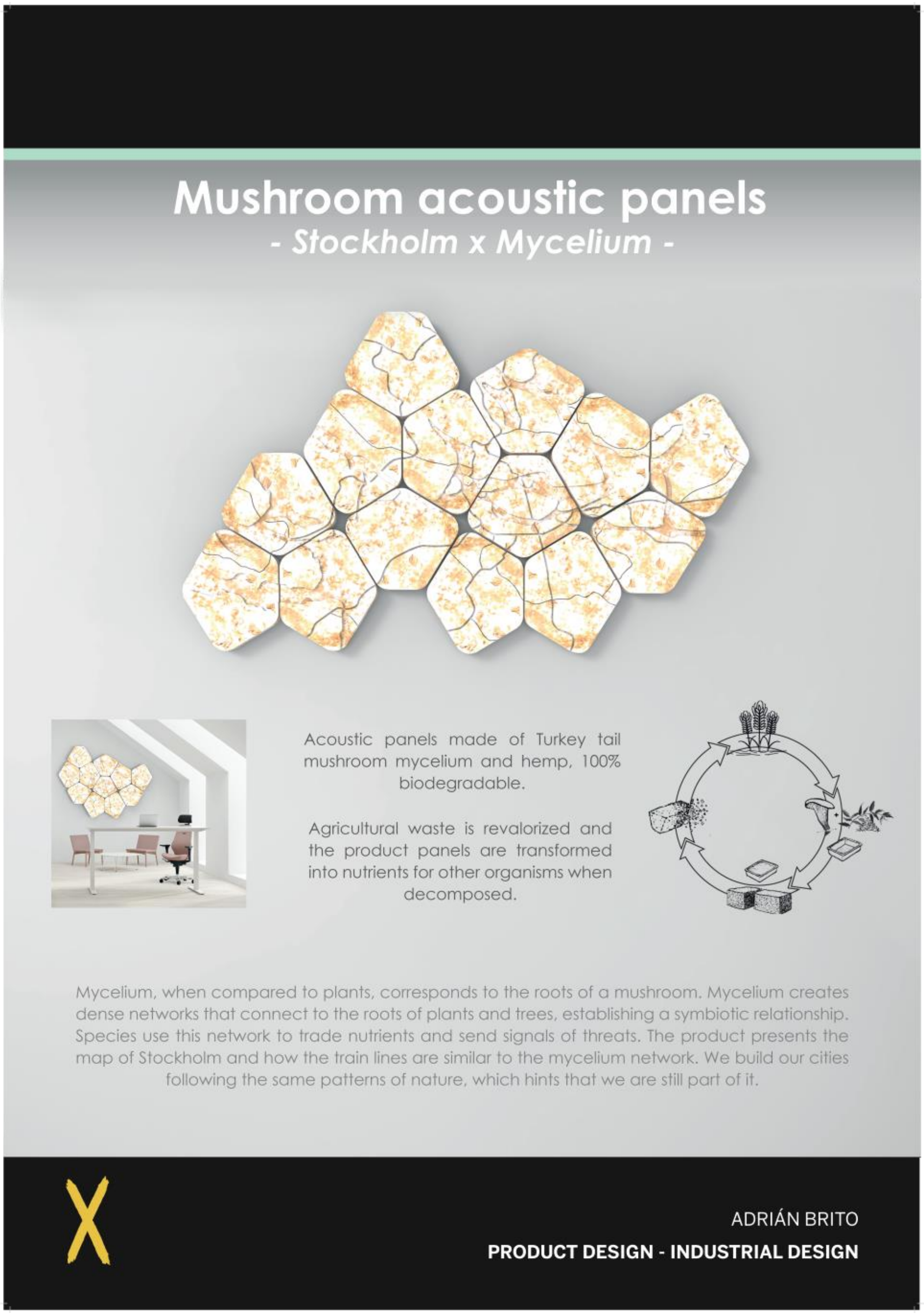


Fig. 70. Poster.

6 Conclusion and discussion

6.1 Research questions

1. What are the existing applications of mycelium composites in product design?

The existing applications were presented in 4.1.2.3. Applications of Mycelium composites. Those are:

- Insulation panels.
- Furniture design.
- Mycelium packaging.
- Construction bricks.
- Clothes.

Regarding product design, insulation applications, packaging and furniture design are the ones that have been developed the most. The project has been focused on insulation since it is believed that so far, is the application where mycelium composites have a higher potential and the ability to compete against unsustainable synthetic foams such as polystyrene and polyurethane. In particular acoustic insulation was the application selected for further exploration and development.

The solution developed when compared to its competitors or other applications, lacks accuracy when defining the different shapes of the map. The patterns created by Mogu for example, one of the companies that also develops acoustic solutions with mycelium composites, manage to develop smooth surfaces and well-defined patterns. Although it hasn't been conducted any sound absorption test, presumably the NRC of their acoustic panels must be higher than the product developed in this project. Other companies that reuse plastics like BAUX or Woven Image, also manage to develop premium surface quality, using as well interesting organic panels. In a world where plastics are still used for almost every product, the fact to recycle this material to create acoustic panels makes complete sense nowadays. However, it is important to keep in mind the importance of developing new solutions that don't rely on plastics, so a future where materials have a minimum impact on the environment can be possible.

The genuineness of this project relies mainly upon the Design Thinking Methodology that has been used for its development and the Design for emotion theory that has been applied to it. This is something that hasn't been addressed so far with this material, as far as the student is concerned or as far as what has been published online.

2. What are the limitations and opportunities of using mycelium in product design?

There are two big limitations regarding mycelium composites. The first one is that it takes time to grow the material. That factor indeed depends on the size of the piece and the amount of grain spawn or liquid culture used. However, growing mycelium until having those cultures also supposes a period that can vary from three days to two weeks. Each stage of the process requires some time and that has an impact on the scalability of the production. Companies like Ecovative, seem to be closer to an industrial level of production. They might have a lot of resources and plenty of cultures, so for them, to develop a product only involved the period since the mould is filled with the substrate and inoculated with mycelium until the substrate is fully colonized. Hence, they can ensure that it only takes a few days for them to grow the material. For small projects like this one, it has been shown how it takes much more time. So, it is not possible to compete with plastics if that is the case. Even for big companies like Ecovative, it must be difficult to compete against plastics in terms of speed of production. A simple injection moulding machine can make hundreds of pieces in only one day.

The other limiting factor is the constant risk of contamination at every step of the process. Even when the material is growing inside the mould under sterile conditions, it can get contaminated by the exterior since the mould is not fully isolated so the mycelium can breathe. The process involved in getting sterile conditions also requires some time. In this project, for instance, there wasn't a pressure cooker at hand, so the times for the mediums sterilization were doubled, as explained in 4.2.9. Sterilization. Composites contaminated can suppose a waste of time and materials. Having professional equipment, the sterile conditions of a laboratory and experienced workers can ensure a high level of success. But again, this is a factor that delays the production process when compared to plastics.

