# MYCELIUM BASED BUILDING

An Industry oriented Exploration of the Sustainable Product Development and the Mechanical Testing of a Fungal Composite based Sandwich Panel

Marc Postel P5 Graduation Report January 2020

# COLOFON

P5 Graduation Report
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- natura artis magistra -

nature is the teacher of art and science
Artis Royal Zoo

# Preface

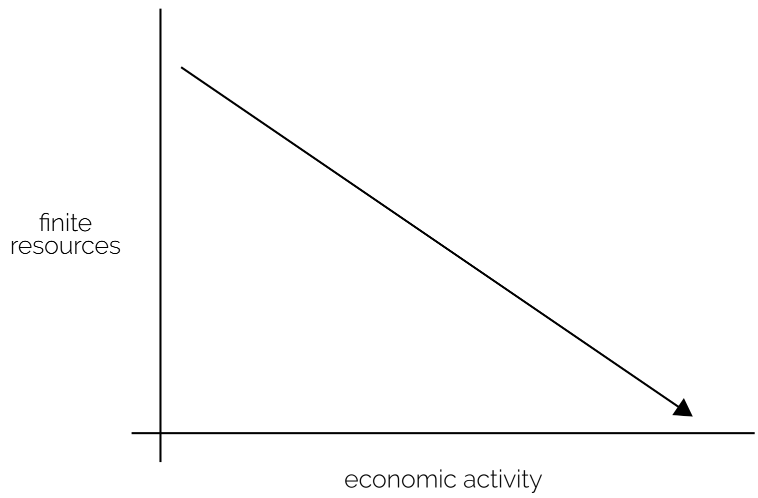
This project has been a journey. A long, to long journey. It has known many difficult moments on which stopping has, at least a few times come to mind. However, inspired by Steven Presfield's The War of Art the resistance was fought and overcome. It is now, finishing it, that most would expect the 'victory' is sweetest. Although the contrary certainly isn't the case, it is a rather neutral sensation. Still so close to it, the scars of the lessons that had to be learned are confronting. But there is also proudness for taking those steps and making that process. A first tendency would be to go back through the project and improve those details, sometimes rather large. The last few days have brought about the understanding that such actions lead nowhere and are the never-ending path of perfectionism. Forward is the way. And forward I shall go.

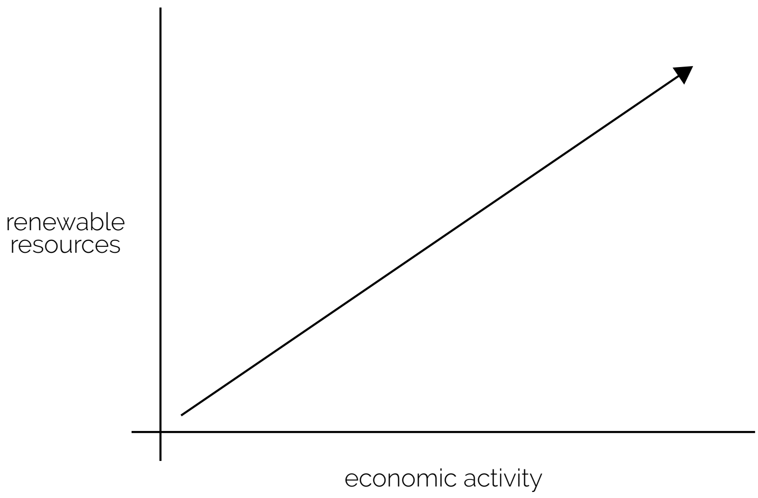
When talking about lessons learned it's important to note that they concern both study related (content) as human behaviour related (method) topics. The work and the machine. As shown in this project, product and process are closely linked. From a personal perspective there also doesn't seem to be a clear difference. Both can be done wrong and both must be learned through experience.

There is one example of such lesson which touches upon both aspects. That left a clear trace, especially in the beginning, of this report. And that lies at the very core of the perpetuate motivation behind this report. As a high school student in the 00's I had a strong interest in sustainability. Early on in my time at university I got interested in the idea of a Circular Economy, before the term was popularised. And from the beginning of my masters I grew a strong believe in the power of nature-based circularity. In my mind it all seemed pretty straight forward, undisputable logic. But writing it down or debating it with others felt like walking against a wall. It can be extremely frustrating, even embittering to not get the proper grasp that is needed to explain and convince on something that is important to you.

So, let me now present the simplest argument for nature-based circularity I can currently give. As you probably expect by now this regards the two graphs to the right. If you peeked and get it, awesome, point made. If not, let me explain:

Most materials currently used are finite. Through economic activity we consume these materials. When things break or become redundant most are near impossible to reuse or recycle. Natural materials are renewable and can be made indefinitely. Economic activity that harvest nature respectfully would make materials abundant. Interested? Please read this report.


finite
resources
economic activity


renewable
resources
economic activity

# Summary

The objective of this project was to illustrate the value of nature-based circularity by illustrating its potential in creating composed and engineered circular products at large, and that of Mycelium-based sandwich panels as perfect embodiment of such product in specific. To effectively explore the feasibility of these panels as a natural and circular alternative, an industry-oriented product development approach was used. Therefore, this research focussed on parameters thought to be crucial in generating interest from industry players. Within the limitation of the research these were the structural behaviour and scaled production of the product.

In an extensive analysis of this novel material both general characteristics as exact properties of Mycelium-Based Composites (MBCs) were explored. This project succeeded in getting a 'feel' for it and has applied that deeper understanding in tackling the further steps in the research.

A potentially promising industry niche was found in the distribution centre construction sector and its dynamics were studied. It was found that this niche sector is extremely sustainability-savvy, accounting for a total share of 16% of all BREEAM certification issued in 2018. While at the same time being responsible for 16% of the nation rigid foam insulation demand. This large quantity simply applied fossil-fuel derived foam was identified as ideal low bearing, 'positive impact', fruit. Through interviews with industry experts and an industry analysis several quantitative and qualitative boundary conditions was collected that formed a foundation for the remaining research.

It was decided to perform a number of 4-point bend test, exploring the fungal sandwich panel's potential to serve as roof plate. Both lose MBC as sandwich panel samples were tested. Based on the data provide by the experiments could be concluded both the properties of the material and the product are currently insufficient for the envisioned application. However, the found result were of an order of magnitude interring enough for further research. The MBC is approximately two to three times weaker than traditional foams. Although, the sandwich samples showed ten times better behaviour its full potential was far from realised. Weak adhesion of the individual components and the following premature delamination were identified as the main cause for this underperformance.

Further development is needed on a material, product and application level to achieve applicability, suggestions of potential fruitful development directions have been made. The order of magnitude of the results is however of such comparable quantity that, especially less demanding, employments of the product can on a short-term be accomplished. It is therefore interesting to see that this research has shown how the production process of mycelium-based sandwich panels could look like. By converting button mushroom facilities, a batch-based production system could be put into place with a scale adequate for the demands from the distribution centre construction industry. Twelve of the envisioned facilities could produce all insulation material for the complete sector.

In this explorative project it has been shown that this nature-based technology holds potential. Sandwich panels can be made with a certain quality and quantity. But although current product performance is not sufficient for the studied application other widespread uses can be foreseen. So, although further research is certainly needed in the development of composed mycelium-based circular products it can be concluded that based on qualitative and quantitative benchmarks these products can and likely will serve as a sustainable and circular alternative to traditional, oil-based, rigid insulation products.

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# 1

# Project Description

## 1.1 Introduction

The term sustainability has been around for quite some time. Although the direct meaning of the word hasn't changed, over the recent years its charge very much has. New and deepened insights in the extensiveness and magnitude of the impact of humanity's actions on the environment have triggered a growing awareness of the need of a comprehensive, global and almost totalitarian form of sustainability. One of the most significant frontiers of this new notion of sustainability is the Circular Economy (CE). A concept that aims to radically change our current unsustainable economic and consumption paradigm. Although being a multi-facetted solution laying importance on business model, market and technical innovation it lies a large responsibility in the realm of design.

A drastically new way of designing is needed to incorporate the idea of endless repeatability of production and consumption, a system in which waste doesn't exist and merely serves as a resource for a new production and consumption cycle. Thereby tackling the problems of finite material resources and the environmental impact of material extraction, processing and waste treatment.

The role that the building industry could play in this transformation is considerable. The sector has, with a 32% share in global energy consumption, 19% share of energy related GHG emissions and 33,5% share in waste produced in the EU, a large environmental impact (Lucon et al., 2014; Eurostat, 2016). Besides a more than significant drop of these percentages the implementation of Circular Economy principles in the design and construction of buildings could have various other positive effects. By improving the upgradability of buildings, they could evolve with the times preventing issues ranging from structural vacancy to sick building syndrome.

The implementation of the circular economy concept in construction industry increases the complexity of the exertion (Geldermans & Jacobson, 2015). Buildings are complex assembles of many different components and materials. This makes the design and construction of circular buildings at this moment a near impossible task. The necessity of incorporating these CE principles in the design process is illustrated by the extreme difficulty demolition companies have with retrieving usable materials from their sites. Materials have been combined and connected in the most durable or cheapest, often irreversible way. This drastically lowers the recyclability and thus most materials are burned or landfilled; wasted.

Preventing this irreversibility is essential in implementing circular economy. Understandably, this has been the aim of industry initiatives implementing circular economy and has resulted in a strategy called 'Design for Disassembly'. Fundamentally different ways of designing and building are investigated to make structures that can be fully taken apart. Although a very useful development it is currently perceived as the only and a complete solution, while it is neither. It assumes that the retrieved materials can be recycled, while the recyclability of building materials is very low (Tam, 2011). Even in the recycling of aluminium 20% virgin material is needed to ensure quality (Huurdeman, 2017; Allwood & Cullen, 2015).

Additionally, this demand for disassembly further increases the precision and complexity of building components. Requiring car industry like assembly and disassembly lines, preferably completely digitalised and robotic. The thus high-tech building elements can surely be very interesting in high quantity for larger buildings but won't form an industry wide solution. Buildings aren't generally as demanding as cars. Although perceived as complex, a building, besides its material complexity, is just a bulky object that remains static for several decades. From that functional perspective, taking their uncircular nature into account, most buildings in number and most building layers in volume don't really deserve these high-tech materials.

The Design for Disassembly strategy puts the retrievability of valuable technical cycle materials central. Whereas a strategy of simplification focussing on the use of less valuable but fully recyclable materials with a lower environmental impact would be based on the use of materials from the natural cycle of Circular Economy. Their full degradability (natural recycling) and lower value would suit many not so demanding buildings very well. Such a Bio-Based approach would require 100% pureness of the materials used, so no hybrids between technical and natural materials (referred to by C2C as monstrous hybrids). And would require strict separation of the inevitable technical materials such as electrical wiring, sinks, etc.

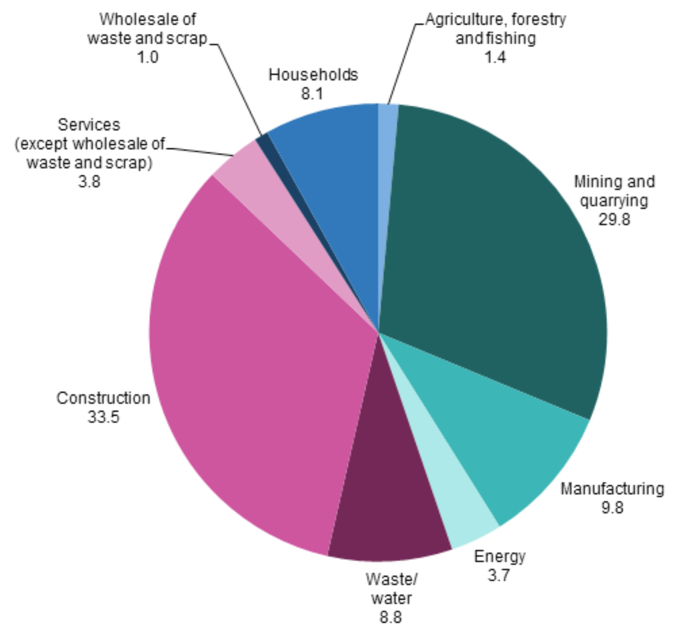



***Image 1.01:*** *Waste produced in the E.U. per activity (EuroStat)*

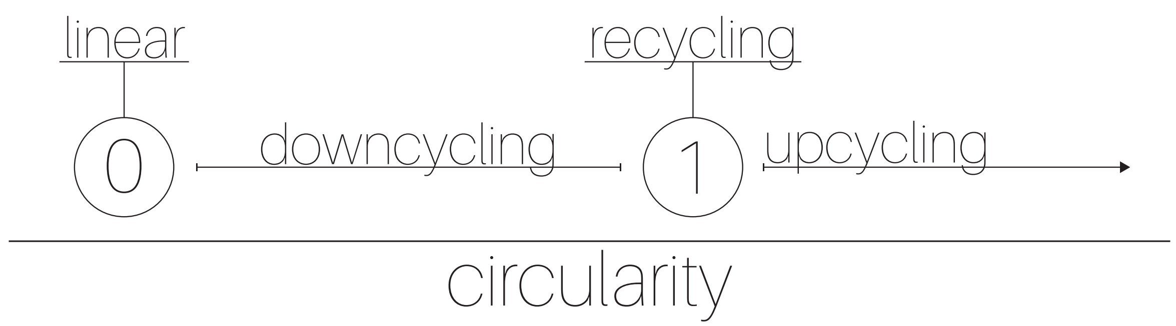



***Image 1.02:*** *Circularity beyond recycling: upcycling*

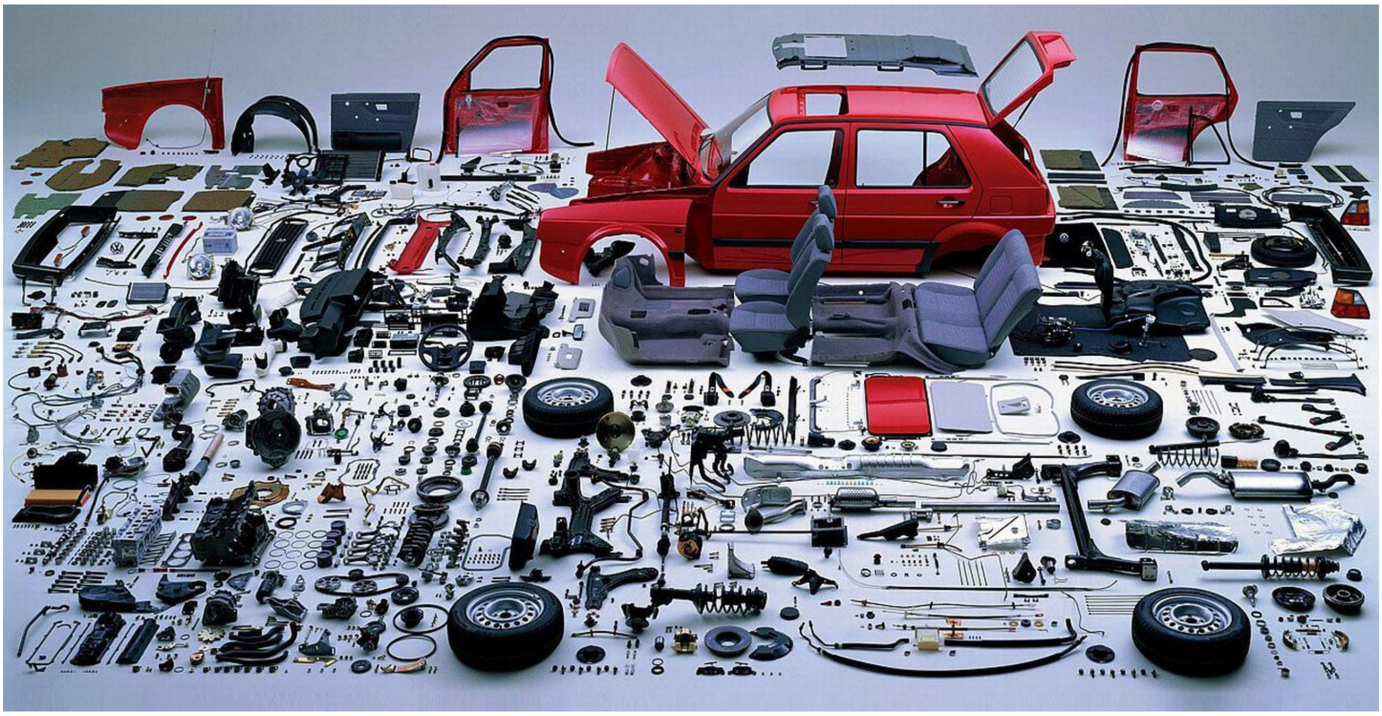


***Image 1.03:*** *The complexity of design for disassembly*

New materials and construction methods are needed to let such a fully natural building meet the contemporary requirements. A big advantage of natural materials is that their full recyclability enables them to be applied combined. Whereas technical materials must be kept strictly pure and separated. Applying materials together for their best possible performance is one of the principles on which modern buildings base their quality. One of the big challenges will be to find natural connection methods and materials that can replace technical ones such as adhesives and screws.

Potentially fungal mycelium could translate this role. This growing network of fungal threads feeds on natural fibres. Together the fungi and fibres form a composite material with interesting characteristics. Its insulating capacities are relatively well known, and its structural potential have been explored. The capacity of fungi to act as a binding agent are however overlooked. If this characteristic of the material is better understood it could form the capstone to both its structural as insulating capacities. And maybe allowing the material to be a commercial success. It is for that reason that this report will investigate this capacity of mycelium to bind to see if the material can translate a significant role in the realisation of contemporary bio-based buildings.

## 1.2 Problem Statement

The development of mycelium-based composites has gotten plenty of media attention over the past years. Especially their potential for applications in buildings has been underlined (Archdaily, 2013; 2018; Dezeen, 2014). Based on the size of the construction industry, the positive impact of successfully implementing such technologies and materials could be tremendous. Unfortunately, despite various ventures pushing their innovation, very little mycelium products have made it onto the market. None, when you take competitive pricing into account.

The success of these endeavours is determined by a wide range of parameters. However, in this case there seems to be an obvious common denominator, a lack of building industry partners. Or in other words, a market pull. The building industry is considered to be very conservative. High investment cost makes the industry risk-averse and thus not keen on experimenting. A lack of enthusiasm or scepticism for a 'revolutionary new technology of growing material' is therefore to be expected. This while stakeholder involvement has been shown to be an important success factor in innovation (Achterkamp etal., 2006)

This doesn't mean that change is unthinkable. A good example of the contrary is the introduction of FRP's (Fibre Reinforced Polymers) not that long ago. Where demands for freeform and lightweight products forced a market entry. Of course, at that point production had been proven in other industries, such as ship-building. But it illustrates that the building industry is open for innovation if a market demand is combined with enough substantiation for a specific product or method.

Interestingly the building industry is currently faced with a challenge of a much larger magnitude than in the example above. As mentioned in the introduction of this chapter, laws and legislation, corporate responsibility and financial incentives are driving it towards a circular economy (RVO, 2018; Rijksoverheid, 2016; MacArthur, 2013). And thus, there is a need for innovative solutions incorporating the principles of a circular economy, such as mycelium-based composites.

In other words, the challenge now in accelerating the application of mycelium composites is to understand with what kind of substantiation industry players can be convinced, and to establish it. Various industry associations and experts underline this complete or partial absence of convincing evidence of innovations, "Regularly, 'innovations' are presented in the media which turn out to be hot air, inflated for media attention." (Van de Groep, 2018). They specifically point at a lack of proof surrounding technical performance and scalability (Barbosa et al., 2017). Understandable, since compliance and supply chain issues are mayor risks and cost factors in building operations (Clavero, 2018).

It can't be neglected that the field of mycelium innovation is working on building the needed support. In the scientific realm more and more papers on the subject are being published (***table 1.02***). And a recent product launch of an acoustic panel was qualitative and quantitively well supported (Mogu, 2019). On the other hand, little of the work touches upon the consequences of the research and the proposed

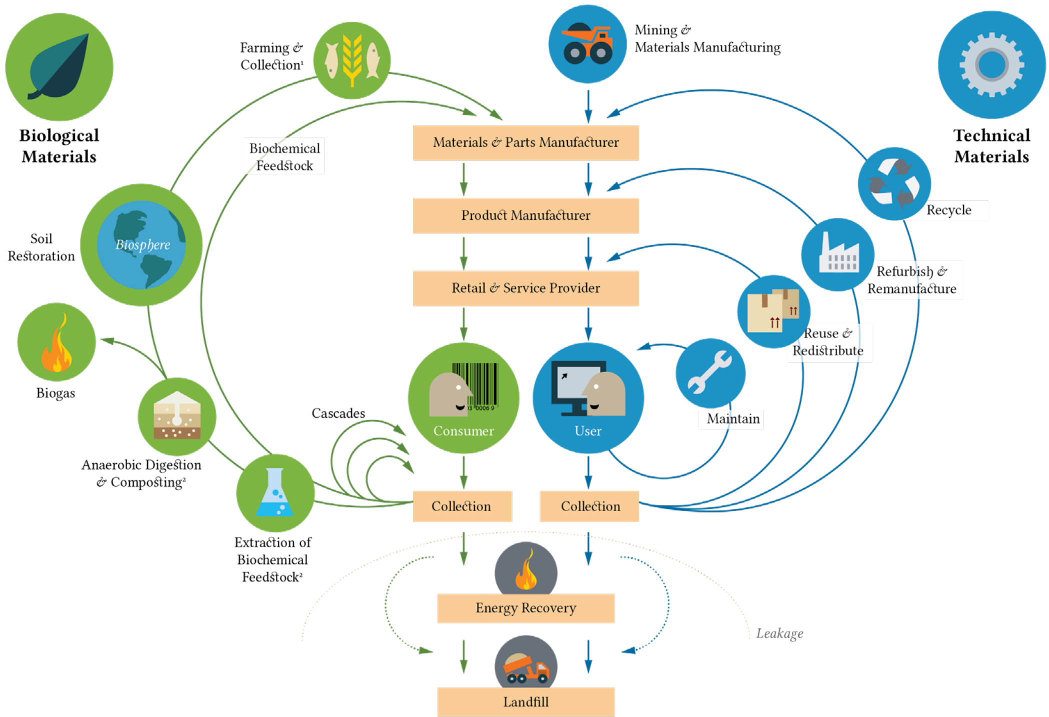



***Image 1.04**: The principle dynamics of Circular Economy - The Allen MacArthur Foundation*

| Building product | Density (kg/m$^3$) | Thermal conductivity (W/mK) | Primary energy demand (MJ–Eq/kg) | Global Warming Potential (kg $CO_2$–Eq/kg) | Water demand (l/kg) |
|---|---|---|---|---|---|
| EPS foam slab | 30 | 0.0375 | 105.486 | 7.336 | 192.729 |
| Rock wool | 60 | 0.04 | 26.393 | 1.511 | 32.384 |
| Polyurethane rigid foam | 30 | 0.032 | 103.782 | 6.788 | 350.982 |
| Cork slab | 150 | 0.049 | 51.517 | 0.807 | 30.337 |
| Cellulose fibre | 50 | 0.04 | 10.487 | 1.831 | 20.789 |
| Wood wool | 180 | 0.07 | 20.267 | 0.124 | 2.763 |

***Table 1.01**: Life cycle assesment of thermal insulation materials*

2009
packaging

2014
temporary structure

2019
temporary structure

***Image 1.05**: A decade of innovation the field of fungal materials* solutions on a larger, production, scale. One of the main scientific contributors in the field underlines this: “More research into the manufacturing is needed to determine the setup and running costs and resources use of the material, and the environmental impacts” (Travaglini et al., 2014). Also, the recent downscaling of the operations at the only semi-industrial mycelium production plant (making mycelium packaging) illustrates that a lot of work still has to be done (Timesunion, 2017).