On the other hand, the material presents a huge competitive advantage regarding sustainability. In a society that is increasingly demanding more sustainable products, mycelium composites can be successful. The most conventional way of producing the material right now is by using moulds made out of plastics, which has an impact on the environment. In this project, to minimize its impact, additive manufacturing was the technique chosen to fabricate the moulds, minimizing material waste. Besides the filament was PLA which comes from organic sources such as starch or sugar cane [117].

As shown in the SWOT analysis, see Fig. 31, the number of scientific publications on this topic is increasing exponentially. This is due to the interesting properties of the material and the increasing popularity of mushrooms, not only in product development but also in medicine. This will probably mean the optimization of the production process, the enhancement of the material properties and the raising of new applications.

Hopefully, this project will serve as an example of how to work with mycelium composites from a design perspective. The work done could inspire academia, teachers and students in universities to implement sustainable materials as part of their design process. Approaches like Material Driven Design should be further developed and taught to students if they aim to get involved in projects like this one, guiding them when it comes to understanding the material, its relationship with design and experimenting with it. Working with sustainable materials give designers a wider view of the impact of their designs and a better understanding of nature, seeing it as a source of inspiration and knowledge. This can be challenging for designers since it is a completely new discipline to learn about. Nevertheless, it can make better designers, better engineers and better humans, which in the long term, will contribute to a better world.

3. What is the user's emotional response when interacting with a bio-based product?

The user response was evaluated according to the three different levels regarding affection presented in 2.4 Design for Emotion, both by P. Desmet et al., and D. Norman [32], [33]. It was done during the Xjobbmässan 2023, where the product was presented along with a poster, the brochure, the packaging and different samples. The first interaction with the product was triggered by its aesthetics, the look of the product aroused curiosity in the user, which made them want to know more. After this first impression, users started to touch, hold and smell the product. Then they looked at the poster which was in front of them, which provided them with the information that the product was an insulation solution made out of mushrooms. The following actions that followed were to look at the catalogue seeking for more information and at the packaging. At this point, users started to understand what the product was about and to create some meaning. Those actions correspond to the first and second levels of experience, according to P. Desmet et al. [32]. After that, all users sought more information by interacting with the student. Then, they were presented with the story behind the product, its relationship with nature, how the product is developed, the impact it has on the environment when compared to plastics etc. When they were exposed to this information, they started to judge the product, and the overall response was positive. Users started to reflect on the product, its performance, its benefits, its tradeoffs etc. This level of interaction could correspond to the third level of design presented in 2.4 Design for Emotion [33].

The results of the interviews and questionnaire are presented in Appendix 5.- Appendix 11. It was concluded that the first reaction when seeing the product was positive, they wanted to touch the product and didn't seem afraid or disgusted by the product in almost all cases. Curiosity seems to be the dominant feeling throughout the whole interaction with the products. All participants found the topic interesting and got the feeling of having learnt something new. The three intended emotions presented in 3.2.6 Definition of the intended emotions were experienced by the users along with a sense of freedom and motivation. So it is possible to say that the product succeeded in that sense. Although the final product could have been much better in terms of surface quality and finish, surprisingly the look of the product was liked. Probably because the users find it different and they seemed to like the organic shapes of the panels. However, they felt a bit reluctant to buy the product before a conventional solution and to have a product made out of mushrooms at home. This might be because users tend to distrust products that are too much innovative or that are from brands that are not well-known. Lately, it was remarkable the positive impact the story behind the product had when users were presented to it. Then, they connected the design with the story and understood the relation humans still have with nature. They were impressed by the role mushrooms play in nature, which was something new for almost all participants. Overall, the response from the users was much better than expected and they enjoyed the interaction with the product. It is curious how users tended to smell the product, this might be something more common in bio-based products than with plastics or other materials, as well as the reluctance to substitute a conventional alternative for a more sustainable one at first.

6.2 Further development

The disadvantages of the material and the treatments for improving its properties were already addressed in 4.1.2.1. Properties of mycelium composites and in 4.1.2.2. Treatments for improvement. So far, the applications of mycelium composites are limited to interior spaces, with just a few exceptions that don't use synthetic coatings. These treatments are still in the research stage, so it would be necessary for some years to pass to see some standardized application of those procedures. The material has impressive resistance under compression and high performance for insulation, so, predictably, more companies will explode those two characteristics that the material already exhibits without any special treatment. There is not that much knowledge on the procedure to follow on how to develop fabrics with mycelium composites, it seems to be covered by industrial secrecy, except for some home experiments that are shared in forums like Biofabforum [118]. The student has never experimented with mycelium leather, but companies like Bolthreads or Mycoworks [119], [78], seem to achieve professional results and be very competitive, so probably in the future there will be more applications within this sector. The upcoming investigations will probably be focused on the testing of new species of fungi potentially good for developing mycelium composites and on the refinement of which ones fit best certain applications. As well as with the substrates used. They will be focused as well on 3D printing, which has revolutionised the way humans produce and in the last decade has become more accessible for everyone. As explained in 4.1.2.5. Latest advancements in mycelium composites, so far, this technology has a lot of progress yet to be done in improving the characteristics of the extrusion. Nevertheless, just the fact that the mycelium can survive the extrusion process and grow inside the 3D printed structure, makes a promising future for the use of mycelium composites in 3D printing. Besides, it eliminates the need for plastic moulds, turning the material into an even more sustainable solution.

The production of mycelium composites could be developed one day together with mushroom farms. Some of the mushrooms that are intended for the food industry could be used for the development of mycelium composites. A mushroom farm already has the laboratory equipment and the perfect conditions for growing mushrooms. So, using some of the resources for developing mycelium composites wouldn't suppose a big investment. Moreover, according to P. Stamets, substrates that have been already colonized by one species, can be reused for a second time as a substrate for growing mushrooms [14]. The new mycelium introduced can get nutrients from the leftovers of the previous organism and the fungi itself. This already colonized substrate could be used for the production of bioethanol as a source of energy as well. According to K. Hoan et al., the mycelium of *L. betulinus* was able to produce ethanol transforming cellulose into sugars [120]. P. Stamets also affirms that *T. reesei* could be key for producing ethanol by degrading agricultural or house waste [121]. Moreover, in his book Mycelium Running, P. Stamets explains how mycelium is loved by animals and insects like fishes, worms and bees as a healthy source of food for them [6]. Not to forget the already illustrated use of colonized substrate as compost for agriculture in Fig. 33. Product Journey Map.

If mushroom farms are located in rural areas, then the production of mushrooms and mycelium composites can establish a circular economy together with agriculture, where both industries benefit. In the paper Mushroom cultivation in the circular economy by D. Grimm et al., the authors go through the different applications of spent mushroom substrate (SMS), which is usually considered a waste product, proposing a circular system where waste is revalorized. The diagram presented in Fig. 71 is inspired by that system [122].

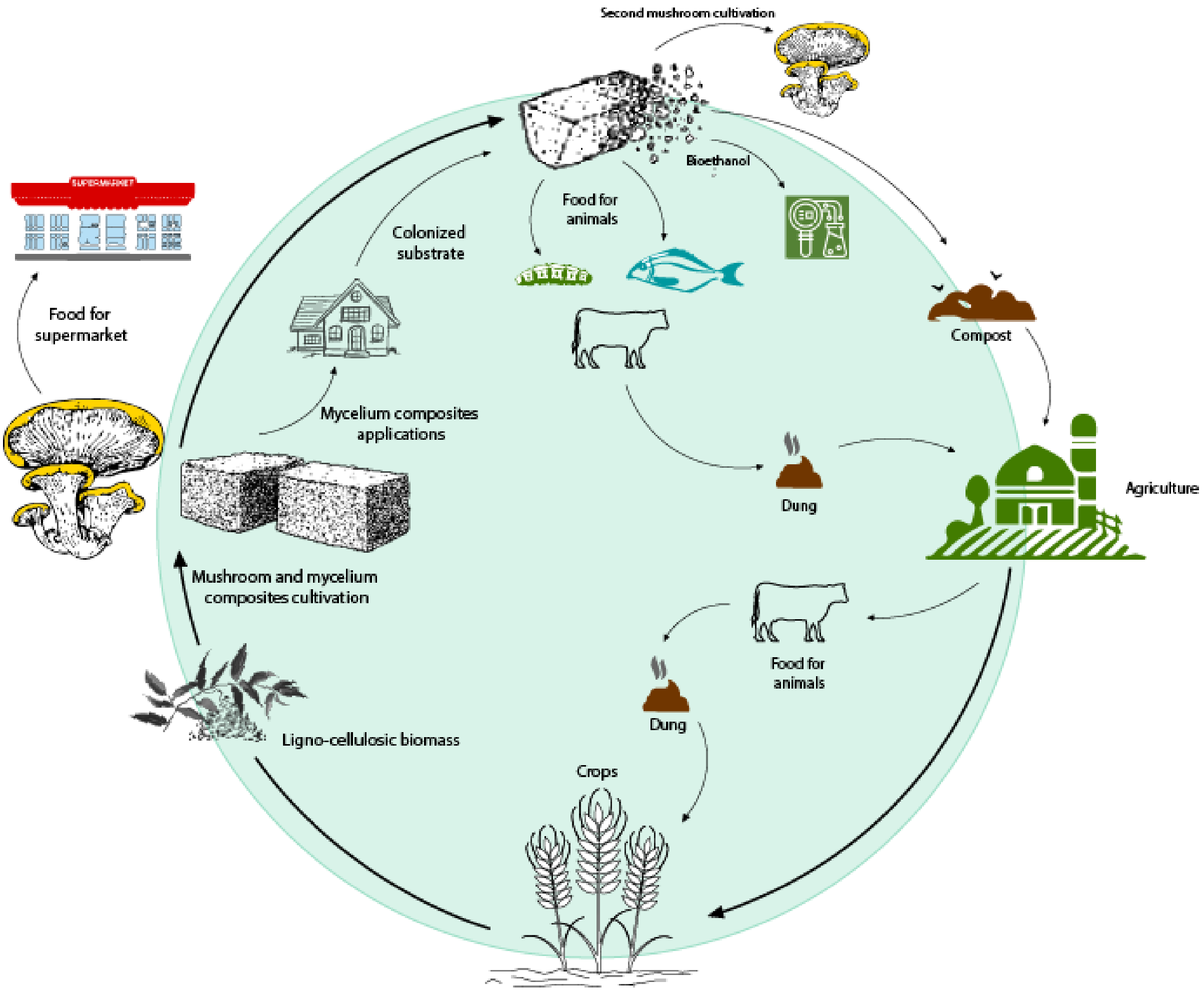


Fig. 71. Diagram showing the different applications of colonized substrates and the relationship between farms and mushroom/mycelium composites production that creates a circular economy. Inspired by "Use of SMS in a circular economy" [122].

6.3 Conclusion

The actual generation of agricultural waste supposes a big impact on the environment. Its incineration liberates big amounts of CO2 into the atmosphere without allowing it to come back to the soil as a source of carbon and nutrients for living organisms. Mycelium composites not only use that waste to create alternatives to plastics, but also they enrich it transforming it into a source for compost, animal food, energy production etc. as presented by D. Grimm [122]. Therefore, mycelium composites can be seen not only as a potential business to invest in for the low value that the raw materials have but also as an ecological project where pollution is reduced, less energy is required, and waste comes back to the initial stage of the cycle. From this perspective, although mycelium composites are still far from competing against plastics when considering fast production and performance in the majority of applications, it is important to continue investigating this material. The potential it has and the opportunities it offers, make a promising future for them. Future research should be conducted together with mycologists, who understand how the species behave, they can guess which are the best mycelium strain to determine applications and they have a broad understanding of how the recycling process of the forest work and the role mushrooms have on it. The knowledge is out there, nature already provides efficient circular systems, it is important to appreciate that and learn from it.

With this project it has been proven how the material can be grown using low-cost equipment at home, making it more accessible to everyone to experiment with it. Most people are afraid of contamination. Contamination indeed happens, but when cultivating at home, it is more about being patient and having multiple options in case some cultures go wrong. A lot has been learnt from trial and error along the project, but it is better to do it this way than merely work on theory. This project offers the tools, knowledge, and steps to follow, to motivate other students to work with mycelium composites. Information on other projects can be found in forums, forming a community that just keeps growing, and on platforms like YouTube, a lot of engaging information is shared on how to grow mushrooms.

According to the results obtained from the user test the product successfully evoked the intended emotions. Users felt related to the city of Stockholm and felt moved by the story behind the product and the role of mushrooms in nature. The final prototype is far to compete against plastics in terms of surface quality. Some parts were seriously damaged when removed from the mould which compromised the look of the different patterns. That is a consideration to be taken into account for future projects, that the mycelium tends to stick to the walls of the mould. Apart from the positive feedback gathered from the users, to sell a product like this one, it is necessary to test its sound absorption capacity, to prove if it has successfully achieved a NRC sufficiently close to the ones provided by synthetic foams. Nevertheless, the product was welcome by the users, which motivate the development of future projects like this one. Hopefully, the project will serve as a guide to design with mycelium composite and will demystify the role of mushrooms in nature and the importance they have for our planet.

Lately, it is concluded that the product offers a good combination of design, art and engineering. Since designing with mycelium composites involves a deep understanding of the material, it challenges designers to use both their engineering knowledge and their creative skills. With the growing demand for more sustainable solutions, works like this one can become more common in the upcoming years.