To conclude, the main problem identified in this project is that a lack of convincing data until now has left the building industry uninterested or hesitant in partaking in endeavours developing mycelium composites. In particular more information is needed about the technical performance and production of the materials. Embracement by industry parties is needed to both accelerate the development of the technology as unlock its full potential for positive sustainable impact. Therefore, in the next chapter will be explored what kind of strategy for tackling this problem would be ideal and suits this project.

## 1.3 Research Objective

As stated earlier, this project aims to contribute to the acceleration of the application of mycelium composites as building materials. It was identified that convincing the building industry is key in this objective. And that the industry is looking for innovations that are well substantiated by performance and production data. Interestingly the performance of a material and the way they are produced are very correlated (Sygut et al., 2012). Surprisingly, no research into mycelium composites until now has explored the consequences of this connection on an industrial production scale. Seeing that this so-called ‘knowledge gab’ lies parallel with the identified problem statement and objective, this project will focus on researching exactly that.

A material producing technology isn’t the same as product. The way a product is produced influences its performance. When investigating the industrial production of mycelium composites, it is necessary to know what is being made. This to understand the scale and challenges in the production process on the one hand. And to have a clue about the desired technical performance on the other, since, requirements vary based on application.

Additionally, finding the right application for the technology is essential in ensuring it will find its way to the market. Mycelium materials have generally been praised for their potential versatile applicability. However, none have found their way into the building industry in a usable manner. The widely proposed mycelium bricks for instance (Ross, 2013; The Living, 2014), have more to do with the general image people have of construction, also know as Lego, than the industry’s actual methods.

This while the applicability of a product could be another pillar on which the industry could be convinced. The idea being that a product with a wider applicability has a larger market potential and therefore will be able to generate more interest. A product meeting market demands and simultaneously solving an industry pain by using mycelium composites to their full capacity, could have a snowball effect on the development of mycelium materials. Bringing the materials better known insulating and structural and lesser known binding capacities together in a product that benefits from the materials circular and sustainable character could be key in breaking open the road towards wider application in the construction industry.

Considering these various aspects and imagining them in coming together in a widely used product type has led to the choice of investigating the development and producibility of mycelium-based sandwich panels. They are composed and engineered products by default and their feasibility has been demonstrated in an earlier test (*image 1.06*). Their composed nature perfectly illustrates the power of a nature-based circularity strategy in which multiple natural materials can be used fused together. Jiang (2014) Acknowledges the potential of mycelium bio composite laminates based on their inherently low energy processes with environmentally benign end-of-life options. Simultaneously their potential to be engineered and broad application, both within and outside the building industry, make them interesting for industry players.

As mentioned earlier, the goal of this project is to illustrate the performance and scalability of such sandwich panels, to convince market parties. The ideal way of doing that is to extensively test the product in accordance to the applicable standards, such as EN- and ISO-standards. This would be a

| Year | Papers Published |
|---|---|
| 2012 | 1 |
| 2013 | 1 |
| 2014 | 2 |
| 2015 | 2 |
| 2016 | 3 |
| 2017 | 6 |
| 2018 | 5 |
| 2019 | 3 |

***Table 1.02:*** *Number of papers published on fungal materials as of 01-09-2019*

***Image 1.06:*** *Fungal sandwich panel, proof of concept*

***Image 1.07:*** *Heijmans-One, a construction sector innovations*

time and cost intensive undertaking, especially when product performance has to be optimised through iterations. The production of the required samples would require a small-scale but well-equipped production facility, to produce at the right quality and quantity. Together with the design of large-scale factory such pilot-plant location would also be part of the ideal proof demonstrating the feasibility and scalability of the production process.

Luckily and unfortunately, the gathering of such 'burden of proof' doesn't fall within the possibilities of this graduation project. To still make a start it has been decided to focus this project on the exploration of the possibility of producing mycelium sandwich panels. The scope of the project will be restricted to the most crucial aspect of product performance, the structural behaviour of such panels, and to the interaction relations between product and production development.

## 1.4 Research Question

The extensive substantiation of the Research Objective is a sign of the comprehensive 'industry-oriented product development approach' used in this research. In 1.6 Methodology this approach will be further explained. In this chapter the Research Objective needs to be boiled down to its core in order to be turned into the research questions that will form the backbone of the research in this report. The main takeaways of 1.3 are therefore briefly stated below.

Based on these objects a main research question and several sub research questions were formulated which can be found below. The main research question underlines the explorative nature of the research and articulates the intended multi-faceted methodology and focus points.

In order to guide the various aspects and directions of the research 5 questions were formulated. The number of questions is equal to the number of chapters of this report, minus this introductory chapter and the concluding chapter. Every sub question corresponds to one of the substantive chapters of this report. They have been formulated in a way that captures the essence of the objective of the research done in these chapters. In 1.5 Research Structure the sequences of these chapters based on the questions below will be explained.

## 1.5 Research Structure

The table of contents of this report gives a good overview of the various chapters and sections of this report. However, this is merely a numeration of its 'components' intended for reference. One cannot understand the functioning of a structure by solely naming its components. In addition, the sub research questions in the previous section of this chapter have given a first glance into the substantive structure of this report. Now, in this section, the full structure of the research and report will be described and illustrated. Also, the thoughts behind and effects of the structure of this report will be explained. How the nature of the researched has shaped its structure and how structure of the research has shaped the structure of the report.

*Image 1.08* is an illustration of the research structure and shows its various layers. The five phases out of which this report exist can be found at the top of the image. The coloured rectangles and circles signify the chapters of this reports, seven in total. Chapters containing research are recognised by the large coloured rectangles containing the chapters titles. The smaller circles signify 'report' chapters that are needed to present the research but don't contain the actual research themselves. They are the essential introductory and concluding chapters of a report and an additional intermediary chapter of which the function will be explained in a bit. These report chapters form the odd phases of the report structure (1, 3 & 5).

The even phases (2& 4) are dedicated to the research, and both exist out of two chapters. The first part of the research is called 'Analyses'. In a traditional research report this would probably have been called 'literature research'. However, in this project the scope of the analysis is broader than the current scientific frontier. This is a direct effect of the used 'industry-oriented product development approach'. Embedding the product development in an industry context requires an additional step; an analysis of the industry context. As a result, the first research phase exists out of two separate but parallel analyses.

## ***research objectives:***

*1. This research wants to illustrate the potential of nature-based circularity by illustrating its potential in creating composed and engineered circular products. Mycelium-based sandwich panels are a perfect example of such products.*

*2. In order to effectively explore the feasibility of mycelium-based sandwich panels as a natural and circular alternative an industry-oriented product development will be used. Not only will there be focussed on the most essential research steps, but all initial research steps will be prioritised in the form of a research plan.*

*3. Therefore, this research will focus on the most important parameters determining the success of this novel product group that are feasible to research in this report, being the structural behaviour and scaled production.*

## ***research* question:**

*Are Mycelium-based Sandwich Panels a Product Category worth Developing further as a Nature-Based Alternative for Traditional Sandwich Products, considering a Suitable Industry context, their Structural Behaviour and intended Production?*

## ***sub research questions:***

*Chapter 2.*
*What are Fungal Materials and Mycelium-based Composites, how do they work and what are  their properties?*

*Chapter 3.*
*Within which Industry-niche could Fungal Composite based Sandwich Panels best be Introduced and what are the current dynamics and demands from within that niche?*

*Chapter 4.*
*Based on the Analyses of the Novel Material and aimed Industry Niche, what Practical Research is Crucial in an Industry Oriented Explorative Product Development Research for Mycelium-based Sandwich Panels?*

*Chapter 5.*
*How well do Mycelium-based Sandwich Panels Perform under Bending Loads, how do they Compare to Other known Materials and Sandwich Products and do they form a Potential Alternative based on these results?*

*Chapter 6.*
*How would the Production Process of Mycelium-based Sandwich Panels be Scaled, Dimensioned and Designed considering the Quantitative and Qualitative Boundary Conditions?*

They analyse, respectfully, the fungal material innovations and the Dutch construction industry suitable for prefabricated sustainable, foamlike insulation materials.

An additional effect of the used method is the intermediary chapter (4). It forms a bridge between the first and second research phase. The chapter is a merger of the conclusions of the analyses and the introduction of the practical research. However, the chapter enables more than just a fluid transition. Frist of all, it is crucial in bringing the findings and knowledge gaps of the two analyses together. This enables, based on the Problem Statement and Research Objective, the formulation of a research plan. The level of cruciality of the various research topics and the possibilities of this project will shape the order of this plan. It will not just describe the practical research that will be part of this project but also for future research in to Mycelium-based Sandwich Panels. As this study is explorative feasibility study the final chapter (7), the conclusion of this report, can be seen as Go/No-Go moment for further research.

Although in this report the research is presented in a linear fashion, it wasn't conducted in such order. The black line in *Image 1.08* represents the course of the research. It shows the parallel course in the first research phase and a linear process in the second, practical, research phase. This linear sequence of the practical research is a result of the interaction of the two chapters (5&6). Results of chapter 5 are used as input in the subsequent chapter. This in contrary to the analyses, where independently of each other the two different subjects were investigated.

## 1.6 Research Methodology

**Methodology**

In the previous sections of this chapter it has become clear that this research project is multi-facetted. The analytical and practical research phase discussed in Research Structure (1.5) is a prominent example. It should therefore not be surprising that a variety of methods was used in the process of this project. All these methods will be discussed in the course of this section. Before going into these individual research techniques however the overall approach of this graduation project will be discussed.

The industry-oriented product development approach has already been named several times in the previous sections. This approach, which was used as an overall research strategy in this project, isn't a scientifically developed method. Its name was just invented as it best described the intended research direction. It does however show some similarities, in its focus on multiple disciplinaries, with scientific design strategies developed in the field of Industrial Design Engineering (IDE). An example of such method that was encountered in the course of this project is the Material Driven Design method developed at the IDE faculty in Delft (Blauwhoff, 2016; Karana et al., 2013). Although similar in some respects to IDE such methods are largely absent from the Building Technology masters.

In the case of this project the theme of sustainability formed an important motive for the use of an unusual approach. In the product development of a 'sustainable' or 'impact' product the notion of running out of time is hard to ignore, therefore effectiveness is of the essence. Interestingly it was found that, although completely based on alternative motives, the Lean Start-up Method, widely used by entrepreneurs, shares the same goal of effectiveness (Ries, 2011). This research has attempted to incorporate this notion of leanness or effectiveness comparable to the Lean Start-up Method in three separate ways.

The first is best expressed as 'failing fast'. Ideas can seem brilliant on paper but only by testing, their true potential can be demonstrated. By identifying the most crucial requirements and development steps and by testing them first is ensured that no time is wasted on an unfeasible product or version of a product. Within this report this concept expresses itself by the presence of chapter 4. Where a development plan is made, and the various research steps are prioritised based on their criticality.

A second way in which the industry-oriented product development approach incorporates the notion of effectiveness goes beyond the pure feasibility of the idea or product. In the case of sustainable product development, it doesn't only look at the potential impact of a solution but also at the scale in which it can be implemented. Sustainable products have until now often existed in the margins of the

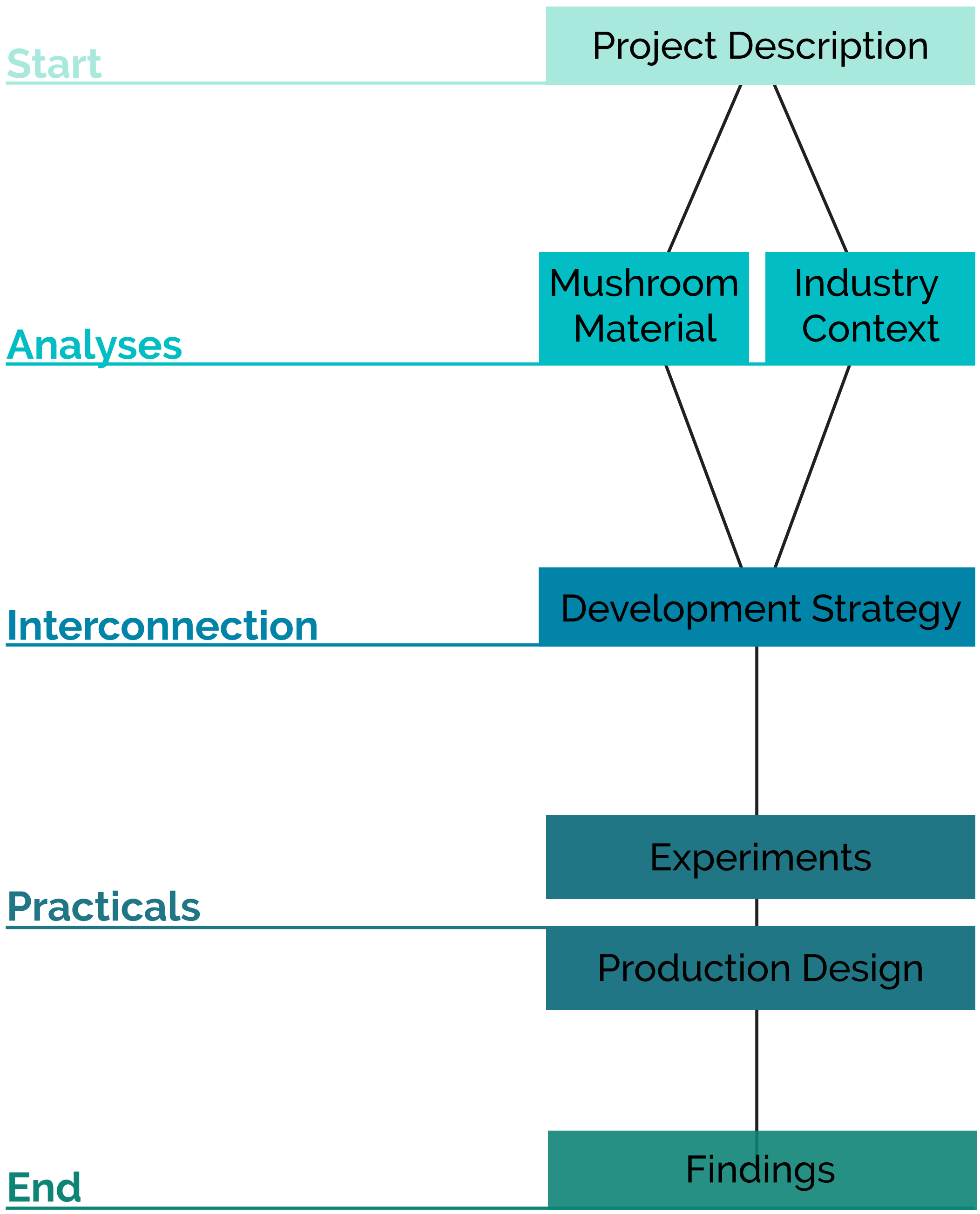



***Image 1.08:*** *Overview of research structure*

industry where their higher price or ineffectiveness is tolerated and compensated by ideology (Williams & Dair, 2007; Young, 2010). In order to tackle the looming catastrophe of climate change sustainability must become mainstream (Bregman, 2019; Van den Berg; 2019). Realising scale is therefore essential as it plays a crucial part in delivering the positive impact of a sustainable product, as explained by the formula to the right. In other words, scale is an effective tool for realising impact. The industry-oriented product development approach aims to increase the effectiveness of the process by incorporate the notion of scale from the beginning on.

The scalability of a potential new product is thus a vital parameter to be aware of in the development process. Which gives rise to the question of how this is done. As products are produced and procured, scale within an industry or product category is an equilibrium between supply and demand (Marshall, 2009). Both quantitative and qualitative parameters influence this balance. For instance, a super cheap, sustainable, easily produced construction material that is unsafe won't be made and used. While on the other hand, if, hypothetically, gold would be an ideal construction metal its limited availability (which dictates its price) would render it useless as there is just not enough material available for the scale of the application.

Within this project this coordinated collidine of qualitative and quantitative parameters from both the industry, application as the production side takes place and has been shaped as follows. During the analytical research phase two separate analyses are conducted. One aiming on building in an understanding of the novel material at hand (Chapter 2) and the other on understanding the industry context in which the to be developed product will be placed (Chapter 3). In both these analyses quantitate and qualitative parameters will be discussed. In chapter 4 the findings will be combined and aligned. In case qualitative parameters this will concern material properties and product requirements. While on a quantitate level, the production method and industry volumes are regarded.

The insights generated by this process of bringing together industry and material data will be used in the formation of a development strategy at the end of chapter 4. The second, practical, research phase will make start with executing this plan while the rest of it will be considered as future research. This brings us to the third and final aspect of effectiveness in this project, which could be called the Star Wars strategy. Again, scale plays an important role, this time in appealing and convincing industry players. Developing a building method is a timely and costly matter, for both scientific as corporate institutions. By investigating the scalability of product from the start on the projected impact is much more probable. This will very likely ease attracting new funds. This strategy is comparable to that of George Lucas. The director of Star Wars, who famously decided to shoot the second half of the saga first in order to make enough money to make the more special effect intensive first half of the movies (Kaminski, 2008).

Within the field of innovation, it is common to refer to great innovators and their innovations that changed the world. Popular examples are Henry Ford with the T-Ford and Steve Jobs with the Iphone. It is the impact of the innovation that appeals and its radicality that is celebrated. However, disruptive innovations are generally celebrated in retrospective, not in advance. The implementation of mycelium-based composites in the building industry, can be seen as a classic example of radical, or disruptive, innovation. But in an actor rich industry it is essential to get as many on board as possible in order to be affective. The 'Star Wars strategy' is intended to turn a seemingly radical innovation into a more incremental and therefore acceptable one.

**Research Methods**

As mentioned a wide variety of research methods was used throughout this project. The prime cause of this is the versatility and multidisciplinary nature of the project. These methods in relation to their corresponding chapter will now be discussed.

Chapter 2 is rather contemplative of nature. Besides building on an extensive literature research which can be found in *Appendix 2* the analysis it contains is mainly based on explorative research done at the start of this project. This intuitive process of scanning though books and googling has led to the understand of mycelium materials as presented in chapter 2.

potential impact **x** scale **=** realised impact

Similar to chapter 2, chapter 3 comprises out of an analysis. However, only the second part of the chapter has the same contemplative nature as chapter 2. The start of the third chapter focusses on limiting and defining the scope of the analysis. Surprisingly, the research that lies at the core of the chapter doesn't hold this dichotomy. For the complete chapter qualitative research methods were used (Groat & Wang, 2013). A combination of literature research and interviews with various industry experts was used (*Appendix 3.1 & 3.2*).

In chapter 4 the insights form the analyses of chapter 2&3 are brought together and formed into a research plan. According to Groat & Wang (2013) these methods are examples of correlational research and logical argumentation.

To the largest extend chapter 5 comprises of classical experimental research, in the form of mechanical tests. 4 point bending tests, to be more precise. The outcomes of these experiments are interpreted and compared to the data of other materials. This will allow the formation of a verdict on the suitability of the material for the envisioned application. Thereby the research in this chapter follows the design by research conception.

Chapter 6 is of a different nature and has more of an opposite approach. The quasi-experimental research methods of prototyping and design research will be used. These less exact methodologies are classic examples of the research by design conception.

## 1.7 Research Scope

Defining the scope of this project has been a process that was an integral part of the research. As with any research there were some rough specifics clear from the beginning onwards, as part of the problem statement and research objective. However, most converging decisions on the course of the work were done during the research. Because of this reason the substation of the research focus is given in the various chapters of this report. This section is therefore merely collection of the essential aspects of the research frame. References to the relevant chapters will be given.

**Mycelium Composites**
This project researches the application of fungal materials in the building industry. Chapter 2 will show that a wide range of materials types can be made using fungi. Not all of these materials are interesting form the perspe3ctive of construction but there are also additional reasons why not all of these materials where studied in the course of this project. It has been decided to solely focus Mycelium-based Composites (MBC's). As they are the most common, easy to make and most widely studied.

**Prefabricated Insulation Foams**
An important part of research is the industrial embedment of the product development process. In chapter 3 an analysis of the construction industry will be made to supply the needed insights for this process. This analysis will be limited to relevant sectors in which prefabricate insulation foams can be applied. The introduction of the third chapter gives an extensive consideration of the inevitable boundary conditions on this part of the research originating from the subject of mycelium materials.

**Distribution Centres**
In 3.1 an adequate market context for the development process is selected. Based on sustainability and construction methods used in various sectors the decision is made to study the Dutch sector of Distributing centre construction. As said, 3.1 is fully dedicated to the substantiation of the decision.

**Bending/ Flexural behaviour**
In chapter 5 mechanical strength experiments will be done. This order to get an understanding of the mechanical behaviour of Mycelium-based Composites. Ideally this done through a full study of the various mechanical characteristics such as tensile strength and compression strength. However, due to the limitations of the project it was decided to only do 4 points bending tests. In 5.1 the full substantiation of this decision is given.