7 References

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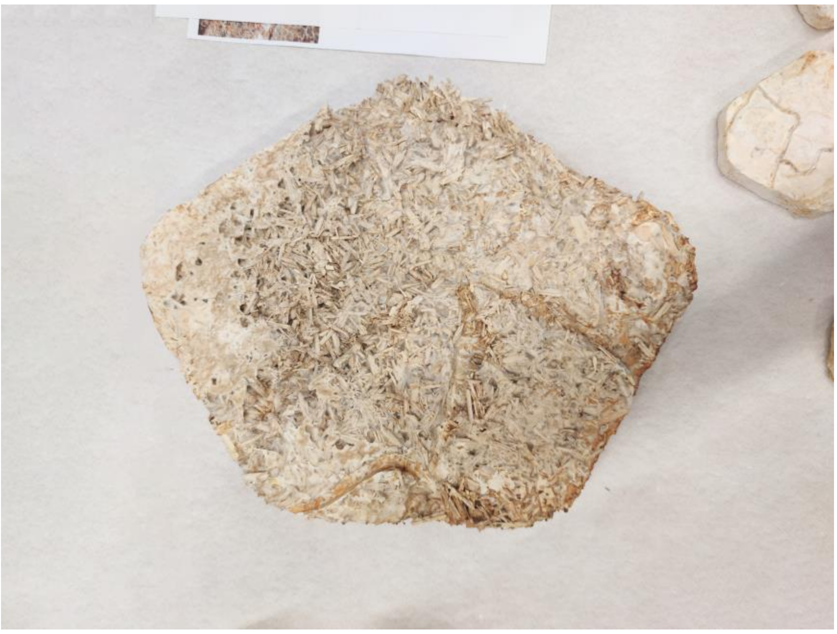
8 Appendix

Appendix 1. Original size of the mould.

Appendix 2. Original size after the inoculation.

The were two main problems with this first plan. The first one was an excess of moisture within the substrate. The second, was that it was expected to have a faster colonization rate. After one month this was the result of this first attend to make the prototype, see Appendix 3 and Appendix 4.

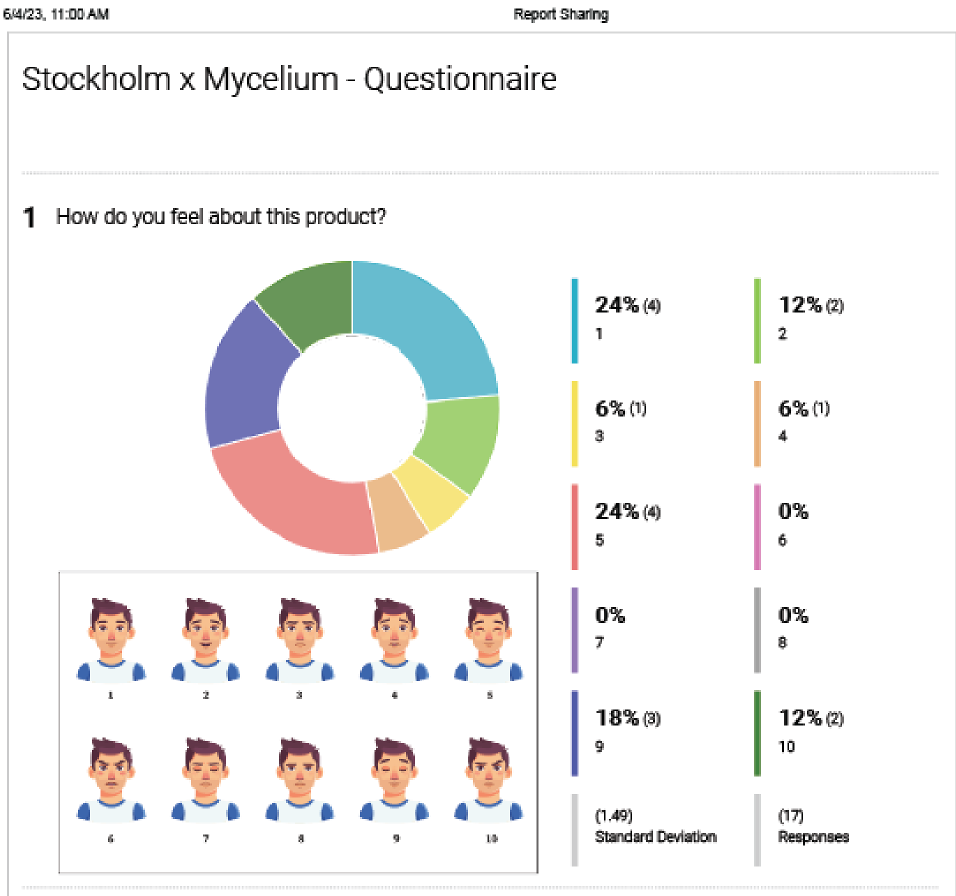
Appendix 3. Original size before taking it out of the mould.



Appendix 4. Original size out of the mould after the drying process in the oven.

As it is seen in Appendix 3 the piece wasn't fully colonized. It was taken out of the mould to be present in the Xjobbmässan that took place the 1st of June in Jököping University. It would have been necessary one more week to get a better result. Moreover, from the 4 pieces that were intended to be produced for this first intended prototype, only this one was taken out of mould and was close to be fully colonized.

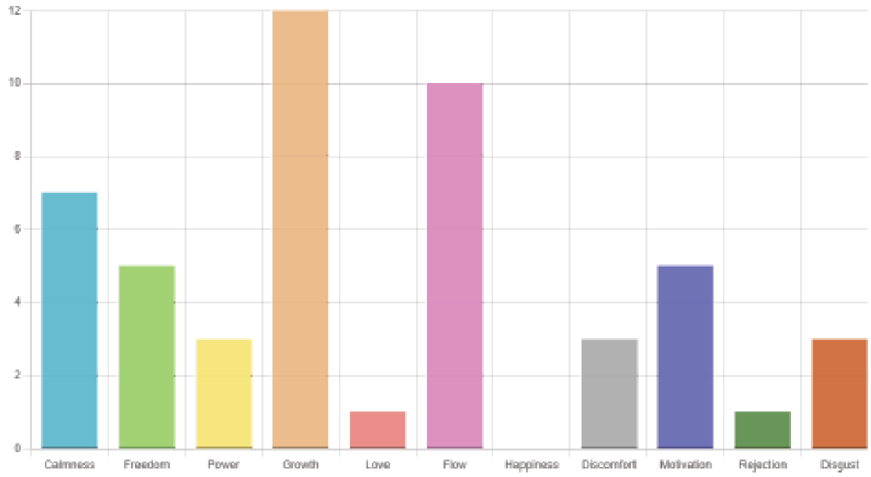
Results of the questionnaire



Appendix 5.

6/4/23, 11:00 AM Report Sharing

2 Among the following emotions which three represent your feelings about the product?



41% (7) Calmness

29% (5) Freedom

18% (3) Power

71% (12) Growth

6% (1) Love

59% (10) Flow

0% Happiness

18% (3) Discomfort

29% (5) Motivation

6% (1) Rejection

18% (3) Disgust

6% (1) Fear

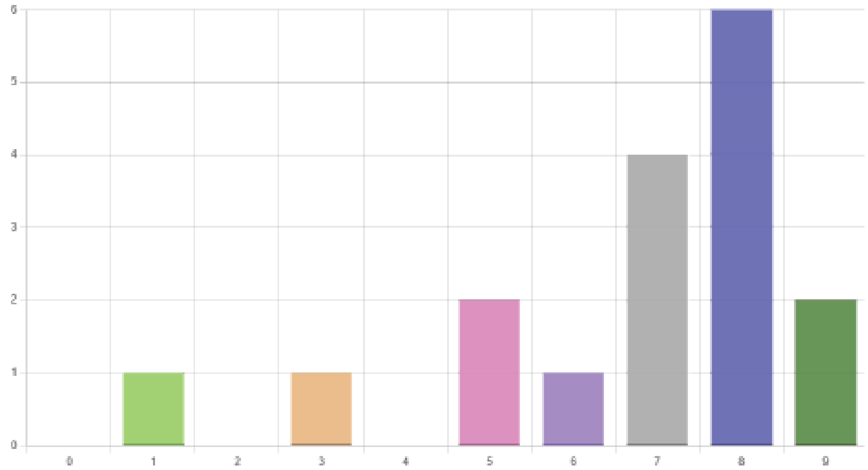
(51) Responses

https://freeonlinesurveys.com/r/GE1Q6R8f 2/7

Appendix 6.

6/4/23, 11:00 AM Report Sharing

3 How much do you like the product regarding its aesthetics?



	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Dissatisfied - Satisfied	0 (0%)	1 (6%)	0 (0%)	1 (6%)	0 (0%)	2 (12%)	1 (6%)	4 (24%)	6 (35%)	2 (12%)	0 (0%)	1.83	17	6.71 / 10
														6.71 / 10

(3) How much do you like the product regarding its aesthetics?

Description (optional)

0	1	2	3	4	5	6	7	8	9	10

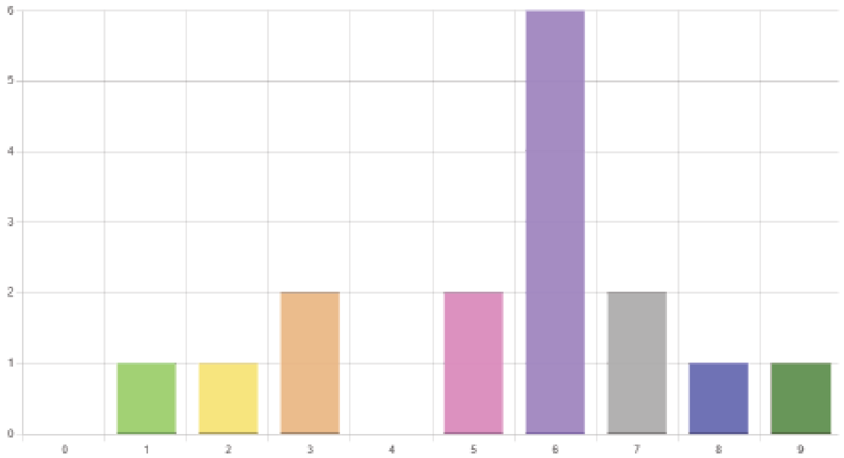
Dissatisfied Satisfied

https://freeonlinesurveys.com/r/GE1Q6R8f 3/7

Appendix 7.

6/4/23, 11:00 AM Report Sharing

4 Would you buy this sustainable solution before a conventional acoustic panel?



	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Never - For sure	0 (0%)	1 (6%)	1 (6%)	2 (12%)	0 (0%)	2 (12%)	6 (35%)	2 (12%)	1 (6%)	1 (6%)	1 (6%)	1.56	17	5.65 / 10
														5.65 / 10

(4) Would you buy this sustainable solution before a conventional acoustic panel?

Description (optional)

0	1	2	3	4	5	6	7	8	9	10

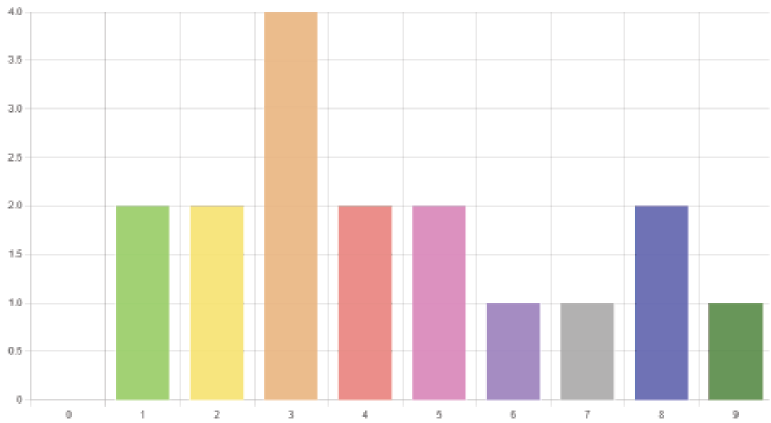
Never For sure

https://freeonlinesurveys.com/r/GE1Q6R8f 4/7

Appendix 8.

6/4/23, 11:00 AM Report Sharing

5 How reluctant do you feel about having this product at home because it is made out of a fungus?



	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
No reluctant at all - Very reluctant	0 (0%)	2 (12%)	2 (12%)	4 (24%)	2 (12%)	2 (12%)	1 (6%)	1 (6%)	2 (12%)	1 (6%)	0 (0%)	1.08	17	4.35 / 10
														4.35 / 10

(5) How reluctant do you feel about having this product at home because it is made out of a fungus?

Description (optional)

0	1	2	3	4	5	6	7	8	9	10

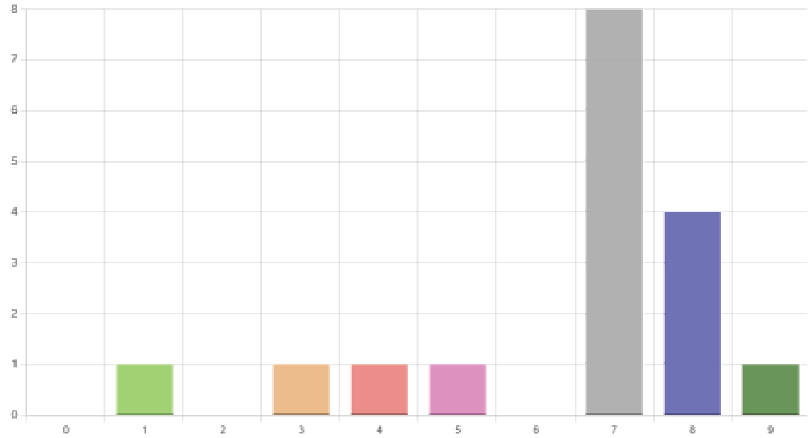
No reluctant at all Very reluctant

https://freeonlinesurveys.com/r/GE1Q6R8f 5/7

Appendix 9.

6/4/23, 11:00 AM Report Sharing

6 Would you recommend this product to a friend?



	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Never - For sure	0 (0%)	1 (6%)	0 (0%)	1 (6%)	1 (6%)	1 (6%)	0 (0%)	8 (47%)	4 (24%)	1 (6%)	0 (0%)	2.31	17	6.47 / 10
														6.47 / 10

(6) Would you recommend this product to a friend?