***Image 1.09***: *MycoTree: a fungal composite development*

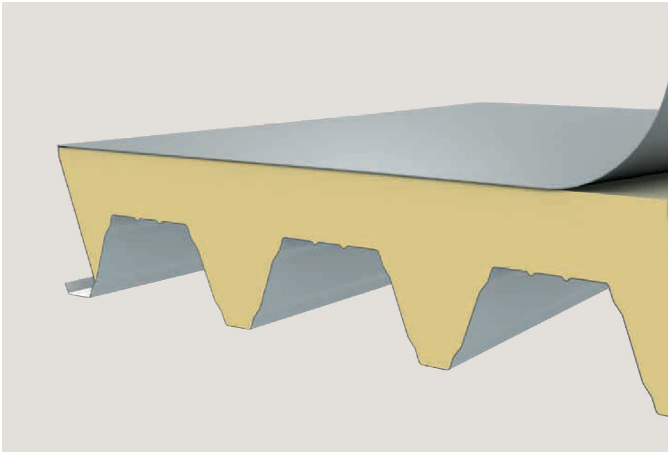


***Image 1.10:*** *Kingspan X-dek: prefab sandwich panel*

***Image 1.11:*** *Distribution centres: a typology on the rise*

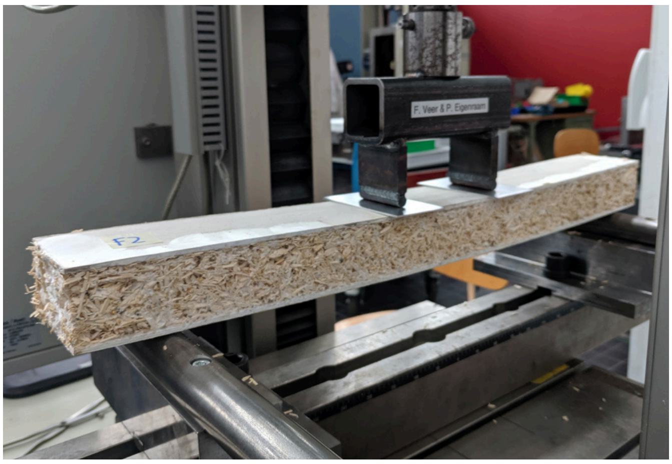


***Image 1.12:*** *4-point bend test*

# 2

# Mushroom Material

What are fungal materials? The scope of this simple question is in fact much broader than it looks from the onset. For one, the question presumes an established understanding of the word fungus. But in the simple form we think of, the raw material of a mushroom or the mould on your bread is not very interesting per se. This chapter therefore aims to deepen the reader's understanding of fungi, their lifecycle and key properties that enable us to transform them specifically into a building material. 2.1 provides a solid treatment of the fungi's ecological system.  2.2 then zooms in to a specific stage of the fungus -mycelium- to study the transformation to a form useful for building, while section 2.3 lays bare the material's (mycelium composites) key properties. Together, these first three sections thus provide the fundaments of mycelium as a material, upon which we subsequently draw in our treatment of fungi in a circular economy (2.5). The attentive reader will have noticed the omission of section 2.4, which reveals some of the secrets to producing mycelium materials. You will get it for free. Lastly 2.6 revisits the key properties of mycelium composites as presented in section 2.3, taking the subject to a deeper technical level and the state of the art.

## 2.1 An introduction into Fungi

Most people have strong first associations with the word fungi. Maybe the think of edible mushrooms or maybe about moulded bread. Despite the recognisability of these first examples the knowledge of fungi commonly doesn't stretch much further. Which is remarkable because fungi play a significant role in most ecosystems (Lumen Learning). And according to renowned mycologist Paul Stamets can turn out to play a vital role in humanity's quest for a sustainable future (Stamets, 2008). Before going into depth about the wondrous world of fungi however the lack of general knowledge of the topic compels this chapter to start with an explanatory introduction into fungi.

Mycology, the study of fungi, is branch of microbiology. Although fungi can grow rather big they all exist out of strains of single cells, called a hypha. These strains grow, split and merge forming a structure of hyphae, called mycelium (*Image 2.01*). Mushrooms are the fruiting bodies of certain type of fungi and grow from the mycelium. A popular term for mycelium is mushroom roots, although calling a mushroom 'the fruit of mycelium' would be a better matching comparison.

Fungi can be found in every environment on Earth but due to their small size are often inconspicuous. Together with bacteria they are the major decomposers in most ecosystems, playing a central role in biochemical life and nutrient cycles (Gadd, 2007). A characteristic which will be elaborated upon in chapter 2.4. Against common believe fungi stand much closer to animals than to plants. As can be seen in the Venn diagram of *image 2.03*, showing natures kingdoms. For example, both animals and fungi converting oxygen into carbon dioxide and generally feed of carbohydrate-based molecules.

The kingdom of fungi is complex and vast, it comprises of moulds, yeasts and mushroom species. Currently around 120,000 species of fungi have taxonomically been described but it is estimated that between 2,2 and 3,7 million species exist (Mueller & Schmit, 2006; Hawksworth & Lücking, 2017). This research will leave moulds and yeasts for what they are and focus on mushroom species since they tend to grow larger, stronger and more coherent structures. Because the English language holds rather overlapping meanings for the word mushroom (the word can be used to describe a specific group of fungi, the fruiting body of this type of fungi and the most common edible mushroom, also button mushroom or champignon) it is important to state that the word mushroom from here on in this report will merely be used to describe the fruiting body of a fungus.

Although hybrid forms exist there are roughly 3 types of fungi to distinguish (Stamets, 2005). The characteristic on which this division is based is the relationship the fungus has with its environment. Saprophitic fungi are pure-bred decomposers, they only live of dead material. Parasitic fungi life of living organisms and slowly kill their host. *Image 2.05* is a striking example of such fungus. The third group exists out of fungi that live in a symbiotic relationship with other organisms. An example of this are Mycorrhizal fungi that acts as an intermediate between plant roots and the soil, truffles and chanterelles both are part of this branch of fungi (*Image 2.06)*.

Fungi also play a far more import role in the evolvement of Earth into the green blue planet we know today. They were the first organisms to come to land 1,3 billion years ago, beating plant with a several hundred million years. They prepared the soil for the plants to start living on, a role they still hold today. In this symbiotic relation with plants above ground and fungi beneath it are fungi that enabled the green cover of our planet. It is in that same role that a fungus became the largest organism in the world. A 2000-year-old mycelium structure in the state of Oregon, United States, which lives in symbiosis with the local primary forest covers roughly 2200 square acres (***Images 2.07 & 2.08***)(Stamets, 2005). Equalling the biggest ever human-made structure, the Fresh Kills Landfill in New York state (John & Mitchinson, 2006), before its reclamation in 2008.

The world of fungi is wondrous and presumably holds many more secrets. Within the field of mycology researchers work to unravel these mysteries. These newly developed insights have over the past decades led to big breakthroughs and hold the potential for many more uses. The relatively high resemblance of fungi and animals make them very interesting form the perspective of medicine. Fungi have given us antibiotics, but research also shows high potency against a variety of viral diseases and even cancer types (Stamets, 2005). Paul Stamets, who became famous with his TED-talk '6 ways fungi

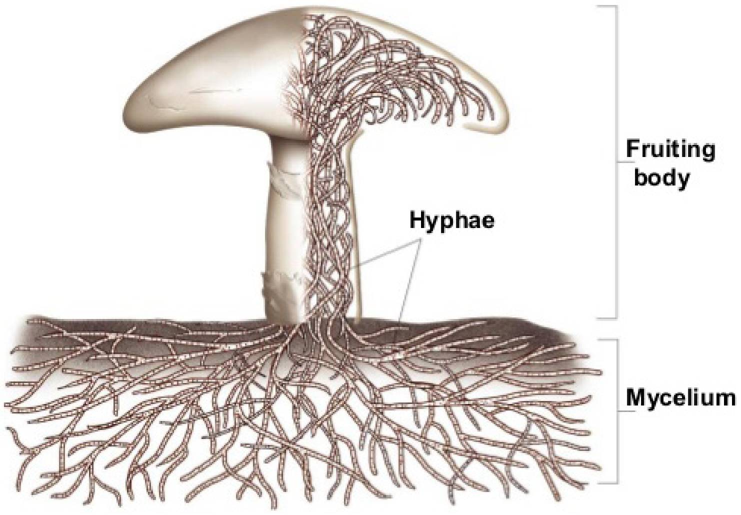



***Image 2.01:*** *The structure of a mushroom fungus*

***Image 2.02:*** *Growing hyphea, a web of mycelium*

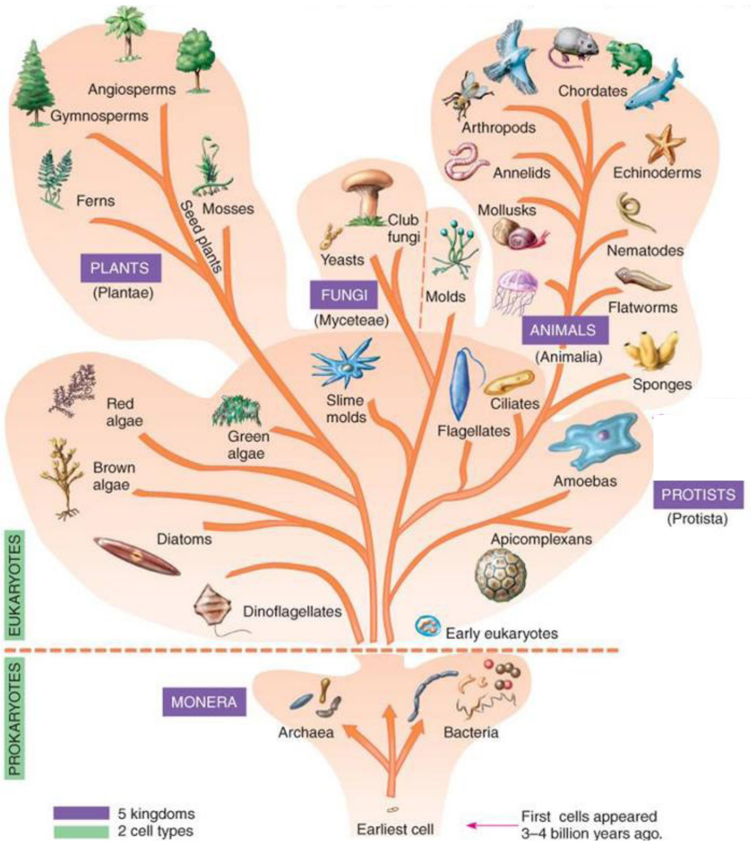



***Image 2.03:*** *The five kingdoms of biological life*

***Image 2.04A:*** *Made with fungi: beer*

***Image 2.04B:*** *Made with fungi: wine*

***Image 2.04C:*** *Made with fungi: blue cheese*

***Image 2.04D:*** *Made with fungi: bread*

***Image 2.04E:*** *Made with fungi: antibiotics*

can help save the world' describes how strategies based on the use of fungi could help overcome a number of global challenges. 1) Revitalising soil enabling quick and large-scale reforestation. 2) Decomposing toxic chemicals for remediation. Using fungal mycelium as a filtration system for drink water. 3) Using fungi to produce so called mycopesticides, making chemical products redundant and enabling sustainable crop production. 4) Using mushrooms as a protein source, fed on organic waste and with a much lower environmental impact than animal-based protein as meat and dairy.

Interestingly, in the last decade and a half a new domain came into existence that Stamets did not foresee at the time, the use of fungi in materials. Based on the knowledge of this chapter in the coming chapter a closer look will be taken into the technology and materials. Additionally, fungi decomposing characteristics and their role in nature will act as input in chapter 2.4 Fungi in a Circular Economy.

## 2.2 Mycelium as a material

Fungi based materials nowadays exists in various appearances, which can be viewed in *Appendix 1,* study of precedents. Most of these materials are the result of recent developments. The insight that mycelium can be used in the formation of materials has only been popular for little over a decade. However, the form in which mycelium materials were first introduced and are still most commonly applied have been used by humans for centuries. This is, and was, in de form of a composite material. Although it was not regarded as such, mycelium-based composites (MBC's) are very common in mushroom production (***Image 2.09***) and probably the best example: Tempeh (***Image 2.10***).

This composite material is formed when a fungus grows on organic particles and the fungal threads, hyphae, (discussed in the previous chapter) bind them together. The long, branching filamentous hyphal structures grow throughout the material and form a large fibre-like network (Bulawa, 1993). The base of organic particles is called the 'substrate' and in the case of tempeh it is formed by soy beans. However, a wide range of natural substances are suitable to act as a substrate.

When in the pursuit of a rigid composite material it is best to use a substrate rich of complex hydrocarbon compounds, such as cellulose, hemicellulose and lignin. These three natural compounds are often found together in nature and form the hard, fibrous parts of plants. Their extensive molecular structure makes them full of energy available for the fungus metabolism but too complex and therefore less attractive for other, simpler microorganisms. In a mycelium composite they fulfil the role that glass and carbon fibres have in traditional composites.

As mentioned in 2.1, an incredibly large amount of fungal species exists. However only a specific group of fungi can decay these rigid, wood like particles into usable materials. These so-called 'white rot fungi' mainly feed on the lignin in the substrate. Leaving the cellulose, which is the main source of strength in these materials. This opposite to 'Brow rot fungi' which specifically break down the cellulose resulting in the pulverisation of the substrate. Brown rot fungi are not unfamiliar to the building industry as they are the main cause of wood rot in for instance wooden window frames.

To the people researching the use of fungi in rigid materials the white rot fungi are of interest. This group is not defined based on any evolutionary classification but is comparable to the terms carnivore and herbivore used for animals. There are thousands of known white rot fungi species, and presumable even more unknown. Most fungi used in the production of mushrooms are white rot fungi. As a result, extensive scientific and practical literature on their grow conditions and production exists. An aspect that turned out to be of great use in the research done for the chapters 2.6 and 6.

All kinds of plants depend on rigid fibrous parts for their stability. An obvious example is wood, which depending on the type exists out of 40 to 50 percent cellulose. Allowing trees to be the sturdy giants they are. But there are many more plants with rigid parts that are widely available. For instance, the straw of all kinds of grains, the haulm of different grasses like reed and elephants' grass but also hemp and even tomato stems.

All are rich on the combination of as cellulose, hemicellulose and lignin. But all have varying ratios of them influencing their characteristics. Not only the origin of the material but also its form and processing are of influence. For example, saw dust and wood shavings from the same wood type have a very


***Image 2.05:** A parasitic fungus killing its host*


***Image 2.06:** Forests, a symbiose between plants and fungi*


***Image 2.07:** The largest living organism from the sky*


***Image 2.08:** The largest living organism on the ground*


***Image 2.09:** Mushroom substrate, the original MBC*


***Image 2.10:** Tempeh, an edible fungal composite*


***Image 2.11:** A white rot fungus*


***Image 2.12:** A brown rot fungus*

different morphology. An aspect of MBC's that will be touched upon on veracious instances in this report.

Just as in non-natural composites, as glass and carbon fibre reinforced polymers, the natural particles in these fungal composites influence its characteristics. Seeing that there are many different sorts of fibrous bio-mass, in different morphologies available globally that can even be mixed in all kinds of ratios. It is imaginable that there is wide variety of substrates resulting in a composite material with a broad range of characteristics.

On top of that comes the influence of the matrix of the material, in this case the fungus. Just as with traditional composites, FRP's (Fibre Reinforces Polymers), the selection of the matrix is used to alter the characteristics of the final material. Besides the high number of suitable fungi varieties, mycelium-based composites have another property that distinguishes them from FRP's, their growth. Growth parameters influence the cellular structure of the growing fungus resulting in varying properties (Haneef, etal., 2017). The parameters of most significance are the feedstock, or in other words the substrate selection, and the temperature, PH- and moisture level of the mixture. In chapter 2.4 will be explained how these parameters are controlled and in the next chapter, 2.3, their global influence on the characteristics of the final material will be explained.

## 2.3 The Characteristics of Mycelium-based Composites

Despite all the tweakable parameters most mycelium materials have similar appearances and characteristics. This probably has to do with the basic from of Mycelium Based Composites in which they have been introduced. This is the most common and easiest way to make fungal materials. It is probably for that reason that the characteristics of these MBC's have formed the base of many imaginative, futuristic projections of its potential applications. When taking a little closer look at these material properties it is not incomprehensible that these 'visions of the future' often look at the building industry. That closer look will be the focus of this chapter. In subchapter 2.6 the precise technical properties of MBC's will be discussed. While the lesser known, other forms of mycelium materials can be viewed in *Appendix 1*, study of precedents.

The common properties of the MBC's have given them the nickname 'nature's styrofoam'. From a marketing point of view the benefits of this sustainable branding as a renewable form of one of the most problematic materials in the transition towards a waste free society is obvious. Jones (2017) shows that this nickname could be questioned when comparing the exact properties of the two material groups. Although not direct copies, the comparison of styrofoam and MBC's makes sense on the level of characteristics, they overlap on at least five.

**Weight - strength ratio**

The first is the molecular composition of mycelium. Mycelium transforms the glucose it derives from the substrate into chitin, a polymer which is also occurs in the rigid parts of lobsters, shrimps and various insects. Since polymer and plastic are synonyms, chitin is a kind of bioplastic. Styromfoam is nothing more than a foamed-up plastic.

This airiness translates into three other characteristics. The relatively high strength/weight ratio, low thermal conductivity and high acoustic absorption of the material. Therefore, all are the result of the cellular organization of MBC's, causing this airiness (*Image 2.15*). The one cell thick hyphae split and interconnect, forming a complex three-dimensional web which mainly encloses cavities. A cubic centimetre of mycelium contains the equivalent of one kilometre of hyphae strings (Cambell et al., 2017). The organisation of the pattern of this web is the result of the laws of nature and corresponds with so called 'string theory'. The theory is also used to describe the astrophysical phenomenon of dark matter and the internet. And some say it's an archetypical pattern of complex efficiency (Stamets, 2005). Certain however is that it resembles other grown natural structures such a sponges and bone structure (*Images 2.16 & 2.17*).

One of the consequences of this open, porous structure is that most of the volume of the material exists out of air, making it very light. Together with the strength of chitin in the fungal cells the mycelium's

***Image 2.13:*** *Straw kept together by mycelium*

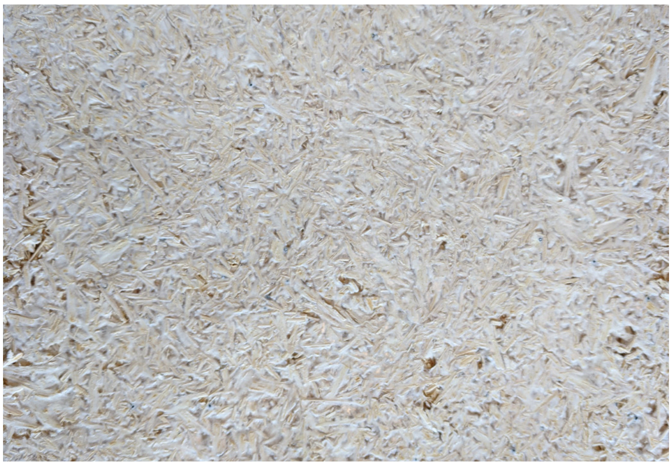


***Image 2.14:*** *MBC: fibres + fungus*

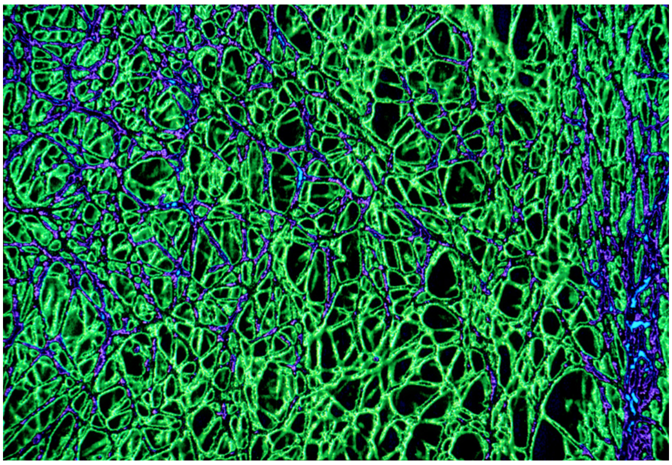


***Image 2.15:*** *The material organisation of mycelium*

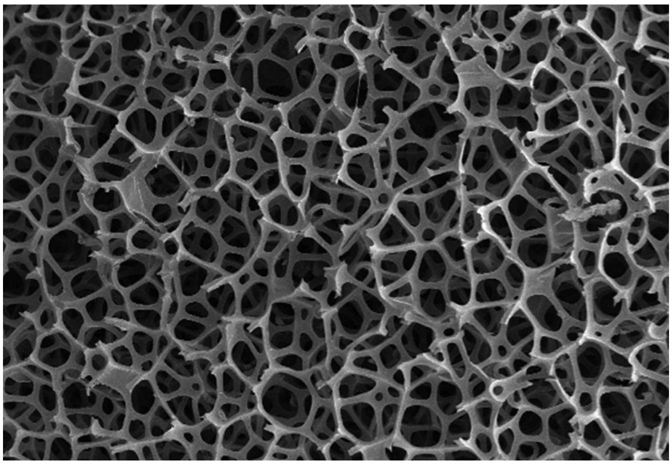


***Image 2.16:*** *The material organisation of sponge*

***Image 2.17:*** *The material organisation of bone*

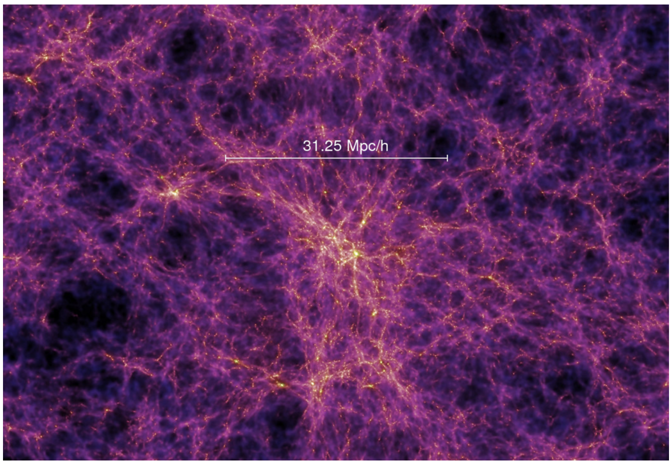



***Image 2.18:*** *Natural complexity: dark matter*

three-dimensional structure ensures optimal distribution of loads. Giving the material a relatively high strength/weight ratio. As will be shown in chapter 2.6 and 5, MCB's are capable of carrying 20 to 30 times its own weight in bending.

**Acoustic absorption**
As said, another effect of this porosity on a micro level seems to give the material a good acoustic absorption performance. Soundwaves hitting the materials surface will get trapped in the microscopic cavities if the mycelium's structure. Growth speed and time, surface quality and substrate selection will determine its overall and specific performance in the various frequencies.

**Thermal insultaion**
A correlative relation between acoustic absorption and thermal insulating capacity has been shown (Srivastava, 2006). The surface bound cavities responsible for the MCB's good acoustic performance are spread throughout the material. According to Travaglini (2015) "The cellular structure of mycology materials make them an attractive option for insulation applications". The mycelium's structure incapsulates air just as insulating foams giving it a low thermal conductivity. Opposed to most synthetic foams, which have closed air bubbles, the mycelium's structure is open. Probably because of the microscopic size of these openings thermal conductivity is better than other 'open' materials. When for instance compared to straw insulating performance is up to 50 percent better.

**Fire resistance**
A characteristic that not necessarily fits the description of 'natures styrofoam' but holds a lot of potential is the fire resistance of the material. In contrast to most natural materials and most insulating materials, mycelium-based composites have a flame extinguishing property. The main substance out of which fungal cells exist, is a complex protein-based polymer named Chitin. The combustion of chitin requires a higher energy input that it yields thus actively slowing down a fire. The chitin derived substance of chitosan is even used in the development of a flame retardant of natural resources (Hu, et al., 2013).