Description (optional)

0	1	2	3	4	5	6	7	8	9	10

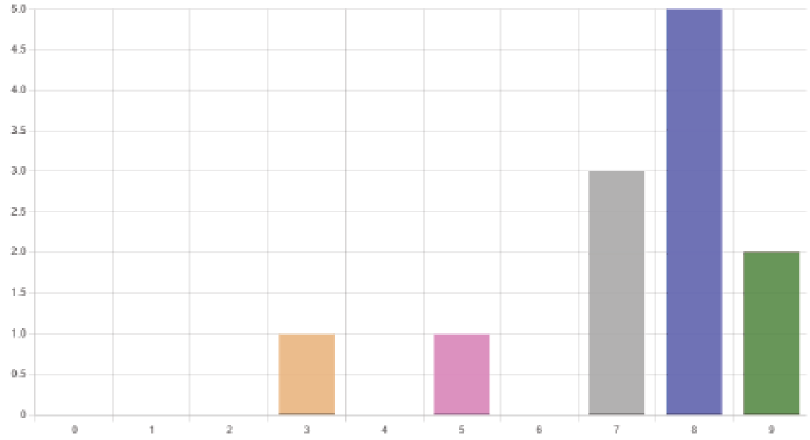
Never For sure

https://freeonlinesurveys.com/r/GE1Q6R8f 6/7

Appendix 10.

6/4/23, 11:00 AM Report Sharing

7 How curious do you feel now about mushrooms?



	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
No curious at all - Extremely curious	0 (0%)	0 (0%)	0 (0%)	1 (6%)	0 (0%)	1 (6%)	0 (0%)	3 (18%)	5 (29%)	2 (12%)	5 (29%)	1.88	17	8.06 / 10
														8.06 / 10

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See how easy it is to create a survey

(7) How curious do you feel now about mushrooms?

Description (optional)

0 1 2 3 4 5 6 7 8 9 10

No curious at all Extremely curious

https://freeonlinesurveys.com/r/GE1Q6R8f 7/7

Appendix 11.

Packaging

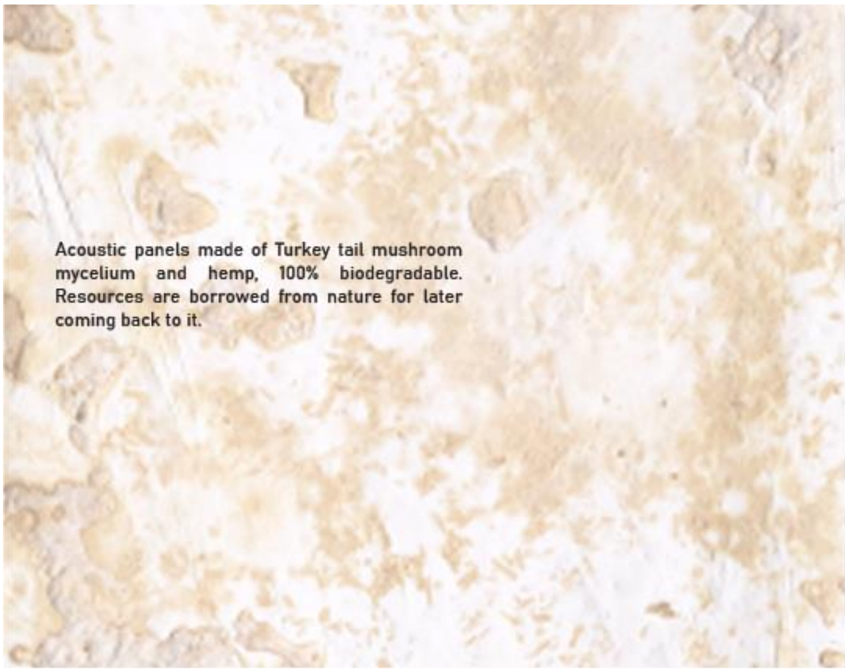
Appendix 12.

Appendix 13.

Appendix 14.

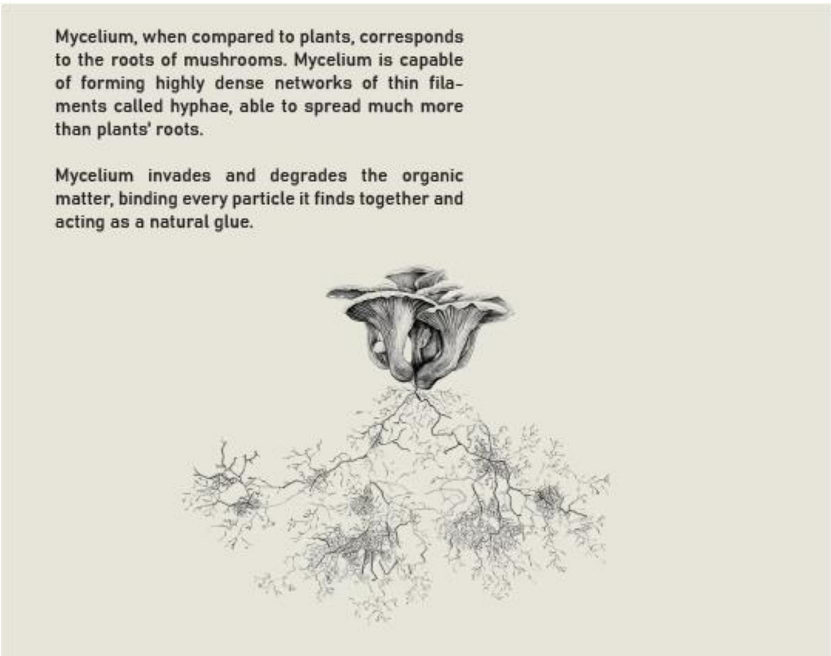
Brochure

Appendix 15. Page 1 of the brochure.



Appendix 16. Page 2 of the brochure.

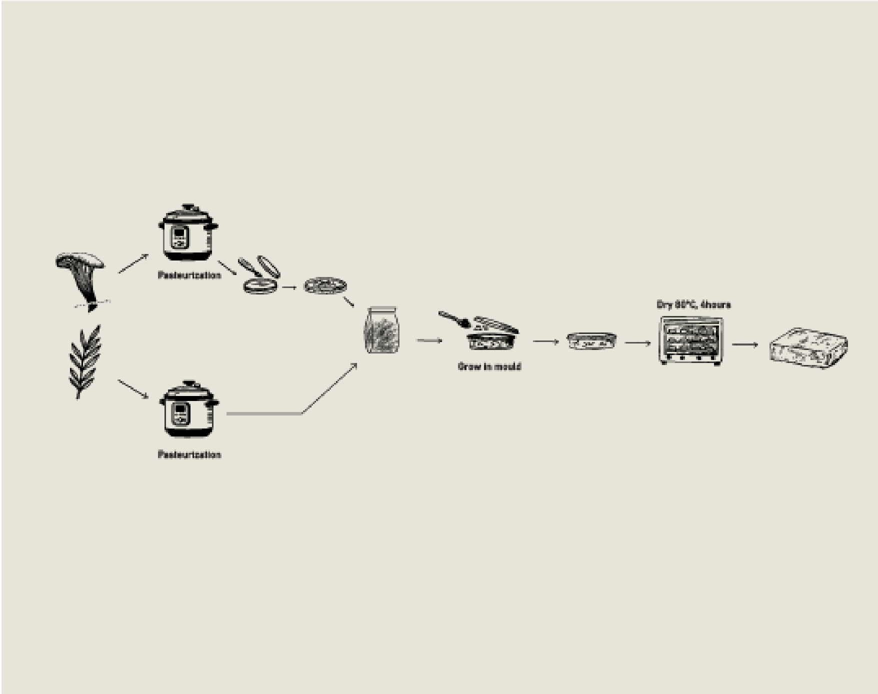
Appendix 17. Page 3 of the brochure.