All substrate particles in the composite are covered with chitin-based fungal threads. Not only do they prevent the substrate from burning completely, the fungus also feeds on the substances that easily burn. Instead, when mycelium-based composites are brought into contact with fire they char. ***Images* *2.19 & 2.20*** show a test sample after approximately one minute of exposure to a torch. This layer of char formed by the fire seems similar to a Japanese technique of wood preservation called Shou Sugi Ban (***Images 2.21 & 2.22***). This technique also has a known fire-retardant effect. The easily ignitable substance on the surface have been burned away leaving a compound substance with higher ignition temperatures. Without the easier burnable substance this temperature isn't naturally met.  How this affects the fire behaviour and classification of composites with different fungi and substrates will be discussed in chapter 2.6.

**Freeform**
The last characteristic comparable with that of Styrofoam is the result of the way the material is formed, growth. Of course, plastics and foams are not grown but the growth of MCB's allows for free-from applications and moulding techniques comparable to plastics. There are indeed also aspects of production by growth that don't necessarily resample plastics or Styrofoam. Obvious examples are the lower uniformity and predictability of the material and the considerably longer production time on which more in 2.4.

The growth of material and products of that material is rather unexplored phenomenon to the building sciences. It gives a new dimension to the act of building. One that is remotely comparable with forms additive manufacturing. Of course, grown materials, such as wood, have been widely used. However, never has it been possible to actively influence material properties through growth conditions. Mycelium materials are not the only novel, emerging natural material in which that is the case. In recent a new field of engineering has emerged focussing on this, bioneering. One of the places where this concept is studied in full width is the MIT Media Lab. A prominent example of their work in this field is an architectural object that was created by manipulating silkworms to weave a designed pattern (***Images 2.23 & 2.24***).

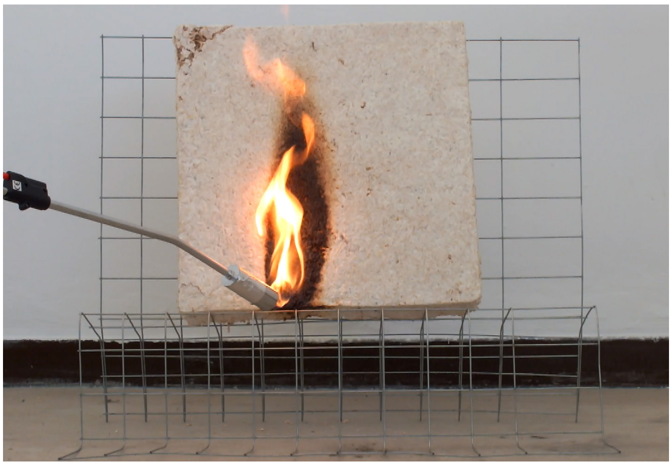



***Image 2.19 & 20*** *DIY fire tests with mycelium-based composites*


***Image 2.21 & 2.22:*** *Shou Sugi Ban: char as a perservent and fire retardant*


***Image 2.23 & 2.24:*** *Silkworm pavilion - MIT Media Lab*

The characteristic of growth comes from the use a living organism in production. Another characteristic that is based that biotechnologic idea of manipulating nature the renewability and biodegradability of MBC's. From the perspective of circular economy, the realisation that nature doesn't know waste is very interesting and will be discussed in depth in 2.5. However, from a material and engineering perspective these givens have profound implications as well. Very much opposite to plastic the danger of degradation during the life span of the material always lures. Preventing and steering this process of natural recycling will be essential in the successful introduction of mycelium materials. For traditional materials accelerated aging tests exists to mimic impact of the elements over time. Parameters as UV, moisture and temperature will also be important in the longevity of MBC's but additional parameters should be considered. When product equals food the decomposition and degradation of products by common (micro)organisms has to be understood. It is likely that additional tests are needed to ensure sufficient quality. Maybe lessons can be learned on this terrain from the food industry which deal with problems by default. Ultimately trail and error will provide all the needed experience. It is questionable if that is ideal due to needed time.

## 2.4 Making Mycelium Composites

The process of making mycelium composites can look very different depending on scale, product and substrate material. There are various ways to approach some of the essential steps in the process. Depending on available facilities, budget and patience an option can be preferable or not. Fundamentally however the principles behind the process stay the same. In this chapter the focus will lie on understanding those principles. They will be discussed based on a small but professional production facility because most GIYers (grow it yourselvers) skip some important steps due to a lack of equipment. To start with the overall process will be discussed after which the separate steps and their options will be treated independently.

Although making mycelium-based composites may seem difficult or complex it is rather simple when broken down into basic phases and steps. Actually, it is rather comparable with baking a cake or bread. The unfamiliarity or difficulty may lay in unavailability of some of the needed machinery and ingredients in a standard kitchen or local grocery store. Due to the duration of the process some may compare it to beer brewing. Which, despite the liquid state, is also accurate since it too consists of a fermentation process.

**The overall process**
The general process of making mycelium-based composites can be broken down into three overall phases. The preparation, growth and finishing phase. In the preparation phase the goal is to condition the substrate. This is done by mixing all the ingredients, defeating all microorganisms in it, and finally adding the fungus of choice. When the substrate has been brought into the perfect condition for growth, the growth phase can start. This consists out of two septs. The goal of the first is to obtain a potent mixture of substrate and growth by allowing the fungus to spread throughout the substrate. In the second step of the growth phase the formation of the material takes place. When the quality of the fungal growth is right it is important that growth is stopped. At this moment the last phase starts. The fungus must be killed, and the present moisture has to be removed from the, by then, MBC. When these steps are done the, inert, material is finished. Often additional steps are made in the production process to turn the material into a product. These widely differ on the product that is being and won't be discussed in this chapter. In chapter 6 one of the main focusses will be the relation between production process and product.

**Working sterile**
Before going into the separate steps of the process it is important to elaborate on one fundamental aspect of growing fungi, working sterile. At the core of the production process lies the growth of the fungus. The conditions are created to provide optimal growth. These conditions are not only optimal for the fungus of choice but also other microorganisms, like bacteria and other fungi. If the selected fungus gets competition of another microorganism this results in a sort of microbiological warfare, harming or even cancelling its growth. An example of a substrate in which such a situation is occurring can be seen in *image 2.23*.

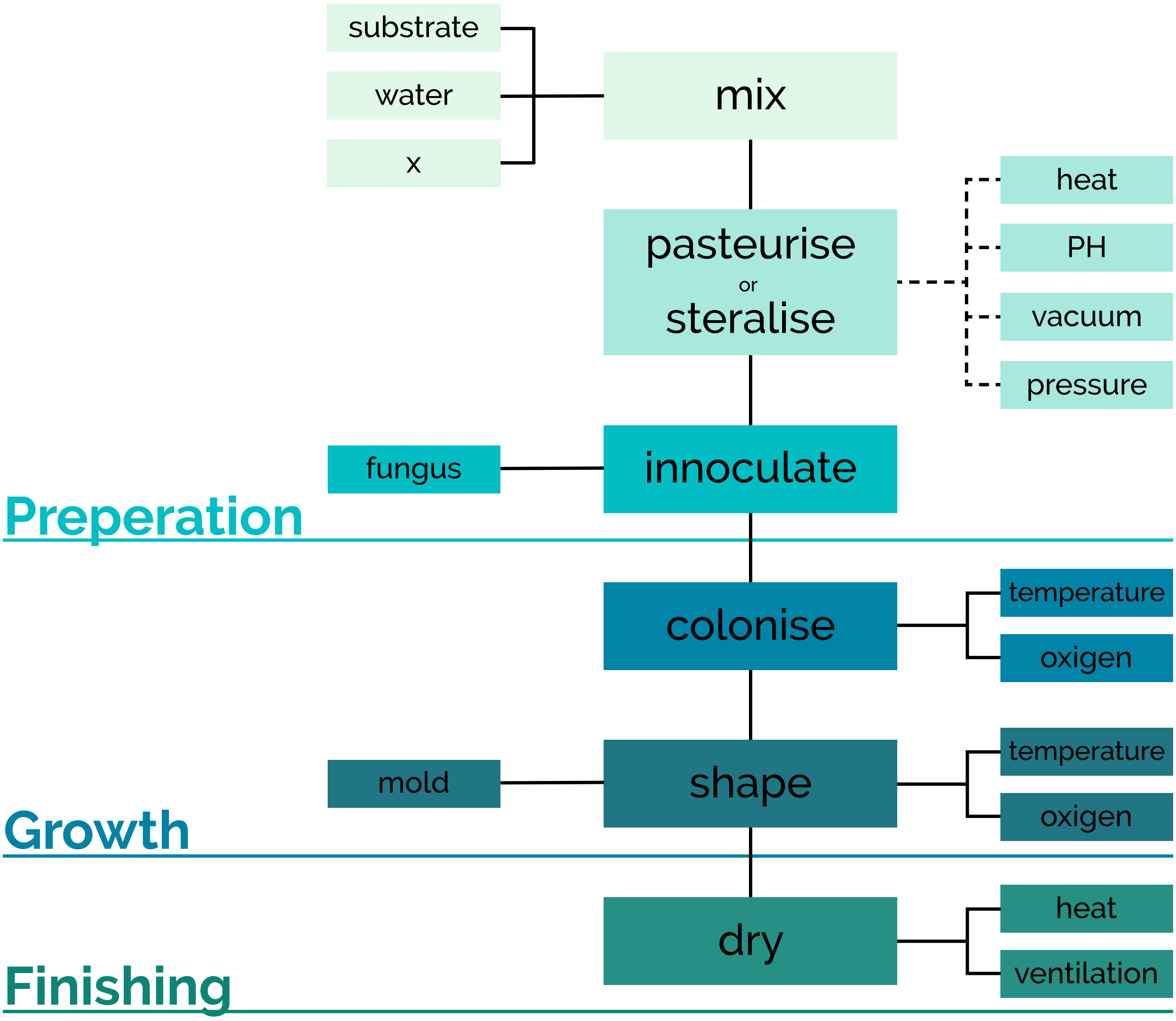



***Image 2.25*** *Overview of the MBC production process*

***Image 2.23 & 2.24****: Contaminated & healthy substrate*

To obtain and preserve sterility in the production process a number of measures need to be taken throughout the production steps. The miniscule size of microorganisms makes them impossible to observe with the naked eye. Therefore, all measures achieving sterility are totalitarian in their nature. Never specific observed microorganisms are killed, rather actions are taken to kill all potentially present microorganisms. Often there are various ways in which this can be done, depending on the scale and available equipment. Although different, these measures generally are based on one of two principles, killing the microorganism or keeping them out. The killing of microorganisms can be done through three general methods. First of all, by applying heat. After 15 minutes at 121 degrees a substance or object is considered sterile. Secondly chemical sterilisation can be used. The cells of the microorganism are broken down, generally with 70% alcohol solution or hydrogen peroxide. Third and last radiation sterilisation can be used. This is mainly done with UV-C or radioactive radiation.

These steps are equipment intensive and damaging for the fungus. For that reason, it is often preferable to keep contamination out after sterility is realised. Since the fungus is depended on oxygen for its growth it is not possible to use hermetically closed volumes to grow the material. According to Travaglini (2014) "Aeration has proven the most common source of infection with competing species, despite the need for free exchange needed for growth". For this purpose, but also to create sterile workspaces, filtration is used. By using very fine filters, with openings of only a few microns even the tiniest microorganisms can get through. Microporous filters are used in growing bags or other growing volumes, examples of which can be seen on ***images 2.23, 2.24 & 2.29***. For ventilation purpose HEPA level 14 filters are used and by creating a constant overpressure in a space infiltration through cracks and crevices are prevented. Such a space is called a cleanroom and used in hospitals and the production fine electronics as computer chips (***image 2.26)***.

**0. Preparations**

An important step that not necessarily is part of the production process but does have a large impact on the properties of the final material is the pre-processing of the substrate. Especially when working with waste stream an additional initial step can be required. Sometimes it is required to separate every from green, non-fibrous parts of plants to plastic out of the substrate. But mostly (extra) shredding is needed. As mentioned in 2.2 the morphology of the substrate can have a large impact of its performance. Mechanically treating the substrate before the growth process can be beneficial.

**1. Mixing**

The start of the production process starts with mixing the substrate with water. For most white rot fungi, a quantity of 60% to 70% water is ideal (Travaglini et al., 2013; Appels et al., 2018). This is the content in weight of the overall mixture, effectively 150% of the dry weight of the substrate is added in water. In general, the added water will take some time to be absorbed by the dry substrate. By intermittingly mixing over a period up to an hour is assured that all moisture is absorbed and evenly mixed. Concrete mixers are ideal for this job.

If various substrate sources are used it is also important that these are adequately mixed at this step to ensure homogeneity of growth later in the process. Sometimes additional substances are added during this step. Although not strictly necessary additives such as ph.-controllers can be used to optimise growth conditions in the substrate.

**2. Pasteurisation or Sterilisation**

In this step of the process the sterility of the substrate realised. As mentioned, there are several techniques to achieve that. In practice, heat-based methods are used in most cases (Stamets, 1993). Common alternative method exists where chemicals such as dehydrated lime, bleach or hydrogen peroxide are used but due to its large environmental impact it won't be discussed further (Stamets, 1993).

From the perspective of contamination heat sterilising is optimal because all microorganisms are killed. This is done in a pressure cooker or autoclave. A pressurised compartment is needed to reach the required minimal temperature of 121'C. This requirement complicates the scaling of this method. Large pressurised volumes can be dangerous and quality equipment is therefor expensive. Heat sterilisation as method is mainly found in laboratory environments where items are small, and execution needs to

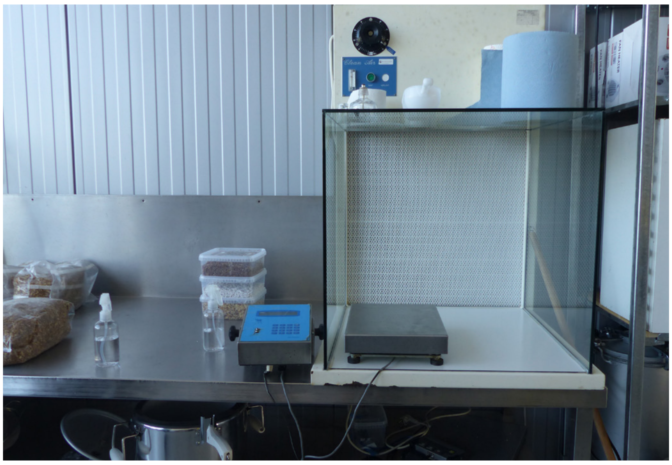


***Image 2.25:*** *Small scale: laminar Flow Hoof (LAF)*

***Image 2.26:*** *Industrial: clean room*

***Image 2.27:*** *Small scale: mixing the substrate*


***Image 2.28:*** *Industrial: mixing the substrate*

***Image 2.29:*** *Small scale: filling the bags by hand*

***Image 2.30:*** *Industrial: filling the bags mechanically*

be perfect.

In medium to large scale mushroom productions sterilisation is deemed too expensive, complicated and rigorous. Subsequently they use the less comprehensive method of heat pasteurisation. By exposing the substrate to temperatures ranging between 70 and 100 degrees Celsius for a number of hours the potency of present micro-organisms is lowered to a level from which contamination isn't likely (Fellows, 2017). In practice water is used as a medium to transfer the heat. This can be in the form of steam in a steam pasteuriser (***image 2.31***) or in the form of water in a hot water bath (***image 2.33***)(Oei, 2016).

From the pasteurisation (or sterilisation) step onward it is essential to maintain sterility. This is done by placing the substrate in a closed environment. This can be entire growing halls (Oei, 2016) but in practice often special plastic bags are used (***image 2.24***). In both case special filters will be placed to provide enough oxygen. In the case of the 'growth bags' the substrate is often already transferred to them at the end of the mixing step. This way the 'cleanness' of the substrate is guaranteed when the bags leave the pasteurisation device, which improves their ease of handling.

**3. Inoculation**

When the substrate has been stripped of any unwanted microorganisms it is time to add the selected fungus. The act of adding the fungus to the growth medium, the substrate, is called inoculation. Adding it any earlier in the process would mean that it would also be exposed to the pasteurisation or sterilisation process. Even exposing the fungus to temperatures lower than 70'C can be harmful. It is therefore important to wait with the inoculation until the substrate has cooled down properly.

There are three important aspects that need to be considered in the inoculation phase. Besides the always crucial contamination risk also the medium on which the fungus is transferred, called spawn and the distribution of this inoculum through the substrate are important.

When the substrate is in closed bags as is custom for small and medium operations. Adding the fungus means opening the bags and causing a contamination risk. There are two methods to limit this risk to the bare minimum. The first is the use of workbench equipped with a laminar flow hood (***image 2.25 & 2.35***). Here overpressure and filtered air are used to keep out any unwanted microorganisms. Another method requires special bags and a liquid spawn. The fungus, grown on a liquid, is injected through a sterile needle and a self-closing rubber patch in the bag. Generally, the first method is used because solid, grain, spawn is much more widely available and more stable than liquid spawns. From the perspectives of substrate homogeneity (not adding a grain kernel) and distribution liquid spawns are superior. Now inoculated substrates are often tossed and shuffled extensively to distribute the grain.

People that are slightly familiar with the process of fungal growth might expect the use of spores in the production of MBC's. Spores have a crucial role in the fungal life cycle as they are the seeds or eggs of the fungus. In the case of MBC production, a spore is to limited in size and strength to act as an inoculum. Instead, the ideal inoculation spawn is made by cultivating a spore. First on a Petri dish, afterwards in a nutritious liquid and finally grain kernel, like millet. With every step the mycelium gains in volume and strength, preparing it for the inoculation moment. This process is an art in itself and spawn therefore is often purchased from spawn cultivators (Mycelia, 2019).

**4. Colonisation**

The purpose of the colonisations phase is getting a fully overgrown, vivid, substrate. A potent, quick growing mixture will lead to fast and high-quality results in the formation phase. It is important that any other microorganisms, still present in the substrate, are overcome. Especially in the case of a pasteurised substrate this is important. By evenly distributing the fungus during the inoculation phase it can spread quickly through the substrate. Another way to speed up this process is by bringing the substrate to the ideal growing temperature of the fungus. For most white rot fungi these lie between 10 and 35 degrees Celsius (Travaglini et al., 2014). Depending on the fungus, substrate and temperature the colonisation phase takes 5 to 10 days (***Appendix 2***).

**5. Formation**

The formation step is the 'moment supreme' of growing mycelium-based composites. The actual

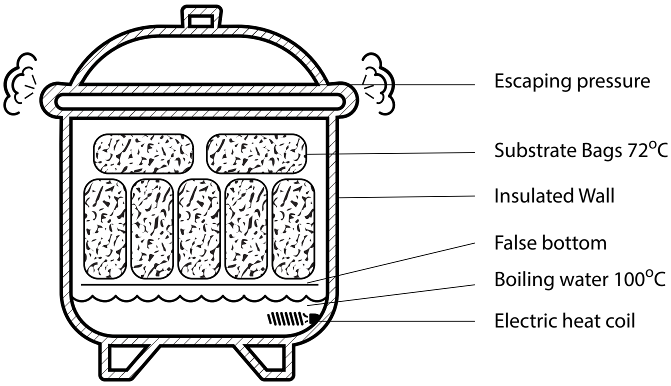



***Image 2.31:*** *Small scale: steam pastheuriser*

***Image 2.32:*** *Industrial: steriliser entrance*

***Image 2.33:*** *Small scale: hot water bath / Weckpan*

***Image 2.34:*** *Industrial: steriliser exit*

***Image 2.35:*** *Small scale: innoculation*

***Image 2.36:*** *Industrial: innoculation*

material or product is formed. But despite all the preparations and measures, things can still go wrong. During this phase the colonised material is taken from its growth environment into the mould that will determines its final shape. Because of the number of handlings involved and its labour intensity this step generally has the highest danger of contamination.

After colonisation the substrate is displaying first signs of rigidity. In order to get it in the right shape it needs to be loosened up. This is generally done by beating and hustling the bags in which the substrate has been growing. When the substrate is loosened up it can be placed into the mould. This has to be done in a sterile environment and the mould needs to be properly sterilised as well. Just as the bags in which substrate grew before the mould needs to provide for sufficient oxygen for the fungus. Microporous tape or microperforated foils are generally used for this purpose. To further ensure ideal growth also the temperature needs to be controlled. The optimal growth temperature is identical to the temperature mentioned in above under colonisation.

One of the main dangers in this phase is that the fungus moves into a state of reproduction, in some cases forming mushrooms. A too long growth time or exposing the substrate to light can cause this (Stajic et al., 2002). Although this can be a tasty surprise it is undesirable. This because the fungus will redirect energy towards the formation of these mushrooms, lowering the quality of the substrate and subsequently the composite.

**6. Drying**

When the MBC is fully grown it needs to be taken out of its mould. At this stage additional and other production steps are possible. For example, an extra growth phase in a humid environment in a can improve the surface quality. The simplest approach however is to stop the growth at this step by killing fungus and drying the material. This is done by heat. Several ideas on how to apply this heat exist, none of which have been adequately studied. The three overall philosophies are drying at low temperature (30-60'C)(Holt et al., 2012; Teixeira et al., 2018; Yang et al., 2017), drying at average temperatures (70 - 100'C) (Heisel et al., 2018; Jiang et al., 2014; Travaglini et al., 2014) or drying at high temperatures (180-220'C)(Travaglini et al., 2013). The main consequences to consider are contamination risk, shrinkage, time and energy consumption. Temperatures above 70 degrees Celsius will lower the risk on contamination, since it is effectively pasteurisation. But at these temperatures the chance on altering the cells of the fungus also increase, improving the risk on deformation and shrinkage. If higher temperatures directly translate into faster drying remains to be seen. The wood drying industry shows that even if optimised drying can be a lengthy procedure. The one thing that surely advocates the usage of high temperatures is killing the fungus. Although desiccating the fungus is an adequate method it less controllable than setting a unsurvivable temperature for a set amount of time.

## 2.5 Fungi in a Circular Economy

The goal of this chapter is to illustrate how fungi and fungal materials in special can contribute to a circular economy and a circular building industry in special. Before going into the various aspects of this topic it is important to underline that circularity is not the goal, it's a means to an end. Creating a closed material or product cycle is a wonderful achievement but not if it doesn't have to exist in the first place. From the perspective of sustainability, it is only the environmental impact that counts.

Having that said, circular economy is a very practical and powerful tool in achieving that. Prior to its surge in popularity the main metric for sustainability was greenhouse gas emissions (Morgan, 2012). Besides not accounting for the tremendous impact waste has on our planet it is also a complex and extensive metric to quantify. The circular economy concept has provided in a more principal decision-making tool.

For a radical innovation like fungal materials this has been very beneficial. Its potential impact is multi-facetted, like killing multiple birds with one stone. Quantifying these various effects can be difficult, especially when the precise application of the material is still uncertain. Circular economy has provided a conceptual framework to test and discuss innovations before they have been implemented. Allowing sustainability to be better incorporated in the product development process (Ellen MCarhtur). Now three

***Image 2.35:*** *Small scale: growth tent*

***Image 2.36:*** *Industrial: growth cell*

***Image 2.37:*** *Filling a large mould in a sterile environment*

different perspectives on how fungal materials have a potential positive contribution will be discussed.