Appendix 18. Page 4 of the brochure.

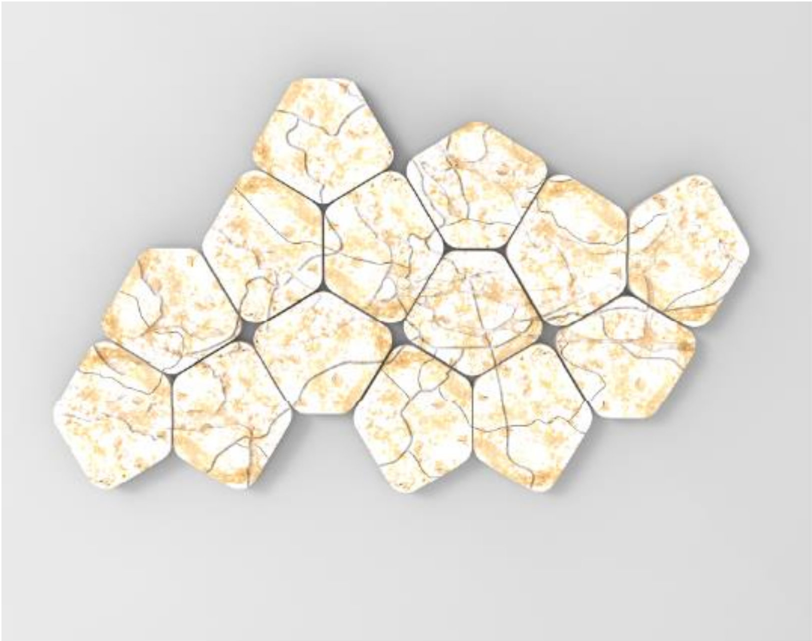
Appendix 19. Page 5 of the brochure.

Appendix 20. Page 6 of the brochure.



Appendix 21. Page 7 of the brochure.

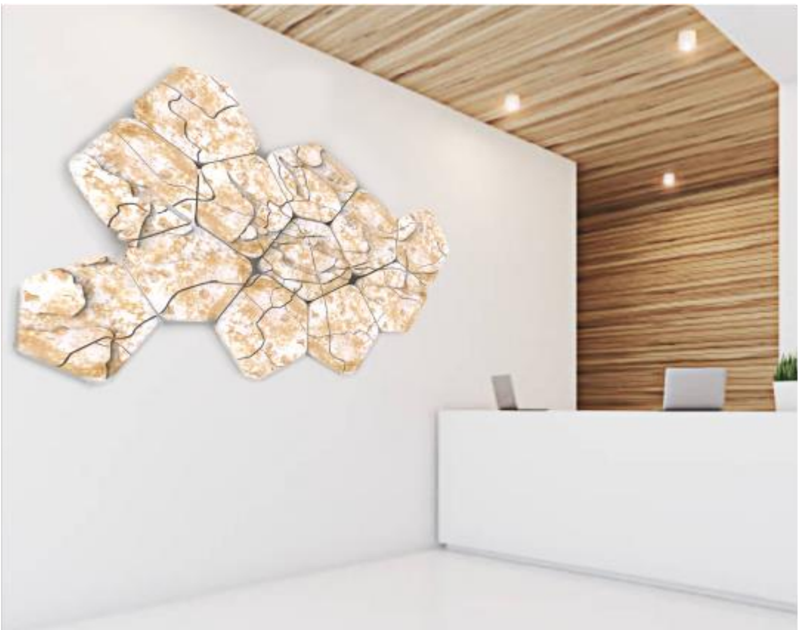
Appendix 22. Page 8 of the brochure.



Appendix 23. Page 9 of the brochure.

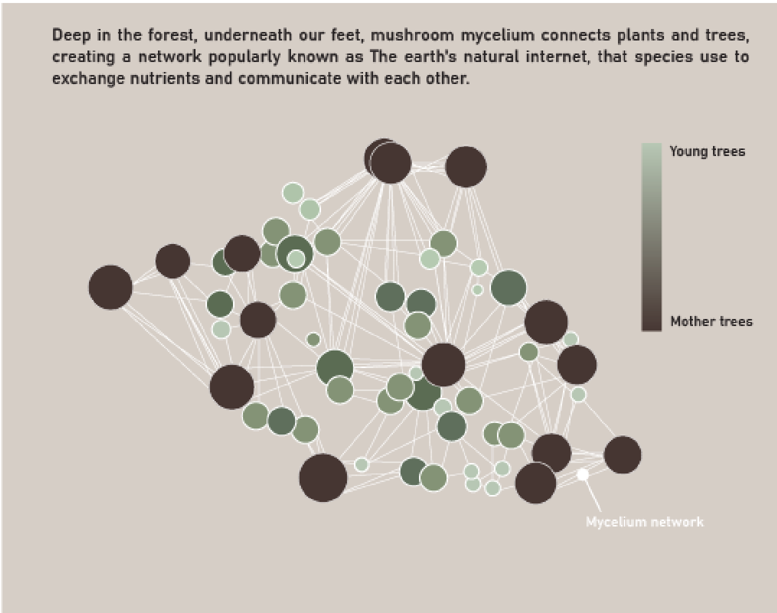
Appendix 24. Page 10 of the brochure.

Appendix 25. Page 11 of the brochure.

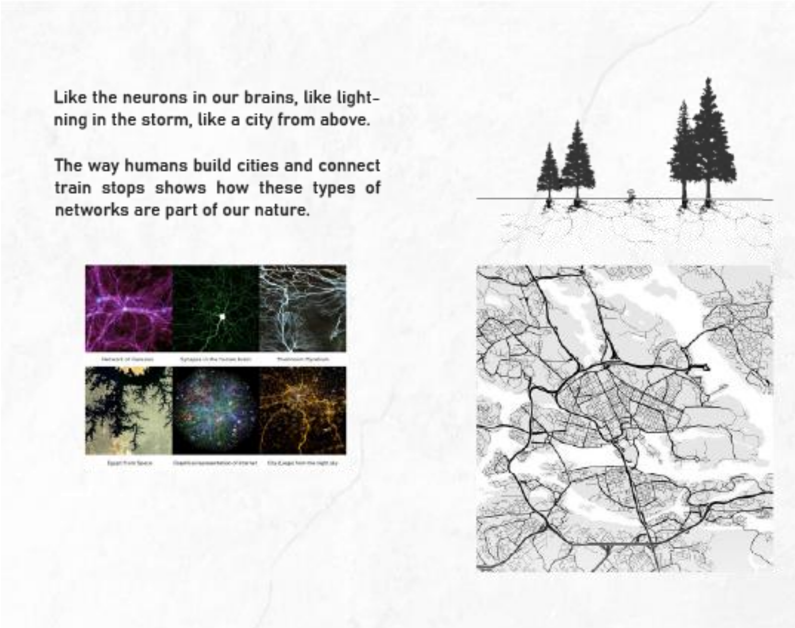


Appendix 26. Page 12 of the brochure.