### 2.5.1 The waste perspective

As already discussed in 2.1, along with bacteria, fungi are the major decomposers in most ecosystems, playing a critical role in biogeochemical cycles (Gadd, 2007). When compared to human society fungi fulfil the combined role of waste treatment facility and material supplier. By turning waste into food, they are, in essence, what makes nature circular.

That fungal recycling mechanism is fascinating on its own. But by using it to make mycelium-based composites it allows for the creation of tangible, usable products. Pressing the pause button on that degradation process adds value, giving a financial incentive to recycling. This in contrast to the recycling of materials from the technical cycle that often are cost and energy intensive to recycle.

Interestingly, a large portion of the waste and by-products produced in todays economy are of natural origin. There is also a lot of natural mater that never is regarded as waste but isn't used to its full potential. Especially the fibrous waste forms, suitable for substrate, are hard to utilize in other methods valorising organic waste (Khanal, 2011). They actually clog biogas fermenters, because the bacteria used in them aren't able to degrade the fibres.

For a large scale and large volume industry as the building industry big uniform amounts of waste need to be available to create materials with uniform properties. continuously produced suitable waste streams from other large-scale would form the ideal source. Industries like the horticulture, agriculture and forestry sector. In the Netherlands large urban areas are intertwined with extremely crop intensive grounds. There, MBC production could lead to a win-win scenario, where the ones problem is turned into the other solution.

But also, in other regions fungal materials could form an interesting circular solution. Fibrous plants parts are available almost everywhere on earth. This given makes fungal materials a local solution with global potential. A recent project called 'MYC Block & ecosystem services" illustrated this potential by showing mycelium's potential to have a trickle-up effect by giving an economic incentive on ecologically beneficial biomass projects (Krabhuis & Singhvi, 2018).

### 2.5.2 The building perspective

From the viewpoint of the building industry fungal material could provide an interesting new perspective. Moving from a linear to a circular economy requires such an enormous transition that a circular building really isn't a possibility, yet (Simons, 2017). Nature based circularity, such as MCB's, could provide an interesting additional pallet of solutions. The universality of natural recycling processes allows for mixed material usage, such as composites and sandwich panels. Thereby opening the option to combine materials and engineer their properties through the synergy of the ingredients back up. Due to the dominant paradigm of reversibility this option had been deemed undesirable. As design for disassembly is currently the main strategy for circularity in the built environment (Bocken et al., 2017).

Despite their versatility from a combined circularity and engineering perspective MBC's have, in the perspective of some a mayor drawback, their biodegradability. This while others perceive it as its greatest asset. This durability vs sustainability contradiction is the core argument of the lifetime discussion. Some will point to historic buildings like the Amsterdam canal houses and say that the environmental impact of their construction has been smeared over all the years they have been around. Other will use industrial areas filled with vacant 90's office buildings falling into decay to make the point that we don't have such a good track record with imagining the future and constructing that aren't at least adaptable to future needs is the purest form of architects creation arrogance.

Ultimately, at this point, there isn't sufficient data on both the durability and environmental impact of MBC's to be able and discuss this intelligently. The future will tell but for now it can be useful to keep this paradoxical debate in mind during the product development phase.

### 2.5.3 The end of life perspective

The use of organic materials enables recycling by natural processes after the user phase. This means however that molecules have to be broken down and completely built up again. In the natural cycle this

***Image 2.38:*** *Eigth types of natural waste available in the Netherlands and suiteble as substrate*

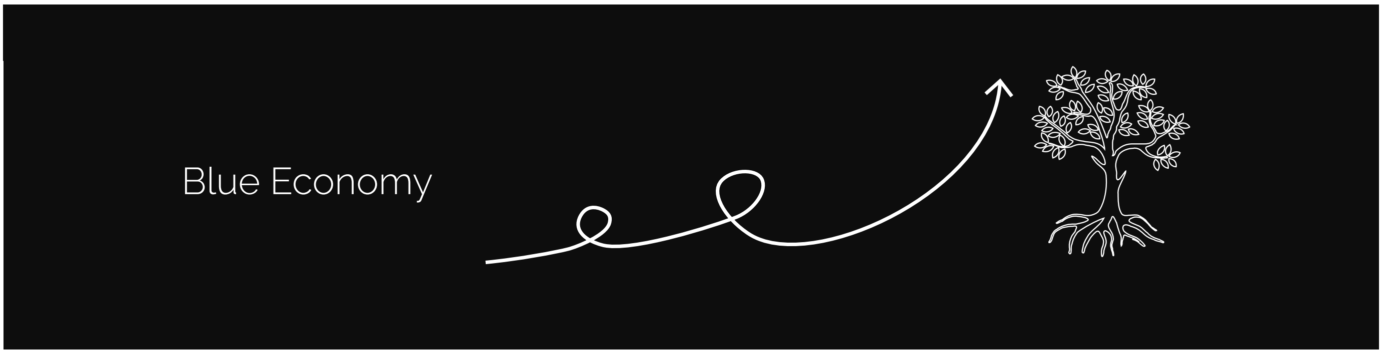



***Image 2.39:*** *The blue economy, waste as a source of growth*

***Images 2.40 & 2.41:*** *Degradable buildings, blessing or burden?*

‘upcycling’ is done using the power the sun, trough photosynthesis. Although this offers a great starting point for circular material usage, more efficient ways are generally sought after. This ‘guaranteed’ recyclability forms a baseline for the materials circularity. It is suboptimal if a product or material is only used once, but at least it will be recycled no matter what.

Since fungal material are still being developed and applications are limited it is likely that forms of reuse will follow in the trail of their development. A course in which such solutions are likely to sprout is that of organic fertiliser. It is expected that due to the depletion of phosphorus reserves, an important resource in the fabrication of fertilizers, the demand for compost will drastically increase in the next decade (Tiessen et al., 2011). According to Grimm & Wösten (2018) fungal decayed fibrous waste streams can be very beneficial as fertiliser. The mycelium composite will be shredded and act as a source of nutrients for new crops. Ultimately leading to the generation of new agricultural waste of which it was made in the first place, a perfect closed cycle. Other reuse or recycling options will surely follow since natures possibilities are far from explored.

## 2.6 The properties of mycelium Composites

This chapter gives an overview of the current known properties of mycelium-based composites. A division will be made between building physical properties, such as thermal conductivity and fire behaviour, and mechanical properties. This to keep the discussion of these two related but separate aspects clear.

The main sources of information used in this chapter have two overall origins. Most material performance data originates from scientific literature. Because of the current lack on quantitative and qualitative data also the information sheets of a view MCB producing companies is used. Although the nature of these sources is not necessarily objective, they are often complete. Opposite to a researcher often investigating one specific property or theme, companies have an incentive to offer a full package of information. Ironicly almost all scientific research, which has the expectation of being independent, is tied to a venture researching, or actively commercializing mycelium-based materials. As can be seen in *Appendix 2* only three of twenty papers were independent. That this effects the usability and quality of respectively the data an the research was also acknowledged by Elsacker (2019) “Many studies do not fully disclose the preparation of the mycelium-composites due to proprietary information preventing a proper comparison or replication” and Travaglini (2014) “the majority of research is being carried out for commercial purposes and therefore remains a trade secrets.”

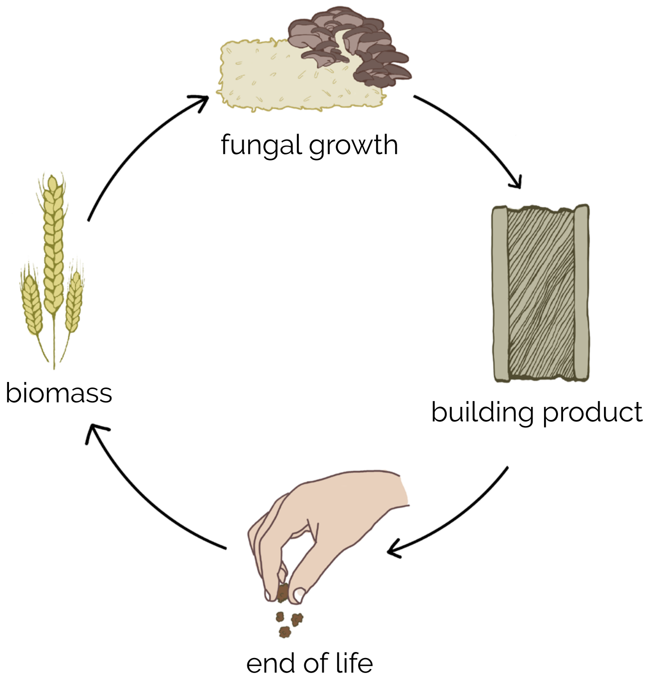
MBC’s are still very much in the development phase (*Table 2.01*). New research and more and more research is being done every year as can be seen in the ***table 2.01***. Therefore, the information in this chapter should mainly be regarded as indicative and a ‘current state of affairs’. As it is likely that a better understanding of the multidisciplinary field of biomaterial engineering will result in materials with improved properties.

### 2.6.1 Mechanical Properties.

As part of the analysis of mechanical properties of fungal materials 16 scientific papers and the data sheet of 2 companies were consulted. The literature research was restricted to sources focussing on MBC’s and not any other fungal material form, although combined studies were encountered (Appels et al., 2019). As can be seen in ***table 2.02*** 11 of the 16 studies were focussing on MBC’s. In seven studies there was at least a partial focus on more complexly produced materials (Pressed, Sandwich, pure). In ***table 2.02*** further a differentiation between Foam like and bricklike MBC’s can be seen. The overall literature has a focus on the foamlike materials over the denser bricklike materials. More about the differences of these two MBC types under the header ‘density’.

For the project the research into bricklike materials was deemed less interesting because of the to be expected high weight and low insulating capacities of such material. As stated by Heisel (2017) this bricklike material is more suited for applications under compression, as bricks. Interestingly, ***table 2.03***, showing the type of research conducted in the literature, reveals an overall focus on the compressive performance of the material. However, this doesn’t align with an overall focus of foamlike materials

*Image 2.42: Life cycly of a mycelium sandwich panel*




| Year | Papers Pub-lished |
|---|---|
| 2012 | 1 |
| 2013 | 1 |
| 2014 | 2 |
| 2015 | 2 |
| 2016 | 3 |
| 2017 | 6 |
| 2018 | 5 |
| 2019 | 3 |

*Table 2.01: Number of papers published on fungal materials as of 01-09-2019*

| Type of material | Number of papers |
|---|---|
| **Total** | **16** |
| MBC | 11 |
| Foam | 9 |
| Brick | 4 |
| Pressed | 2 |
| Sandwich | 4 |
| Pure | 1 |

*Table 2.02: Number of papers per material type*

| Type of test | Number of papers |
|---|---|
| **Total** | **16** |
| Compression | 10 |
| Tensile | 4 |
| Bending | 4 |
| Structural Design | 1 |
| Thermal | 3 |
| Production | 2 |
| Computation | 2 |

*Table 2.03: Number of papers per types of test*

| Autor | Density (kg/m3 | Substrate |
|---|---|---|
| **Appels (2019)** | 100 - 170 | Straw, Sawdust, Cotton |
| **Elsacker (2019)** | 88,8 - 159,3 | hemp, flax, softwood, straw (loose, chopped, dust, pre-compressed, tow) |
| **Heisel (2018)** | 420 - 440 | woodchip+sawdust, sugarcane+casave roots |
| **Holt (2012)** | 66,5 - 224 | Cotton |
| **Lelievelt(2015)** | 170 - 260 | hemp (particles, mat, fibres), wood chips |
| **Travaglini (2014)** | 318 | Wood chips Red Oak |
| **Yang (2017)** | 160-280 | Sawdust alaska birch + wheat Bran |
| **Ecovative 029** | 110 | Hemp |
| **Ecovative 570** | 190 | Aspen Chips |
| **Ecovative 584** | 140 | Aspen Shavings |

*Table 2.04: Overview of densities found in literature*

as material subject for these papers. This rises the question if the conducted research had a focus on knowledge gathering or was application oriented.

Considering the focus of the project, the overall focus in the literature study was put on sandwich panels and bending performance. For the completeness of the here presented image of the material a brief overview of the found performance range of compressive and tensile strength and elasticity will be given. First however the more general property of density will be discussed. To more elaborative part of this subchapter will start with the review of 3 papers on and will finish with the discussing of 3 papers on mycelium-based sandwich panels.

**Density**

One of the main characteristics that was searched for in the Literature study (*Appendix 2*) was the density of the tested materials. This simple metric tells a lot about the characteristic of the materials. Simple rules of thump as the structural insulation paradox (*image 2.43*) are based on density insights. A large portion of the studied papers however didn't report on the density of their material (*Appendix 2*).

As can be seen in *table 2.04* the literature provides a range of material densities from 66,5 Kg/m3 to 440 Kg/m3. All these materials are, according to the definition stated in 2.2, mycelium-based composites. And thus, not compressed or alter in with any other production method. This clearly shows that MBC have a wide range in characteristics. As it is to be expected that a material with a density of 440 Kg/m3 has different properties than a material of 66 Kg/m3. This range in material performance will be further elaborated upon in relation to specific properties further on in this chapter.

What *table 2.04* clearly shows is that there is clear tie between the substrate of the material and its density, as said to be expected in 2.3. This is especially well demonstrated by the density data of the Ecovative MycoComposites. Where different substrate materials lead to a different density. But also, clearly is the difference in morphology is shown between the Aspen Chips and Shavings.

**Compression & Tensile Forces**

The cellular organisation of the mycelium makes that MCBs generally have a higher maximum compressive load than tensile (Heisel et al., 2017). The reviewed literature clearly aligns with this theory. A range of 0,07 – 0,6 MPa for compressive strength and 0,01 – 0,14 MPa for tensile strength was found (*Appendix 2.3*).

An approach similar to FPR production could improve tensile performance. A study would be needed into MBC with a different substrate morphology. Just like the Mycelium Tectonics project by Gianluca Tabellini shown in *image 2.44*, long continues hemp fibres could be used. For three-dimensional approaches a woven mat could be used.

However, with its current compression to tensile ratio the material is more like a weak natural concrete. Heisel et al (2017) understood and exploited this property in their structural design paper describing the development process of the MycoTree (*Image 2.45*). The three-dimensional bricks used in this column are very compact. They are made of sugarcane and cassava root sawdust and have an abnormally high density of 440 Kg/m3. This resulted in the highest compressive strength found in the literature, 0,6 MPa (Heisel et al., 2018). Which is an almost 50% improvement compared to the second highest value of 0,41 MPa (Ecovative, 2019).

**Bending capacities**

It is remarkable that of the limited but increasing amount of studies done on MBCs only 2 have studied the bending of the material. 3 when you also consider the baseline measurement from Travaglini's research on sandwich panels (Travaglini et al., 2014). Luckily both consulted commercial data sheets provided data on the bending behaviour of their material. Based on a not described normalisation method distorting the data from Holt (2012) the results from that study were not taken into account and are therefore also not part of *table 2.05*.

The overview in *table 2.05* gives a clear image of the flexural performance of MBC materials. A range of 0,05 MPa up to 0,29 MPa in flexural strength can be seen. The only abnormality is the 1,4 MPa from Travaglini (2014). The Flexural Modulus of the same study also shows an abnormality. Together

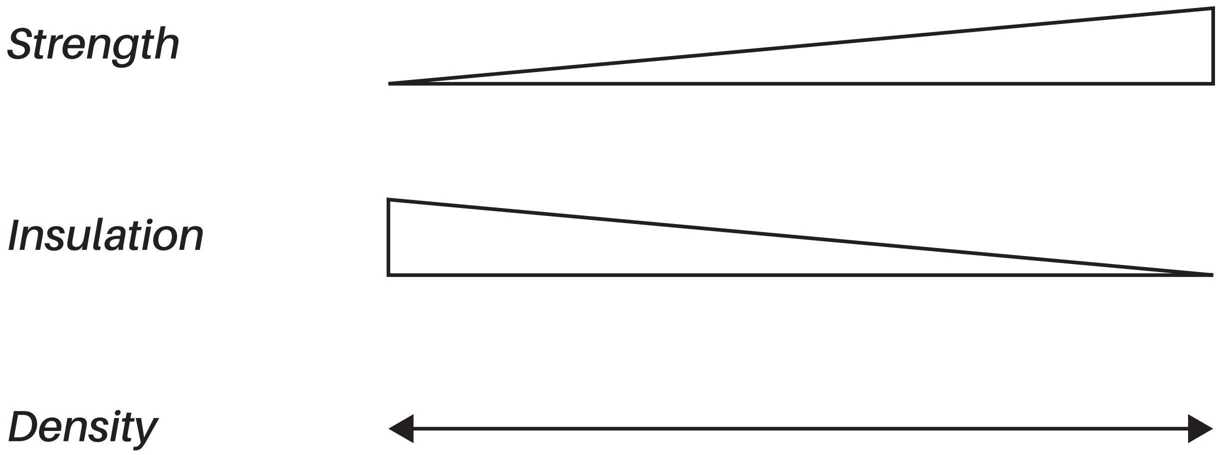



***Image 2.43**: The paradox of a structural insulation material*

***Image 2.44**: Mycelium Tectonics - Gianluca Tabellini*

***Image 2.45**: MycoTree - Heisel (2017)*


***Image 2.46**: Sandwich panel from canvas and MBC by Jiang (2016)*

***Image 2.47**: Sandwich panel from carbon fibre and MBC by Travaglini (2014)*

with the 150 MPa of Mogu – P01 it deviates approximately a factor 10 from the other values. Origin of this significant improvement is unclear. The substrate used in these cases are not comparable in origin and morphology. Although extraordinary fungal selection could have such an impact. The biggest improvement by altering fungi found in the literature was a factor 10 in compression (Teixeira et al., 2018). Similar improvements in bending are not to be expected because a bending load result in local compression ánd tensile forces. The most likely explanation is that the values are based on differentiating measurement methods. Something that will be further discussed in chapter 4.1.

**Sandwich Panels**
Interesting is to see that 2 of the 3 studies on mycelium-based sandwich panels also the bending strength of the panels is tested. As can be seen in ***table 2.05*** the found values for Flexural Strength and modulus can hardly be compared. In a laminated product much more parameters influence the overall performance. When these are not controlled and kept similar results are hardly comparable.

Such drastic differences were found between the two papers. Jiang (2016) uses different natural fabrics as outer layers which grow together with the mycelium in core. Travaglini (2014) uses a polyurethane glue to attach two layers of carbon and bamboo fibre composites to the cores. Besides starting to sketch the outlines of a range in which the performance of mycelium-based sandwich panels are placed these studies only illustrate a careful fist interest this product typology. Much more research is needed to better understand the interaction between core and outer laminates and their optimal performance.

### 2.6.2 Building Physical Properties
Besides the mechanical properties of a material there is a wide array of properties that influence how a material contributes to a comfortable and safe indoor environment. Often these properties are application specific. As for instance acoustic absorption isn't normative in the material selection for a window frame. Although a broad understanding of a material's properties is important in its successful implementation these properties are not crucial in the explorative part of product development.

Therefore, a broad range of properties found to be investigated in the literature won't be discussed. For topics such as the acoustic and water absorption, surface hardness, thermal expansion, specific heat capacity, accelerated aging and compostability is referred to the consulted literature. The topic of thermal conductivity is crucial to this research and will therefore be discussed first. For all building related products fire safety is a key property and will there fore also be discussed.

**Thermal Conductivity**
As elaborated upon in 2.3 It is the cellular structure of MBCs that give them interesting insulating properties (Travaglini et al., 2015). Despite a broad consensus in the fungal material community that building applications are among the most promising for the material (Jones et al., 2017). Only three papers were found where the insulating properties, or thermal conductivity, was studied. Both consulted commercial datasheets did mention these values.

In *table 2.06* an overview of the found thermal conductivity values can be seen. Although there is some variance, a general correspondingly image of the materials performance is given. A rough trend seems to be that lower density have lower thermal conductivity values. The extremely high-density materials by Travaglini (2015) still have workable insulating capacities. Suggesting that the upper limit of the materials is far from dramatical.

The results from Mogu are in line with those conclusions. Showing a midrange performance from a material with a midrange density and most importantly a function as acoustic tile. The values by Ecovative and Elsacker (2019) show a well preforming insulating material at low range densities. Especially the deviation in the hemp-based material from Elsacker indicate the potential of further optimisation. In chapter 4.X a further comparison will be made with other insulation materials to explore potential directions of such optimisation process.

An interesting addition to the research by Travaglini (2015) was that the thermal conductivity of two sandwich panel samples was established. It was concluded that those results indicate no positive or

| | Info | | | Ingredients | | Mechanical Properties | | |
|---|---|---|---|---|---|---|---|---|
| Nr | Name | Manufacturer | Data origin | Substrate | Fungus | Density | Bend strength | Elastic modulus |
| | | | | | | kg/m3 | n/mm2 | n/mm2 |
| 1 | MycoComposite 029 | Ecovative | Ecovative (2019) | Hemp | - | 110 | 0,10 - 0,20 | 7,20- 13,0 |
| 2 | MycoComposite 570 | Ecovative | Ecovative (2019) | Aspen Chips | - | 190 | 0,12 - 0,21 | 10,0- 16,0 |
| 3 | MycoComposite 584 | Ecovative | Ecovative (2019) | Aspen Shavings | - | 140 | 0,076 - 0,11 | 5,5 - 9,7 |
| 4 | Mogu - P01 | Mogu | Mogu (2019) | Cotton | - | 200 | 0,05 | 150 |
| 5 | Appels - TRN | Mogu | Appels (2019) | Rapeseed Straw | Trametes multicolor | 100 | 0,22 | 3 |
| 6 | Appels - TBN | Mogu | Appels (2019) | Beech Sawdust | Trametes multicolor | 170 | 0,29 | 9 |
| 7 | Appels - PRN | Mogu | Appels (2019) | Rapeseed straw | Pleurotes ostreatus | 130 | 0,06 | 1 |
| 8 | Travalingi - MBC | MycoWorks | Travalingi (2014) | Northern Red Oak | Ganoderma lucidum | 318 | 1,4 | 168 |

***Image 4.05:*** *Overview of all bending data from the literature*

| Info | | | Ingredients | | Data | |
|---|---|---|---|---|---|---|
| Nr | Name | Data origin | Substrate | Fungus | density | Thermal conductivity |
| | | | | | Kg/m3 | (W/mK) |
| 1 | MycoComposite 029 | Ecovative (2018) | Hemp | - | 110 | 0,042 |
| 2 | MycoComposite 570 | Ecovative (2018) | Aspen Chips | - | 190 | 0,061 |
| 3 | MycoComposite 584 | Ecovative (2018) | Aspen Shavings | - | 140 | 0,047 |
| 4 | Mogu - Acoustic Natural | Mogu (2019) | Cotton | - | 180 | 0,05 |
| 5 | Mogu - Acoustic Fire-proof | Mogu (2019) | Cotton | - | 180 | 0,05 |
| 6 | Elsacker - FC | Elsacker (2019) | Flax (chopped) | Trametes versicolor | 159,3 | 0,0578 |
| 7 | Elsacker - HC | Elsacker (2019) | Hemp (chopped) | Trametes versicolor | 94 | 0,0404 |
| 8 | Elsacker - SC | Elsacker (2019) | Straw (chopped) | Trametes versicolor | - | 0,0419 |

***Table 4.06:*** *Overview of all thermal insulation data from the literature*

negative influence by the presence of the two layers. Indicating that the development of such products could best be done parallel to the further optimisation of the insulation performance of the core.