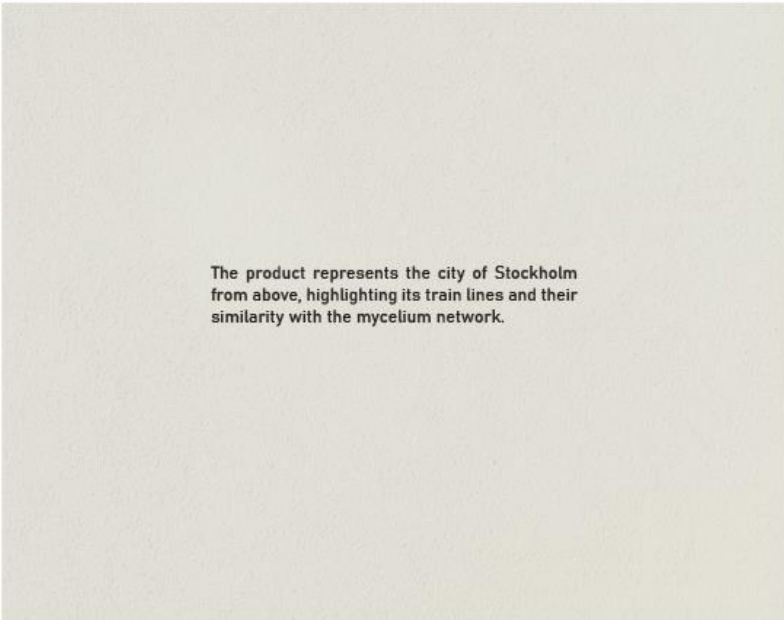
Appendix 27. Page 13 of the brochure.



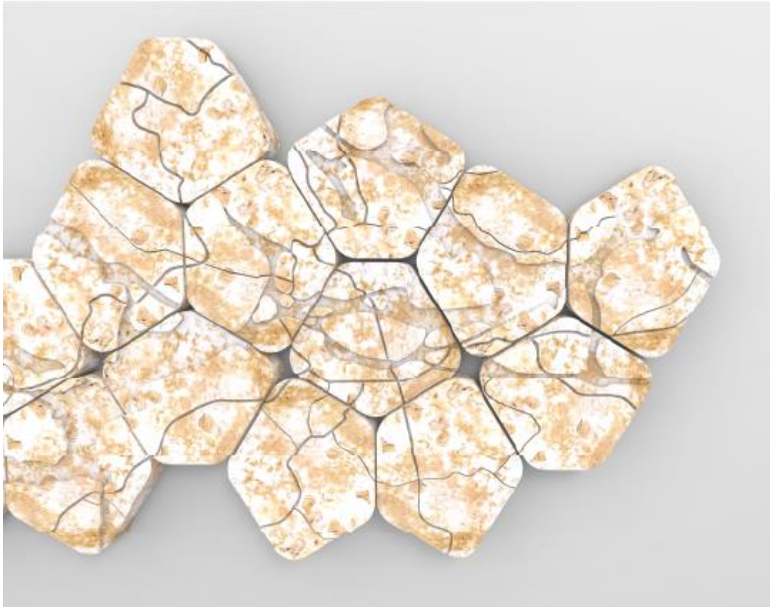
Appendix 28. Page 14 of the brochure.



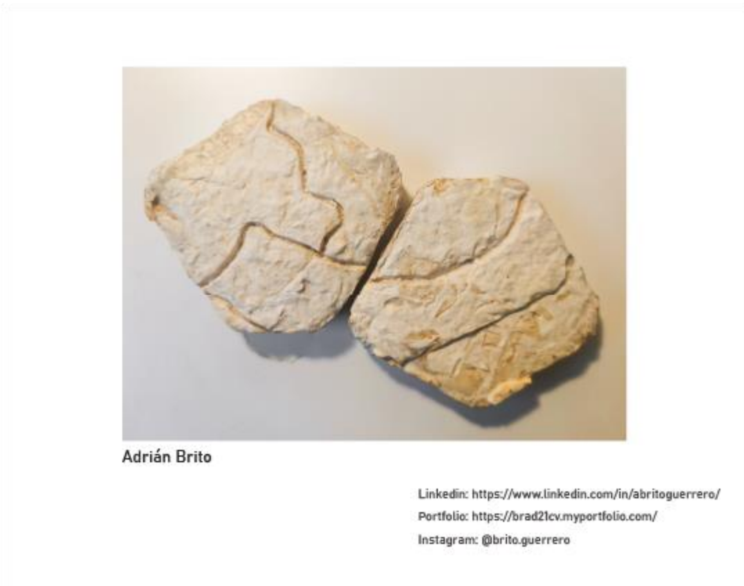
Appendix 29. Page 15 of the brochure.



Appendix 30. Page 16 of the brochure.

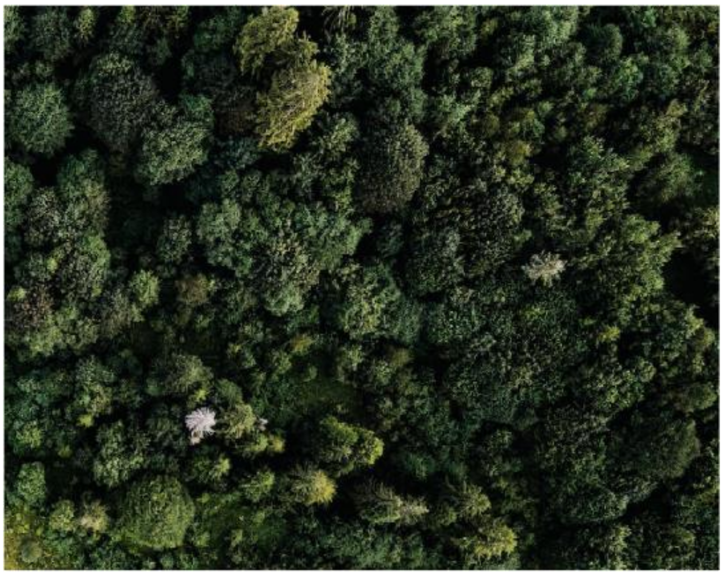


Appendix 31. Page 17 of the brochure.



Appendix 32. Page 18 of the brochure.

Appendix 33. Page 19 of the brochure.



Appendix 34. Page 20 of the brochure.