**Fire behaviour**

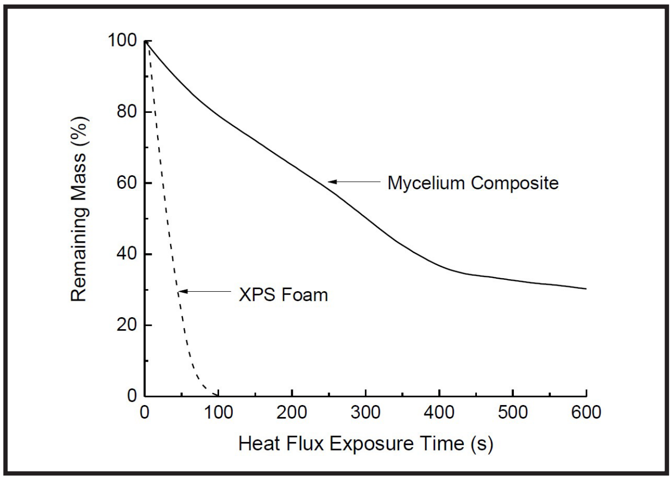
Fire safety is a crucial aspect of the construction discipline. Relatively recent catastrophic events have remembered the world about the crucial role insulation materials (BRON Glenfeldd tower). Their open, sponge-like structure enables optimal combustion through the presence of plenty of oxygen. Especially the oil-derived insulation foams such as EPS form a large risk. But also, natural fibres are easily burnable and therefore potentially dangerous.

As previously stated, MBC's are supposed to have good reaction to fire properties. This would make them a unique natural insulation material. Also, in the rigid insulation materials would this property by unique. Some exploratory research was done illustrating the effects of fire to a MBC (***images 2.19 & 2.20***). They shows the result of a minute-long exposure to a yellow flame. No combustion occurred, the material only smouldered which stopped as soon as the flame was taken away.

The literature also provides an optimistic image of the fire behaviour of MBCs. Jones (2017) shows their superior behaviour when compared to XPS, see ***images 2.48 & 2.49***. Jones further states that "Mycelium composites are a viable fire-resistant material for non-structural and semi-structural applications in place of synthetic foams and similar materials". In further research Jones shows that increasing the silica content of the substrate further improves the fire performance (Jones et al., 2018).

Both Jiang (2014) and Travaglini (2015) show the safe temperature range of MBCs in their research. Respectively finding an ignition point of 300 and 390 degrees Celsius. In European regulations however, these ignition points are not directly taken into account in the fire reaction determination process. Generally an SBI-test (Single Burning Item) has to be conducted in accordance to EN 13823:2014 (Efectis, 2016)(***image 2.50***).

The only record of a 'European' reaction to fire test was found in the technical data sheet of the Italian acoustic panel company Mogu. Their natural acoustic tile has D label and their fire safe, treated, tile has a B label. Which translates into respectively the use normal use in low-rise and the use in fire safe areas in low-rise as well as normal use in high rise. This matches with the earlier named statement of Jones. Who, in the reach of the conducted literature study, seems to be the expert in the domain of fire safety and fungal materials. In his latest research he went as far as stating that "The widespread use (of mycelium composites) in civil construction would enable better fire safety in buildings".



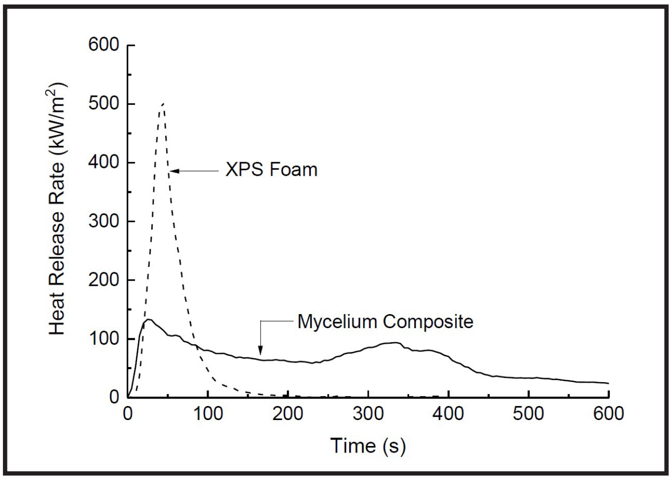



***Image 2.48 & 2.49:*** *Results from reaction to fire tests by Jones (2018)*

***Image 2.50:*** *Single Burning Item (SBI) test at Efectis Nederland*

# 3

# Industry Context

This chapter seeks to understand the context in which the proposed solution would be placed. In order to incorporate contextual input in the development process.

In the problem statement of this report (1.2) several reasons were identified for the lack of success until now in the development of mycelium materials for applications in the building industry. A dominant focus on the material and technology resulted in solutions that weren't properly embedded in the industry's context. Important requirements from the industrial or market context were overlooked. As a result, mycelium materials haven't got a lot of industry interest as many players fail to see how it can help them.

At the root of this problem lies the usage of an inadequate product development method. A strategy mainly focussing on the technology or innovation often results in solutions for problems that are not experienced. A two directional product development process avoids this. In such a process feedback from both the problem (industry) and solution (innovation) side is used to iterate. Not only does this ensure better embedment in the industry context. The process often incorporates direct involvement of industry players who, in the case of successful development, are drawn to the innovation, increasing a technology's adaptation rate.

Within this chapter the focus will lie on creating an in-depth understanding of the industrial context for which the proposed solution will be developed. Together with the analysis of the innovation of chapter 2 the contextual analysis of this chapter will form the main source of input for the rest of the research. First, in 3.1, an industry niche will be selected as context for the product development of the mycelium composite based sandwich panel. This will be done based on analyses of the Dutch sustainable building and Insulation market. In 3.2 the dynamics within the selected niche will be explored among other things through a number of interviews with industry experts. This chapter will conclude with 3.3 where a quantitative and qualitative analysis of currently used products and methods will be made.

## 3.1 context selection

As mentioned in the first chapter of this report researching the possibility to develop a mycelium composite based sandwich panel is very interesting from the perspective of circular economy. The sole use of natural materials overcomes the problem of recycling that arise when using multiple materials in a composed product. To investigate the feasibility of that development a context is needed. As explained earlier a sandwich panel is not a product, it is a product typology that can still be used to develop many different products. The principle of a sandwich panel is used in everything from façade elements to doors, IKEA furniture and refrigerators.

As the name suggests this chapter will be used to identify a suitable application and context as its details will act as input for the research. The selection will be based on both an analysis of the current market for insulation materials as an analysis of trends in the sustainable building sector. However before going into these analyses a few aspects of the material innovation, as touched on in chapter 2, will be discussed as they will provide a framework for the findings. An extensive superimposition of the material and industry analyses will be made in chapter 4.

One aspect, so obvious that it has already been named above, is that is being dealt with an insulation material. Some other qualities of MBCs further categorising them are their rigid texture and alleged low environmental impact and recyclability, or in other words sustainable character. Finally, one other given is the materials-controlled production environment. The laboratory like environment in which it has to be produced limits the materials applicability rather significant as it makes any In Situ production highly unlikely to be successful and demands off-site prefab manufacturing and.

**The insulation industry**
Based on overall numbers an exploration of the Dutch insulation materials market was made. The report Market Information Insulation materials, insulation glass and High-Efficiency Boilers 2010-2017 by the Netherlands Enterprise Agency (RVO) was used as input. The two most important tables from that report can be seen in ***table 3.01 & 3.02***, respectively the total sales of mineral and natural wools and total sales of synthetic foams.

Firstly, by adding up the totals of both tables can be seen that the most recent total size of the Dutch market is slightly over 50 million square meters. 28,8, close to 60%, of that 50 million consists out of

| | 2010* | 2011* | 2012* | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|
| Verkoopinformatie (oppervlak in mln. m²) | 20,8 | 21,6 | 19,8 | 16,8 | 17,6 | 20,3 | 22,4 | 23,1 |
| Verkoopinformatie ($R_d$ in m²*K/W) | 2,9 | 3,0 | 3,4 | 3,1 | 3,2 | 3,2 | 3,4 | 3,8 |
| Nieuwbouwinformatie (oppervlak in mln. m²) | 10,6 | 10,3 | 9,3 | 7,7 | 7,6 | 8,3 | 8,5 | 8,9 |
| Nieuwbouwinformatie ($R_m$ in m²*K/W) | 2,4 | 2,9 | 3,3 | 3,3 | 3,6 | 3,8 | 4,0 | 5,0 |
| Bestaande bouw (oppervlak in mln. m²) | 10,1 | 11,4 | 10,5 | 9,1 | 10,1 | 12,0 | 13,9 | 14,2 |
| Bestaande bouw ($R_m$ in m²*K/W) | 3,1 | 3,2 | 3,5 | 2,9 | 2,8 | 2,8 | 3,0 | 3,0 |

***Table 3.01:** Sales of miniral and organic wool insulation in the Netherlands*

| | 2010* | 2011* | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|
| Verkoopinformatie (oppervlak in mln. m²) | 16,9 | 18,6 | 18,4 | 19,1 | 20,8 | 22,3 | 27,2 | 28,8 |
| Verkoopinformatie ($R_d$ in m²*K/W) | 2,7 | 2,9 | 3,1 | 3,0 | 3,1 | 3,3 | 3,5 | 3,5 |
| Nieuwbouwinformatie (oppervlak in mln. m²) | 11,5 | 11,3 | 13,3 | 11,9 | 11,6 | 11,2 | 11,9 | 13,4 |
| Nieuwbouwinformatie ($R_m$ in m²*K/W) | 2,8 | 3,2 | 3,2 | 3,1 | 3,5 | 3,6 | 3,6 | 4,3 |
| Bestaande bouw (oppervlak in mln. m²) | 5,4 | 7,3 | 5,1 | 7,2 | 9,2 | 11,1 | 15,3 | 15,4 |
| Bestaande bouw ($R_m$ in m²*K/W) | 2,4 | 2,5 | 2,7 | 2,8 | 2,7 | 3,3 | 3,3 | 2,8 |

***Table 3.02:** Sales of rigid foam insulation in the Netherlands*

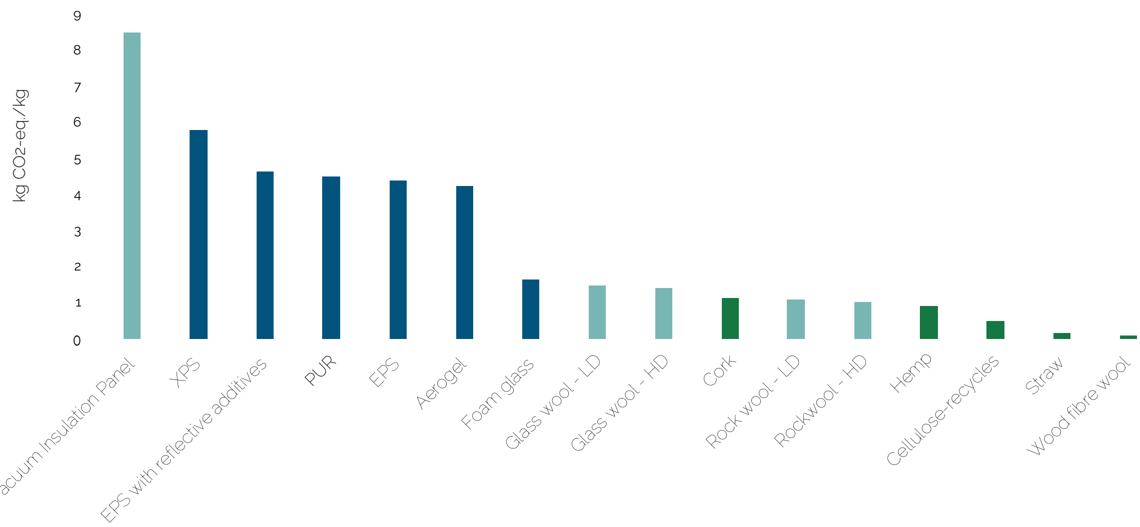



***Image 3.01:** Carbon footprint of thermal insulation, per mass*

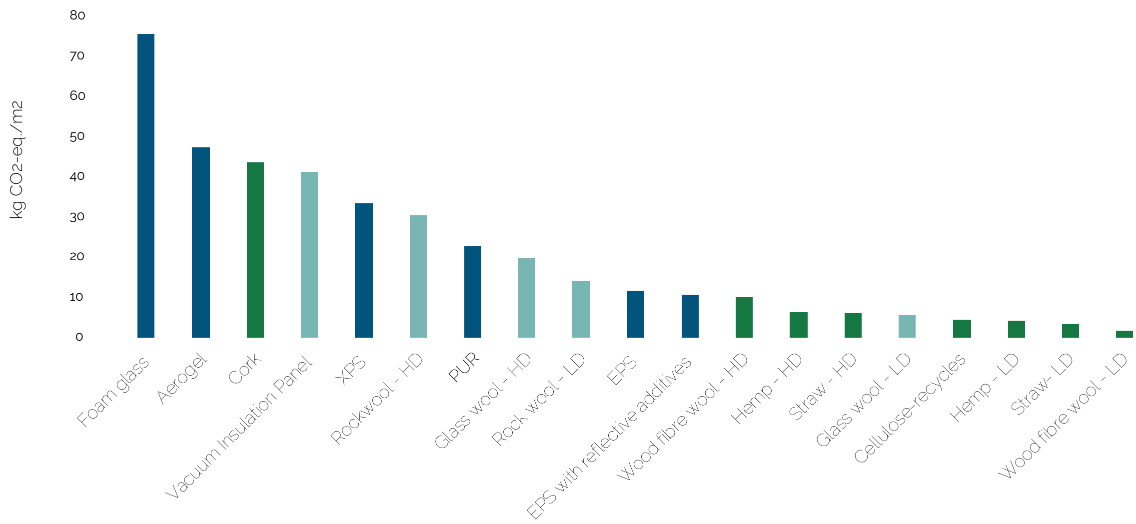



***Image 3.02:** Carbon footprint of thermal insulation, per functional unit* *for U=0.20 W/(m2 K)*

synthetic foams. Only since 2013 have the sales of these rigid foams be higher than the more traditional wool-like materials. A clear trend towards the production and sale of these foams can be established.

What is further remarkable about these numbers is the ratio between the application of these two material types in new construction and renovation projects. Taking the current situation of the Dutch building industry into account it is understandable that for both types sales in renovation are higher. This due to current challenges in improving the energetic performance of the existing building stock (SER, 2013). Despite that prominent focus, over 40% of insulation materials was used in new constructions. Of which 65% was synthetic foams. It can therefore be established that within new construction projects these foam insulation materials in general are the preferred industry option.

In *images 3.01 & 3.02* the environmental impact, in carbon dioxide equivalent emissions can be seen. *Image 3.01* shows this metric per Kg of material and *3.02* per m2, thus taking the insulating capacity of the material into account. Illustrated by the highlighted bars, rigid foams tend to have an above average environmental impact, in both graphs. Together with the insights provided from *table 3.01 & 3.02* can be concluded that although the insulation market is essential in the construction of sustainable buildings the industry is moving towards more environmental burdening materials.

In search of a rigid foam like insulation material one alternative was found, BioFoam. This is bio-based PLA variant of EPS foam being developed in The Netherlands by the company Synbra. Despite being introduced in 2009 the product is not commercially available. After a brief inquiry it turned out that upscaling of the production is experiencing some stubborn difficulties. The material also has an E-level reaction to fire score (Synbra, 2017), which makes the material far from perfect. The existence of there material proves however that the need for a sustainable rigid foam insulting alternative exists. And as shown above, the realisation of such material could have a significant impact.

**The sustainable building industry**

Sustainability in the building industry is a hot topic. This has resulted in an abundance of labels and certification quantifying sustainability (kiesuwlabel.nl). They are based on different views and philosophies about sustainability. As a consequence, a deeper understanding of their core principles is need when valuing these methods. This complicates things when looking for trends in sustainable construction. As the method studied will influence the results.

Ideal would have been to select a label focussing on circularity but unfortunately such label isn't used in the industry yet (Circle Economy et al., 2018). To bypass a necessary additional research phase into these labels it was decided to focus on the seemingly most versatile and comprehensive label, BREEAM-NL. The label focusses on nine different facets of sustainability in construction, including material use, and is available for all typologies (Dutch Green Building Council, 2018).

The annual BREEAM-NL proceedings reports provides an overview of the granted certificates per building typology. The charts of the last four years are shown as *image 3.05*. These four charts display a clear development. Since 2015 the percentage of certified industrial buildings has risen from one third to over 50%. This while office and retail certification have dropped respectively with 25 and 80 percent. An explanation for this development is not given in the consulted reports (Dutch Green Building Council, 2018; 2019).

The absence of residential buildings is remarkable although the reports mention them to be part of the 'others' category. According the Dutch Green Building Council the certification of residential buildings with comprehensive certification is hard to implement (Dutch Green Building Council, 2018-B). Therefore, they recently launched another label, called 'CDBG Woonmerk' solely for this sector.

It has to be assumed that the BREEAM-NL numbers are therefore to a certain degree misrepresenting. However, it is questionable if the residential building industry is suitable for a product that needs to be prefabricated. And if rigid foam insulation foams are currently the material of choice in that sector. It can be debated, especially anticipating a future with more digital fabrication, if this is and will be the case. Still, the conviction that industrial buildings are more prone to prefabrication and standardisation will largely be undisputed. A focus on this typology was thereby justified and thus chosen.

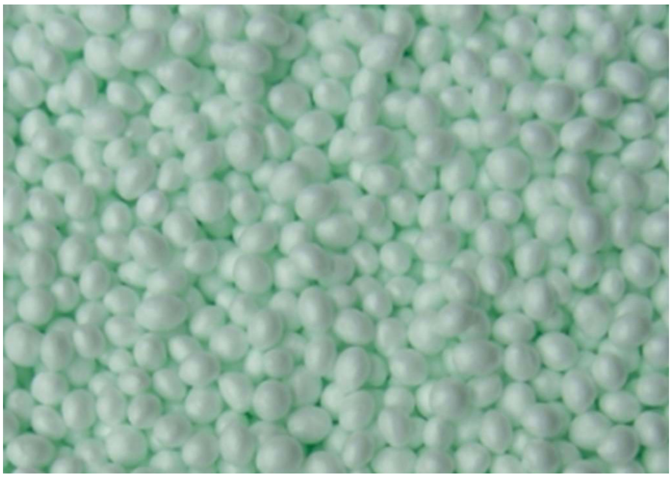


***Image 3.03 & 3.04 :*** *Biofoam: PLA based rigid insulation foam*

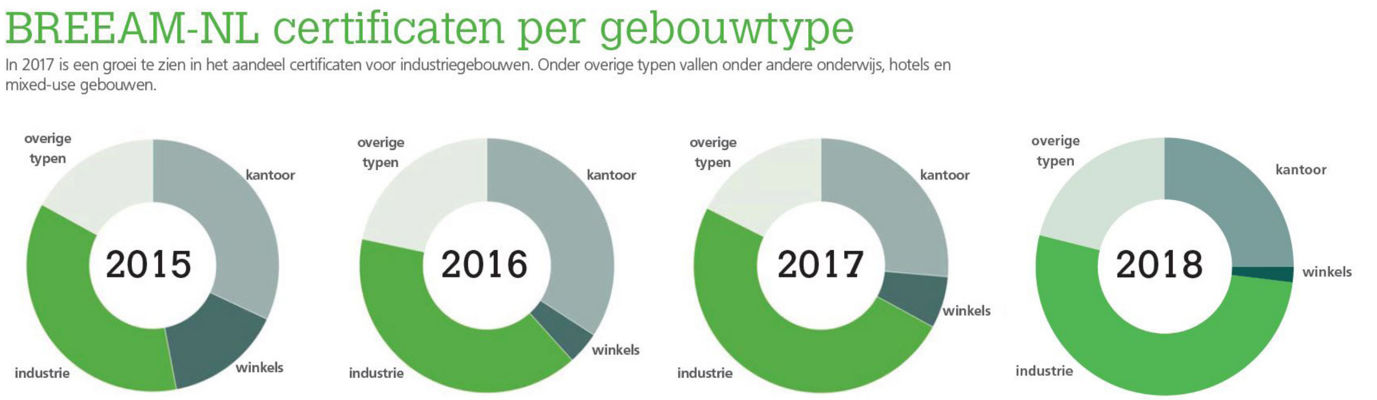



***Image 3.05:*** *Overview of BREEAM certification per building typology*

| **Total** | **60** |
|---|---|
| Showroom | 9 |
| Office+ | 5+6 |
| Warehouse | 6 |
| Distribution centre | 20 |
| Production facility | 14 |

***Table 3.03:*** *Overview of typologies within BREEAM-NL Industrial*

When the BREEAM-NL numbers where further studied 119 projects with the highest grade of certifications, 4 and 5 starts, were found. 60 of them, so again 50%, were industrial projects (BREEAM-NL, 2019). These 60 projects were broken down into sub-typologies in an attempt to understand the dynamics behind this trend in sustainable industrial buildings. The result of that endeavour, of which the result can be seen in ***table 3.03***, revealed an interesting overrepresentation of large industrial halls of Production Facilities, Distribution Centres and Warehouses. Especially the large number of distribution centres is remarkable, one third of certified industrial buildings. It is likely that their certification is part of corporate responsibility policy and showcase of the owner's sustainability goals.

Distribution centres, or DC's, are just like the other industrial halls are large volume low-rises with mostly one story. This makes them, together with their predominantly closed skins, buildings that volume wise mainly consist out of insulation material. Opposed to for instance office high-rises where glass is the main façade material and the ratio between roof and floor surface is very small. Additionally, their construction largely depends on prefabricated and standardised construction methods. Where it is likely that sandwich panel-based facade or roof products are already used or are suitable for this application.

Because of the seeming fitness of the typology for the introduction of a sustainable and circular sandwich panel the decision was made to focus on distribution centres. Their direct ties to large corporations and the future perspective of the typology also played a role in this choice. In the coming chapter an analysis of the main dynamics within the DC-construction industry will be made.

## 3.2 Industry trends, challenges & practices

The goal of this chapter is to build a deeper understanding of the distribution centre construction sector. By investigating the industry from various angles, it is expected that a coherent and accurate impression can be created. Understanding the motives and incentives at play is a crucial step in successfully anticipating on industry needs and incorporating them in the development process. It is in this process that the link between socio-economic problems and technical solution can be found. Therefore, it forms a crucial part in a market-oriented product development method.

The research that led to this chapter was multidimensional of nature and incorporated various sources. To understand the macro dynamics of the industry a market research report was consulted. In order to learn about its pressing issues a few recent articles from the logistic sector itself and national newspapers were used. Footage of various construction sides was studied to better understand the technical side of the building practices. Although very inciteful, the investigating of these sources presented some contradictions and left open some blanks. Several interviews with market experts were conducted to tackles this. Some background information on these experts can be found in the *Appendix 3.2*. The results of this process will now be presented.

**Industry dynamics**

Distribution centres may not actively be subject of many peoples lives or of large news coverage. The industries to which they are an essential piece of real estate are. The e-commerce sector is changing our society (Laudon & Traver, 2016). *Images 3.06, 3.07 & 3.08* from the report 'Logistic real estate in numbers 2017' shows trends that very much support that image (Bak, 2018). In *image 3.07* can be seen that the demand for new logistic real estate tripled between 2014 and 2017. And clearly shows that this increase is caused by the fast shipping sector; e-commerce.

**Sustainability**

As shown earlier in this report (3.1) many DC's apply, and are granted, a sustainability label. Large consumer-oriented companies like LIDL, PostNL and Albert-Heijn choose to get a sustainability label (BREEAM-NL, 2019). Apparently, they see the added value of such certification. Koen Harleman, Sustainability & Innovation Specialist at LIDL, underlines that "Our marketing department is able to translate our sustainability strategy into a motives value. Of course, we think it is very important, but it helps a lot that it's just a great way to expend our business and make money."

**A call for circularity**

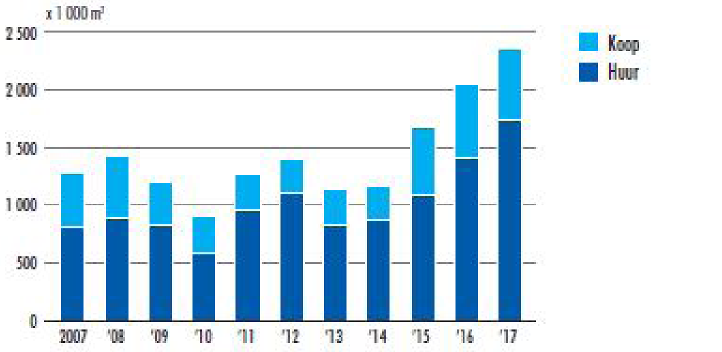



***Image 3.06:*** *Demand for logistic real estate, ownership*


***Image 3.09:*** *Total covered land area in the Netherlands*

*Source: NRC 29-10-2019*

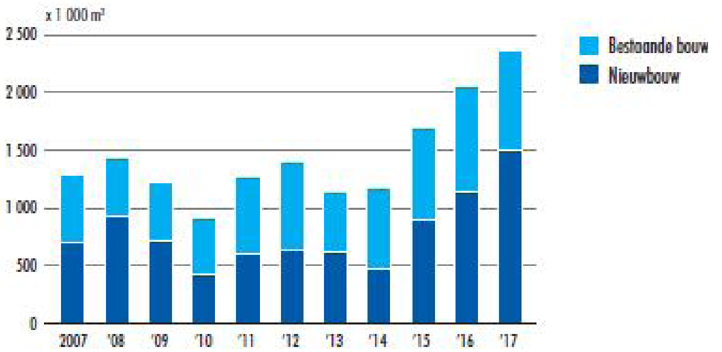



***Image 3.07:*** *Supply og logistic real estate, new or existing*

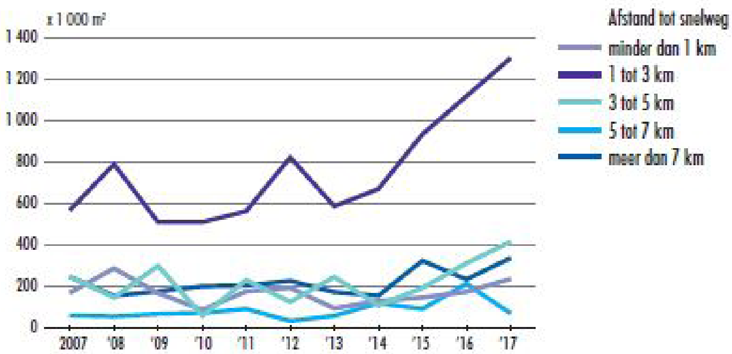



***Image 3.08:*** *Demand for logistic real estate, reachability*

*Source: Logistiek in vastgoed 2017*

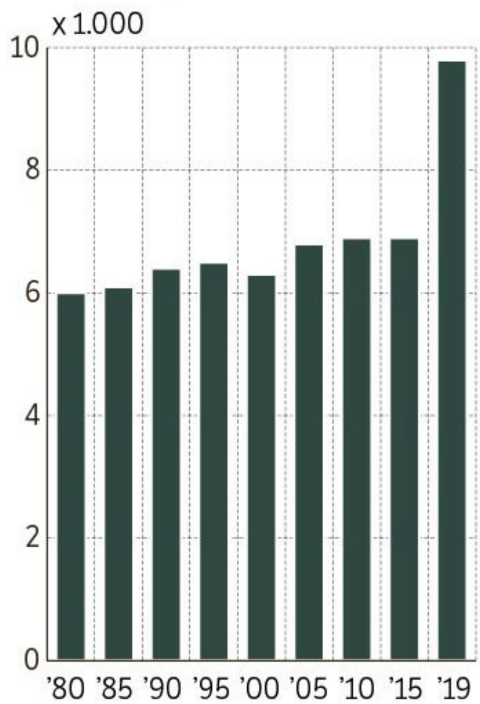



***Image 3.10:*** *Avarage size of a distribution centre*

*Source: NRC 29-10-2019*

When asked about circularity Harleman states: “Implementation of circular economy is something we are looking into a lot at LIDL. We encounter a lot of thing we can make more efficient, something which suits the LIDL mentality”. On the question how this currently effects their building practices for DC’s he responds: “Currently we mainly focus on our shops and offices. There is talk about DC’s, but the solutions are just not there yet. If those come available, it is very well possible LIDL will go for them. Especially on the level adjustability and expendability I think we will start to run into problems in the next 10 years or so”.

Harleman isn’t alone in those concerns. Luc Baltus, CEO of DC construction company VDR, warns about the consequences of the current DC construction practices. “We are cannibalising our land. – What are we going to do with all those empty shoe boxes? – We are building DC’s like they will always be needed but they are just as much a depreciated tool as a truck.” (Van Wijnen, 2019). Six months after the statements of Baltus and two months after the interview with Harleman the first official recommendation by a government body was made which advocates for containing the proliferation of ‘Distribution Boxes” (Van Bokkum, 2019).

The call for reversibility and remountablilty seems to be a universal concern. Alijd van Doorn, Sustainability director at Heembouw, sees it as the way towards circular DC’s (Dijkhuizen, 2019). In an industry that ought to be highly standardised it would seem fairly easy to implement such practices. Using insulation foams as an example Baltus explains that it isn’t that simple: “Modern insulation foam can’t just be reused or recycled, certainly not when it is stuck to a roofing material. Burning is often the only solution.” (Van Wijnen, 2019).

**Construction method**
A study of footage of various DC construction projects (***Appendix 3.1***) revealed practices that are indeed not easily reversed. To keep a focus on roofing, although highly optimised and standardised the universally used method does not rely on large elements that can be reused. Rather, as can be seen in ***images 3.11 & 3.12***, an in-situ methodology is used which is bonded into one. As soon as part of the steel or concrete structure has arisen it is covered with corrugated steel plates. Two layers of rigid foam blocks, often Kingspan, are then laid on top as insulation. This is done manually in a cross-linking pattern. Afterwards, the blocks are attached to the steel and each other using PUR-spray and clamps. The total is then covered with a bitumen-like roofing material which is glued on top. As a result, the roofs of DC’s exist out of a monolith of in some cases over hundred thousand square meters. Imaginably this is hard to deconstruct or repurpose.

**Why not use sandwich elements?**
In an attempt to understand the use of this seemingly slow and labour-intensive method two industry frontrunners and a Kingspan engineer were interviewed. Cor van Dijken, Sustainability manager at Nexteria, explained that there are two corresponding issues preventing the use of sandwich panels in the roof. The first in transportation, it limits element size to a maximum of 20 by 2,5-meter. All sequential seams would form a risk for leakages and other corresponding problems. Additionally, due to the immense surface area the interconnected layers of metal and foam could start bulging under high sun loads. Which would have potential catastrophic consequences for the drainage system.

Vincent Grieten, Technical Service Engineer at Kingspan, can’t agree with this technical concern: “Although I understand the concern and phenomenon, bulging shouldn’t form a problem when the panels are mounted in the right way. Our X-dek product is specifically designed for these applications.”. However, he also acknowledges that sandwich panels aren’t the common roofing solution in DC-construction but attributes that purely to price. Diederik de Jonge of Habeon Architects, the inhouse architecture firm of Heembouw, agrees: “Its’s a penny game, small price differences are multiplied with a large number of square meters and quickly from an additional 20 thousand euros expense.

On the question if the mantra ‘time is money’ didn’t affect the construction of DC’s Koen Harleman had an interesting insight: “Building a DC is an extremely large and strategic investment for us. It’s an almost military planned operation that requires years of preparation. A time saving of a couple of weeks really doesn’t matter to us. Besides, the construction sites are so large that multiple construction phases can


***Image 3.11:*** *Foam isolation being applied on DC, mannually in blocks*

***Image 3.12:*** *Men on top of DC during construction, applying insulation mannually*



***Image 3.13 & 3.14:*** *Nexteria: pilot project of first circular DC*

easily be executed simultaneously for optimal time use.".

That sandwich panels are widely used in the construction of DC roofs doesn't mean that they are often applied. In the study of industry construction methods (*Appendix 3.1*) various instances were encountered in which sandwich panels were used as façade cladding. In the interview with Cor van Dijken this use of the product was also mentioned. The circular DC pilot project of Nexteria (*images 3.13 & 3.14*) has façades made with BRUCHA, wood fibre core, sandwich panels. Apparently and understandably, water tightness and structural issues are less of a concern in the façades while aesthetics become more important. This combination of factors leads to a situation in which sandwich panels become more of a preferred option.

**The frontrunner perspective**
The interviewees were asked about their perspective on the future of the sector. This in an attempt to get not only an insight in the current state of affairs but also in the prospects of the industry. Like the reports discussed in 3.1 and earlier this section Diederik de Jonge, of Habeon Architects, stated: "There is a lot happening on the level of sustainability, but it remains a difficult puzzle. In DC design the Excel files (financial calculations) are just so determinative. Circular DC's are the next step. Currently there isn't enough space in our projects to investigate this. Therefore, we have assembled a 'circular taskforce' to be ready when the time is there.". When specifically asked about the solutions for insulation materials he answered; "Ultimately we're also stuck with Kingspan. I'm convinced they are working on it but can't throw away their business model suddenly. It's just waiting for a large corporation that can offer the right quantities for the right price. What worry about more is the concrete, it's 90 percent of the weight and it's just really hard to replace.".

Cor van Dijken has a different perspective. He believes in just doing, giving of a signal and solving the problems you encounter along the process. "We have to start small, show that it's possible and expand from there. Specifically, for the building skin our goal is to prevent the use of PIR foam. We use Brucha sandwich panels with wood wool insulation in the façade and Biofoam for the room. It's the first application of Biofoam in a roof. Both were challenging to implement, especially with fire safety. PIR is just such a good insulant and also preforms better in fire safety. But also, Biofoam can't support solar panels. However ultimately, I believe in the direction of biomaterials.".

Interestingly there seems to be a strong believe in nature-based solution amongst the two frontrunners, Nexteria and Habeon. The latter promptly answered "1. Bio-based, 2. Remountability & 3. Reuse." when asked about the building technological solutions they believed in most. From their contributions however also arises the image that these solutions are the most difficult to implement or at least currently most underdeveloped and proven. It has to be concluded that these perspectives leigh aligned with the development of mycelium-based sandwich panels, as long as the quality and quantity is right.

**Potential game changers**
An aspect that arose from all interviews was the current impossibility to make a circular DC. Non the less they are all working or looking in to it on various levels. The question 'what is holding you back?' gave some interesting insights. First of all, both Harlemen, Van Dijken as De Jonge underlined the imposing role regulations could play. A strict and obligated MPG-score (Environmental Performance Buildings) which considers the shadow costs of the materials was named. Currently MPG-scores aren't obligated for utility buildings and for residential and office buildings the current score of € 1,0/m2 is easily obtained (Duurzaam Gebouwd, 2017). Another potential regulation that was mentioned is Carbon-taxing, based on LCA (Life Cycle Assessment) data. A material would be taxed according to its environmental impact. This would potentially be beneficial for natural materials as they actively store Carbon (Hill, 2019).

Stricter regulation on a national level seems to be the advice. However, De Jonge mentioned that on a municipal level the governmental interference should be less or more constructive. "Now experimental and new things are often not accepted because 'they have never seen it before'". As accountable governmental body their risk averseness is understandable but a more of a cooperating role could understandably be beneficial. Nexteria's Cor van Dijken also pointed in the direction of collaboration.

Specifically, that between the various construction partners, as he had seen the positive impact and enthusiasm that it sparked it their own circular DC pilot project (Nexteria, 2019). Interestingly the notion of collectively coming to solution correspond well to the identified problem of a lack of industry involvement. It remains to be seen if identified solution of data driven convincing also formers a solution.

## 3.3 Existing products: Specifications & Volumes

In the previous section came to light that sandwich panels aren't the current industry standard in roofing solutions for distribution centres. However, a sandwich panel-like product does hold the most potential for the needed reuse and flexibility in the sector. During the interview with Kingspan their X-Dek panel was named as the most suitable sandwich panel solution for this typology. Talking to the other industry experts and in the study of the DC construction methods (***Appendix 3.2***) the dependence on Kingspan products was an aspect that came to the surface. As their products are leading in the field of rigid insulation and rigid insulation products, such as sandwich panels, this section will kick-off with a qualitative analysis of the Kingspan's X-dek product. In addition, also the Brucha DP-H panel will be analysed. This is the roofing alternative to the panel used in the Nexteria circular pilot DC and will be reviewed in order to get an image of any drawbacks of current bio-based panels. Because of the current use of in-situ solutions the quantitative analyses of later in this section will use a mixture of DC-industry and insulation market data.

### 3.3.1 Specifications

As said, the specification of two sandwich panel products will be analysed in this section. This will be done based on the specification data sheets provided by the manufactures Kingspan and Brucha (Kingspan, 2017 & 2018; Brucha, 2018). The analyses will go into the following five different topics: Dimensions, Materials, Fire safety, Strength and Application. The key data of the two products can be seen in ***table 3.04***.

**Dimensions**

The lengths mentioned in the specification documents are, with 13,4 and 15,3 meters, comparable. However, the almost two additional meters of the Brucha panel can be significant. It has to be said that X-dek panels are available in larger sizes than mentioned on request and that the 15,3 from Brucha is an absolute maximum. It can very well be that X-dek panels are available in larger sizes. Chances are that such panels come at a higher price point. Since that has already been identified as one of the key reasons sandwich panels are currently not used in DC construction it is questionable if larger panels should be desired. An additional difficulty, and potential expense, is the necessary special shipping mandatory from lengths of 13,6 upwards (Brucha, 2018). It could very well be that for this reason the X-dek length is slightly less than this length.

A noticeable compresence between the two product ranges is in the width in which they are produced. Both products are made in 1000 mm width and even their profiled sides are made in with the cadence of 333mm. This resemblance suggests that this 1 meter width measurement is an industry standard.

When regarding the thickness of the products it catches the eye that Brucha offers a more than double the amount of varieties in thickness when compared to the X-dek range. As will be discussed in a bit, the insulating properties of the X-dek core are much better than that of Brucha's DP-H. This makes that with less thickness a similar insulating performance is reached. Kingspan thus can have a much more effective product range. Width that given in mind it is remarkable that Brucha also offers a thinner panel than Kingspan, probably for very undemanding purposes.

An additional noteworthy aspect regarding the thickness of the panels is the difference in core and total thickness. Both companies refer to the thickness of their panels while actually talking about the thickness of the insulting core. This gives the idea that total thickness is not much of an issue. However, both products have a considerable difference between the two. This is caused by the bends of a profiled metal sheet on one of the outer layers of the panel. In case of the X-dek this sheet is placed at the bottom while the Brucha panel has its profile at the top, a difference that will be discussed under 'Application'. The thickness of those profiles also very significantly. 42mm for the DP-H panel against

106mm for the X-dek 106, which apparently derives its name from this dimension.

As can be seen in ***table 3.04*** the weight of both products is comparable. This is noteworthy because both products achieve this weight with a different composition. The wood fibre insulation used in the Brucha panels is much heavier than the PIR in the X-Dek panels. The 110 Kg/m2 density of the wood fibre is almost four times as heavy as the 30 Kg/m2 of PIR. When comparing the 80, 100 and 140 mm versions of both product ranges only the last of three is lighter in the X-dek variant. As will be discussed in the materials section this is likely due to thinner outer sheeting in the Brucha panels. Which explains the larger increments in weight in these panels as the core thickness increases. This also shows the small influences the core material has on the overall weight as both panels use steel outer layers.

**Fire safety**
As can be seen in the specifications table the fire behaviour performance of both products is almost similar. The Brucha DP-H panel only performance a little better on smoke production. As briefly touched upon in section 2.6 a B score in fire behaviour is good. The level at which this score is normative for the applicability and fire safety of a DC is questionable. DC's are large well-arranged hall from which fleeing is relatively easy. Human safety will probably not be crucial. The stored good probably will. From a safety point of view, when regarding dangerous compounds, or from a financial perspective, as in the stored capital. The application of a sprinkler installation will in both cases likely be the most effective. Because of that reason the fire safety demands for the building skin will probably be based on the risk of fire transferring to adjacent halls or fire compartments. Both consulted specifications sheets didn't disclose any data on the fire resistance of the products, probably because this depends on the rest of the structure in which the panel is applied.

**Materials**
Sandwich panels are composed products existing of at least two materials. Generally, a lightweight insulating core and two strong metal or wooden outer sheets. First the insulating cores of the two selected panels will be reviewed. The Kingspan X-Dek 106 has a core completely existing out PIR foam. The Burcha DP-H panel has a wood fibre core. As can be seen in ***table 3.04*** the PIR foam has a thermal conductivity half of that of the wood fibre. Less thermal conductivity means less energy transport so a better insulation material. Thereby the 0,02 W/mK of the PIR foam is far superior to the 0,04 W/mK of the wood fibre insulation. Additionally, PIR has a significantly lower density. That is in itself quite logical, as there is less material to conduct the heat, giving the material its lower thermal conductivity.

However, there is more to insulation than only the thermal conductivity of a material. The goal of insulation is to lower the energy need and increase the comfort of a building. Especially in extreme weather condition, freezing winter nights or scorching summer days, the heat capacity of a building skin is of importance. With a high thermal capacity, the skin can act as a buffer diffusing the temperatures of those mid days or nights. The specific heat capacity of wood fibre insulation is approximately 1,5 times greater than that of PIR. However, because the density of the wood fibre is almost quadruple that of PIR. Therefore, the energy it is able to store per square meter is 6 times higher. An interesting capacity to make buildings resilient against more extreme weather conditions. It must be noted that mitigating these issues can be done based on other building technological principles, such as green roofs or solar panels.

Finally, the insulating cores differ significantly in their material composition. The PIR core of the X-Dek panel is homogenous. PIR is a fossil based synthetic material that can't be recycled and releases toxic chemicals when burned (Stec & Hull, 2011). Its unrenewable origin, poor recycling options and the fact that it is glued two metal sheets makes it from a circular economy point of view a non-adequate product. Although ultimately only based on LCA data of the two products, which wasn't available for this research, a statement can be made on the sustainability of the product the wood fibre core of the Brucha panel pretends to be an eco-friendlier option. However, it has to be noted that in fact the core of this panel exists out of a mixture of wood fibres, PUR resin and paraffin. In Cradle to Cradle terminology such unreversable mixture of materials from a technical and natural material loop are called a 'monstrous hybrid' (McDonough & Braungart, 2002). From a circular economy perspective this makes the Brucha equally bad, or maybe even worst than the Kingspan X-dek panel.

| | | Kingspan X-Dek 106 | | | Brucha DP-H | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dimensions** | | | | | | | | | | | |
| Length | m | 6 - 13,4 (larger possible) | | | max 15,3 | | | | | | |
| Width | mm | 1000 | | | 1000 | | | | | | |
| Thickness (core) | mm | 80 | 100 | 140 | 60 | 80 | 100 | 120 | 140 | 160 | 200 |
| Thickness (total) | mm | 182 | 206 | 146 | 102 | 122 | 142 | 162 | 182 | 202 | 242 |
| Weight | Kg/m2 | 20 | 22,9 | 24,5 | 17,3 | 19,5 | 21,7 | 23,9 | 26,1 | 28,1 | 32,2 |
| **Fire safety** | | | | | | | | | | | |
| Fire behaviour | | B-s2-d0 | | | B-s1-d0 | | | | | | |
| **Insulation core** | | | | | | | | | | | |
| Thermal Conductivity | W/mK | 0,02 | | | 0,04 | | | | | | |
| Heat Capacity | J/KgK | 1400 | | | 2300 | | | | | | |
| Density | Kg/m3 | 30 | | | 110 | | | | | | |
| Materials | | PIR | | | Wood fibre + PUR + Paraffin | | | | | | |
| **Outer Materials** | | | | | | | | | | | |
| Upper layer | | bitumen / mineral wool PVC / metal sheet | | | metal sheet + PE coating + PVC film | | | | | | |
| Thickness | mm | 0,7 (metal) | | | 0,6 | | | | | | |
| Bottom layer | | Zi-Al alloy + PE coating | | | metal sheet + PE coating | | | | | | |
| Thickness | mm | 0,9 / 1,1 | | | 0,6 | | | | | | |
| **Application** | | | | | | | | | | | |
| Minimal roof pitch | ° | 1° | | | 3° | | | | | | |

***Table 3.04:*** *Comparison of traditional sandwich properties*

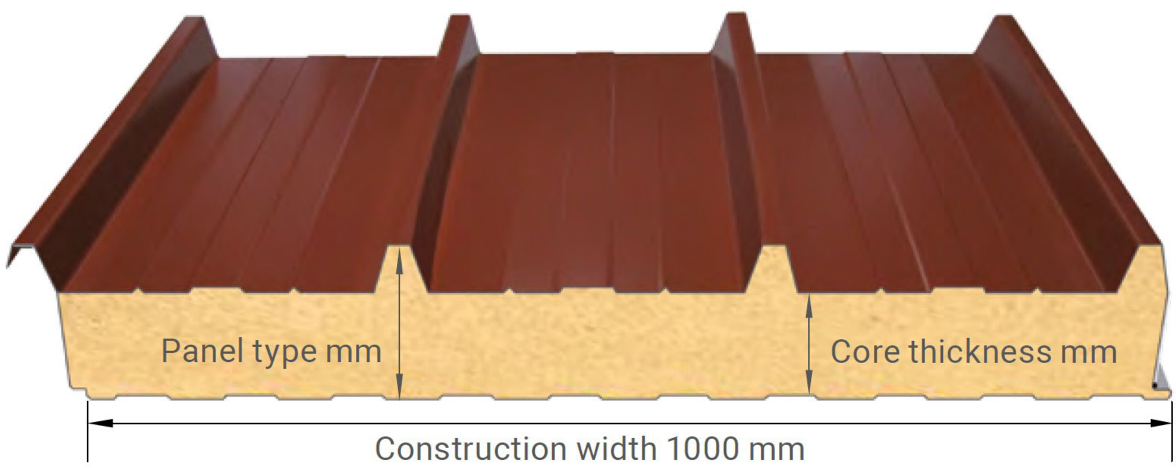



***Image 3.15:*** *Brucha DP-H, sandwich panel for roof application with wood fibre core*

When regarding the outer layers of the sandwich panels some other noteworthy difference come to the eye. As can be seen in *table 3.04* the Brucha panel is available with a set outer and inner metal sheeting. Although various colour options are available technically only one product is offered. This whilst the X-dek panel is available in four outer layer varieties which are all available with a 0,9 and 1,1 mm inner metal sheet, making eight varieties in total. *Image 3.17 A,B&C* shows three of the four outer finishes of which only one is a, 0,7mm, metal sheet. The other three are foils, allowing for a different finish to be applied after installation, such as green roofs, EPDM and TPO. Interestingly only one of the four available types have an upper layer that can contribute to the structural performance of the panel. This while a double sides structural component is one of the most fundamental aspects of a traditional sandwich panel. In comparison to the Brucha panel Kingspan's X-dek panel counteracts this weaker upper side with a heavier bottom sheet. With 0,9 and 1,1 mm it is considerably thicker than the 0,6 mm sheets of Brucha. Their double sheets total on 1,2 mm which is just over the single sheet thickness of the X-dek. Their thickest double layer product has total 1,8 mm of steel, probably making it the stronger product.

**Strength**
Unfortunately, there was no data available of the Brucha panels regarding their mechanical properties. The X-dek panel however was extensively documented with tables for all core thicknesses, all different outer layers and outer thicknesses and multiple assembly configurations (Kingspan, 2018). The strongest variant with and without metal sheeting on top can be seen in tables 3.05 and 3.06. As can be seen in those tables the largest stated span is 7 meters, while panel up to 13,4 are sold standard. Bending compression values at that point for most panels lie beneath 1,0 Kn/m2. Which for a flat roof configuration would mean that it couldn't support standard snow loading. At larger spans values would decrease even more rendering their application useless. However, 7 meters is practically half of the maximum length of 13,4 probably proving that larger panels are designed for triple mounting. Unsurprisingly, Double field spans are also recommenced in the Kingspan brochure, as can be seen in *image 3.18* (Kingspan, 2018). As to be expected the strength difference between the double and single sided metal sheeting is clearly visible. Especially at larger spans its loading capacity is almost double, showing the effectiveness of the Sandwich Panel concept.

**Application**
Although the X-dek and wood fibre Brucha panel are to an extend comparable sandwich panels their application range differs quite significantly. The origin of this difference lies with the opposite side on which the products have their profiled metal sheet. Kingspans X-dek panels have a profiled bottom and flat upper sheet. The versions without a metal top require the application of a final roofing material after their installation. With the panels very low minimal pitch of 1 degree this allows the realisation of large flat roof, making them suitable for a range of applications, even green roofs. This opposed the the Brucha DP-H which has a larger minimal pitch of 3 degrees. Although still considered a flat roof this triple incline is less ideal for ultra-flat applications. This higher pitch also translates into better drainage and therefore, this requires less rigorous waterproofing. In case of the Brucha panel this is solved in the rising profiles overlapping while the X-dek panels require for afterwards applied welded watertight roofing material.

### 3.3.2 Volumes
The goal of this quantitative analyses is to get a clear image of the industries size. These insights in the scale of the industry will be used as input to the production development process in chapter 6. Unfortunately, there weren't any sales data of sandwich panel roofing solutions available for this research. This would have helped determining the current size at which sandwich panels are applied. However, as established in section 3.2, sandwich panels currently aren't the industry's go-to roofing solution. But, as mentioned at the start of this section, the use of sandwich panels does align with the industries goals and need to move towards circular principles. For this quantitative analysis this would have meant that the sandwich panel sales data would have needed some interpretation and extrapolation. Instead, the in 3.1 discusses reports of the insulation materials sales and logistics real

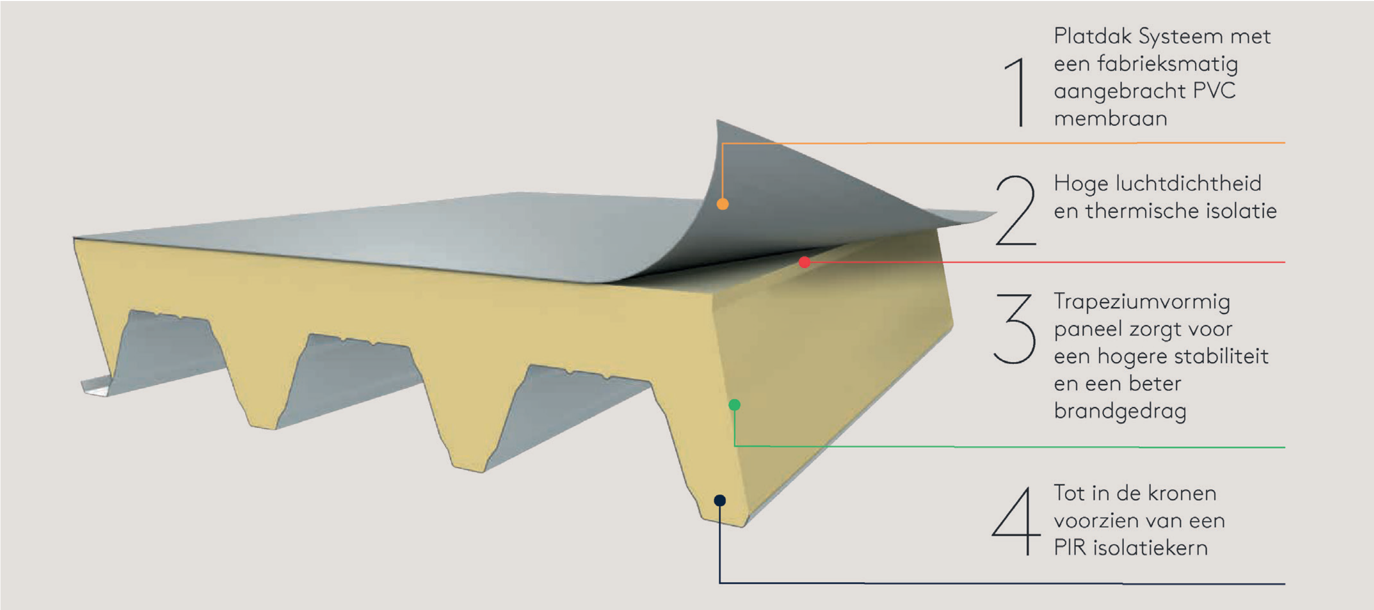



***Image 3.16:*** *Kingspand X-dek 106 sandwich panel for roof applications with PIR core*

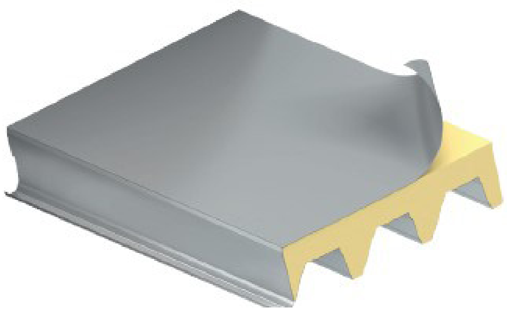


***Image 3.17A:*** *Kingspand X-dek 106, 1,5 mm PVC top*

**Variabele belasting (kN/m²), CC2, enkelvelds**
Staaldikte: Buitenplaat 0,7 mm, binnenplaat 1,1 mm

| Kerndikte (mm) | Belasting Type | Overspanning (m) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 3,00 | 3,50 | 4,00 | 4,50 | 5,00 | 5,50 | 6,00 | 6,50 | 7,00 |
| 80 | Druk | 6,51 | 5,56 | 4,31 | 3,07 | 2,23 | 1,64 | 1,21 | 0,90 | 0,67 |
| | Zuiging | 6,80 | 5,84 | 5,13 | 4,32 | 3,27 | 2,53 | 2,00 | 1,61 | 1,32 |
| 100 | Druk | 6,72 | 5,74 | 4,87 | 3,54 | 2,62 | 1,97 | 1,49 | 1,13 | 0,86 |
| | Zuiging | 7,02 | 6,04 | 5,30 | 4,73 | 3,78 | 2,97 | 2,37 | 1,92 | 1,58 |
| 140 | Druk | 6,72 | 5,74 | 4,87 | 3,54 | 2,62 | 1,97 | 1,49 | 1,13 | 0,86 |
| | Zuiging | 7,02 | 6,04 | 5,30 | 4,73 | 3,78 | 2,97 | 2,37 | 1,92 | 1,58 |

**Variabele belasting (kN/m²), CC2, tweevelds**
Staaldikte: Buitenplaat 0,7 mm, binnenplaat 1,1 mm

| Kerndikte (mm) | Belasting Type | Overspanning (m) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 3,00 | 3,50 | 4,00 | 4,50 | 5,00 | 5,50 | 6,00 | 6,50 | 7,00 |
| 80 | Druk | 3,93 | 3,37 | 2,95 | 2,63 | 2,36 | 2,15 | 1,96 | 1,81 | 1,57 |
| | Zuiging | 4,51 | 3,93 | 3,49 | 3,14 | 2,86 | 2,64 | 2,45 | 2,28 | 2,14 |
| 100 | Druk | 4,16 | 3,56 | 3,12 | 2,77 | 2,49 | 2,26 | 2,07 | 1,90 | 1,76 |
| | Zuiging | 4,77 | 4,14 | 3,67 | 3,31 | 3,01 | 2,77 | 2,57 | 2,40 | 2,25 |
| 140 | Druk | 4,16 | 3,56 | 3,12 | 2,77 | 2,49 | 2,26 | 2,07 | 1,90 | 1,76 |
| | Zuiging | 4,77 | 4,14 | 3,67 | 3,31 | 3,01 | 2,77 | 2,57 | 2,40 | 2,25 |

***Tables 3.05 & 3.06:*** *Kingspand X-dek 106, span width*

***Image 3.17B:*** *Kingspand X-dek 106, bitumen top*

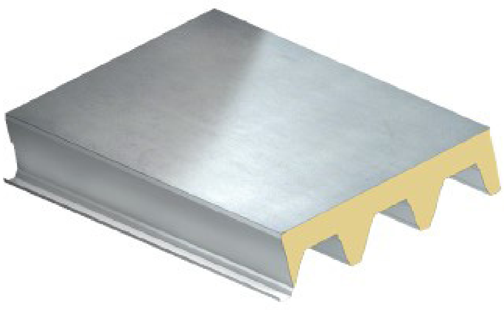


***Image 3.17C:*** *Kingspand X-dek 106, steel top*

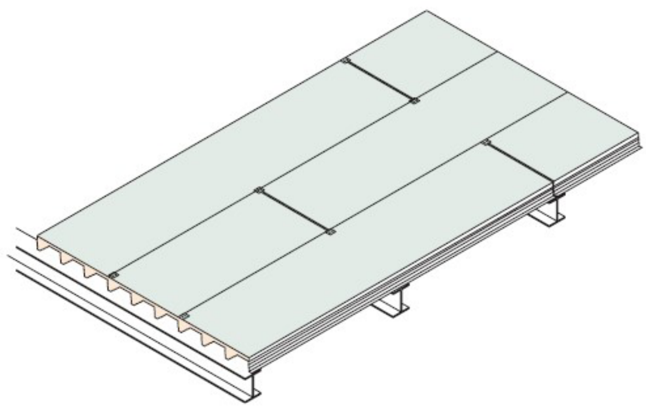


***Image 3.18:*** *Kingspan recommanded application: triple support and half brick bond for equal load distribution*

estate will be used for the determination of a potential industry size.

At the end of 2018 there was 33.343.000 m2 of distribution centre in The Netherlands (Van Wijnen, 2019). An equivalent of 6600 soccer fields divided over 2000 buildings. In 2018 90 new buildings were constructed with a joined surface of 2.154.000 m2 (Van Wijnen, 2019). As distribution centres are a rather simple typology, nothing more than a large empty box. The conversion from total square meters to the number of square meters of roof is very simple, namely: 1:1. For the ease the research and due the probable insignificance the percentage of offices and other facilities is neglected. Thus in 2018 the total amount of roof insulation in DC's was 2.154.000 m2. From ***images 3.01 & 3.02*** can be derived that this was 10% of all insulation material applied in new buildings and 16% of al rigid foam insulation. As ***image 3.06*** shows there is an upward trend currently within the construction of DC's. This makes that the total probable amount for the coming years will lie somewhat higher than the 2018 number. ***Image 3.20*** (building stock) shows that over the last ten years although a decrease in construction during the financial crisis years a steady production rate has been realised. A production of higher than 2.5 million square meters annually therefore seems to be unrealistic.

***Image 3.19:*** *Distribution Centre LIDL Waddinxveen*

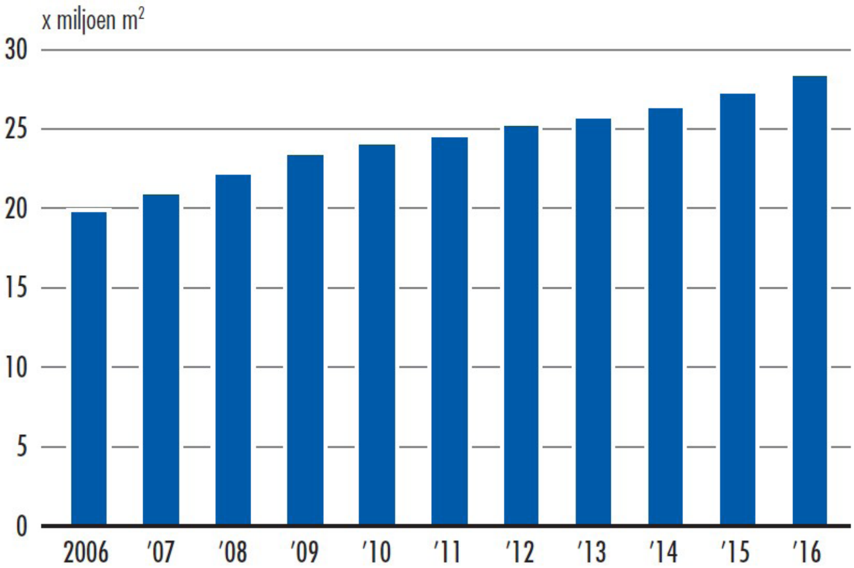



***Image 3.20:*** *Development of logistic real estate building stock per m2*

# 4

# Development Strategy

This is a transitional chapter which looks back at the analytical research of the previous two chapters and based on its combined insights opts for development and research strategy for the second part of this project and beyond. Based on what is currently known on MBC's and what is demanded from the DC construction industry relevant quantitative and qualitative knowledge gabs will be established in 4.1. In 4.2 these knowledge gabs will be prioritised based on their criticality in the success of the development of the product. Based on those insights and considering the restrains of this project a number of practical research steps will be formulated.

## 4.1 Knowledge Gaps

In chapter 3.1 was shown that for new buildings rigid, synthetic insulation foams are used most. Especially in the construction of large-scale industrial halls like distribution centres the materials are used in enormous quantities. At least 16 percent, of all produced foams finds its way into the DC typology and probably a lot more into smaller but similar industry halls. Since no sustainable rigid insulation currently is available a large impact can be made by providing an alternative for these products. In order to answer the question if MBCs can form such a sustainable alternative the in chapter 3 identified demands and in chapter 2 discussed material performances will now be compared. As it is likely that at this stage of the technologies development that certain knowledge gaps exist, further sections of this chapter will focus on turning these in actionable research.

However, first, the findings of chapter two and three need to be reduced to their combined core. It was found that there are roughly two types of aspects important in this regard; qualitative and quantitative parameters. An additional parameter that was identified to be of importance here was the product, or at least its design and functioning. Because functionality and design can be both the input and output of a development phase it was chosen to discuss these issues separately in section 4.2. There, based on the perspective of product development, the investigation of certain research gaps will be prioritised. Leading to the formulation of the research steps for the continuation of this project.

### 4.1.1 Quantitative Pwarameters

As discussed, substituting traditional foam insulation with MBC in the construction of distribution centres forms a great opportunity to achieve positive environmental impact. Scale is needed to meet the 'hunger' for insulation material from that sector. With efficiency and repetition being essential in that industry scale is also needed to become an appealing alternative. Interestingly, scale is also exactly what is needed to interest construction industry players and investment. "Financers are actively looking for investments that help lower C02-emissions. They have to report on their activities to contribute to the pushing back of greenhouse gas emissions" (Duurzaamgebouw, 2017). It can thus be concluded that also from the perspective of sustainability it is necessary to research the production of MBC's and the scalability of such production.

During the literature review of *Appendix 2* some scarce initiatives were found looking into the production of fungal materials. The schematic depiction of Ecovative's, now closed, production process for mushroom packaging (Image 4.01) was discussed by Holt (2012). This was merely a numeration of the research method's steps and not an exploration of the relation between product and production. Such an approach was found in research conducted by Jiang (2014; 2016 & 2017). However, the applied approach was focussed on the development of a specific method and not, as in this project, industry and therefore production oriented. In this case mycelium-based sandwich panels have to be introduced into a well-established and highly regulated industry. Instead of developing and optimising a perfect production process, the focus should lie with generating the interest of industry players. Because in the highly regulated construction sector it will be the industry that forces the innovation to be sound and proven.

From that perspective it is the question 'What scale can be obtained in MBC production?' that prevails. Looking back at the projects and literature studied in chapter two and corresponding *Appendices 1 & 2* (study of precedents and literature study) it must be established that knowledge gaps currently prevent answering and researching that question. Before a valid response can be formulated, first has to be explored if large MBC object can be made, as no projects were found of a size near that is needed for the envisioned application. And secondly how would a product facility making MBC-based sandwich panels look like?

### 4.1.2 Qualitative Parameters

In the industry analyses of chapter 3, three qualitative parameters were found to be of the highest importance. This because they directly influence the applicability of a product. The aspects were: fire safety, thermal conductivity and structural performance. All of them have been discussed during the course of chapter 2, in 2.4 and 2.6. Considering those findings potential knowledge gabs will be looked for per individual subject.

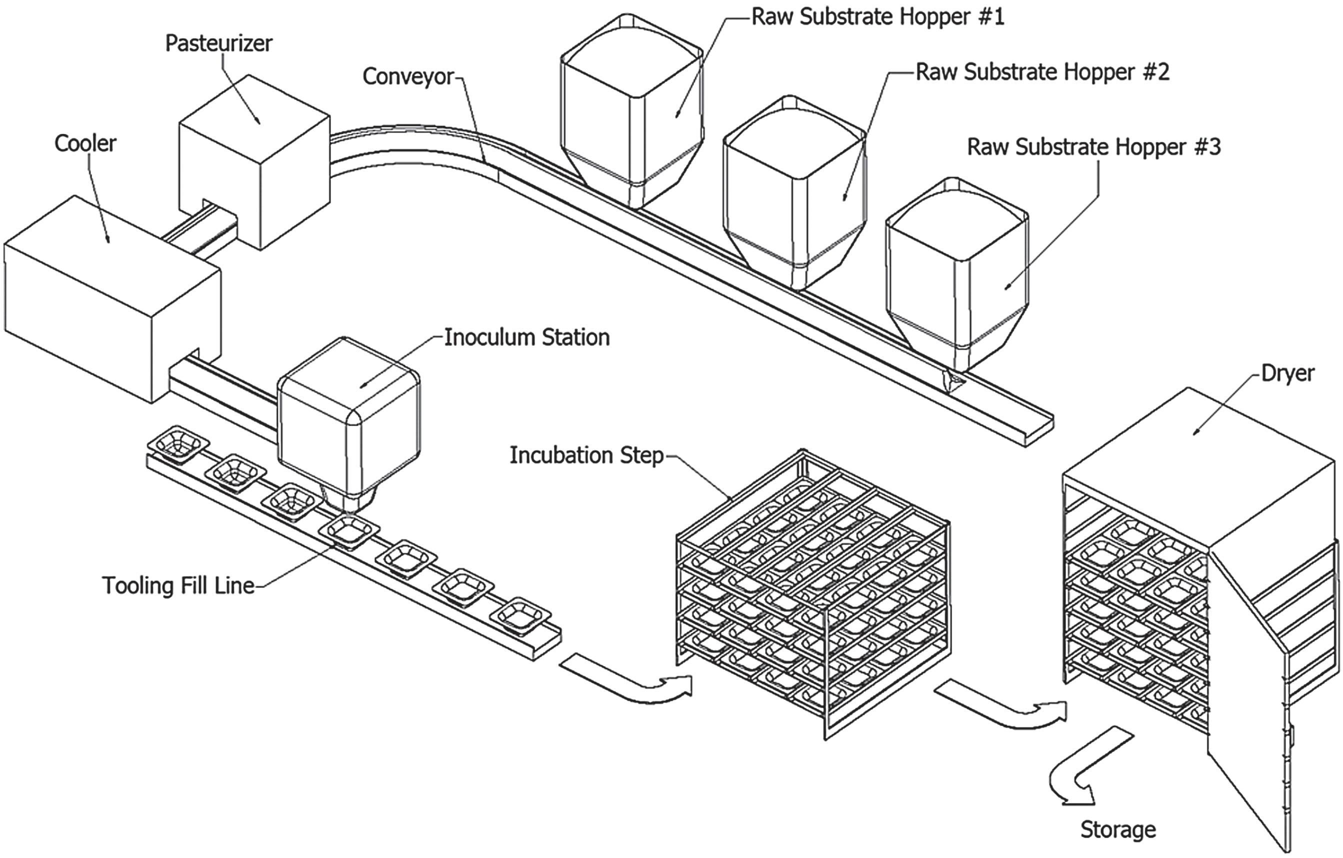



***Image 4.01**: Schematic depiction of Ecovative's pilot facility*

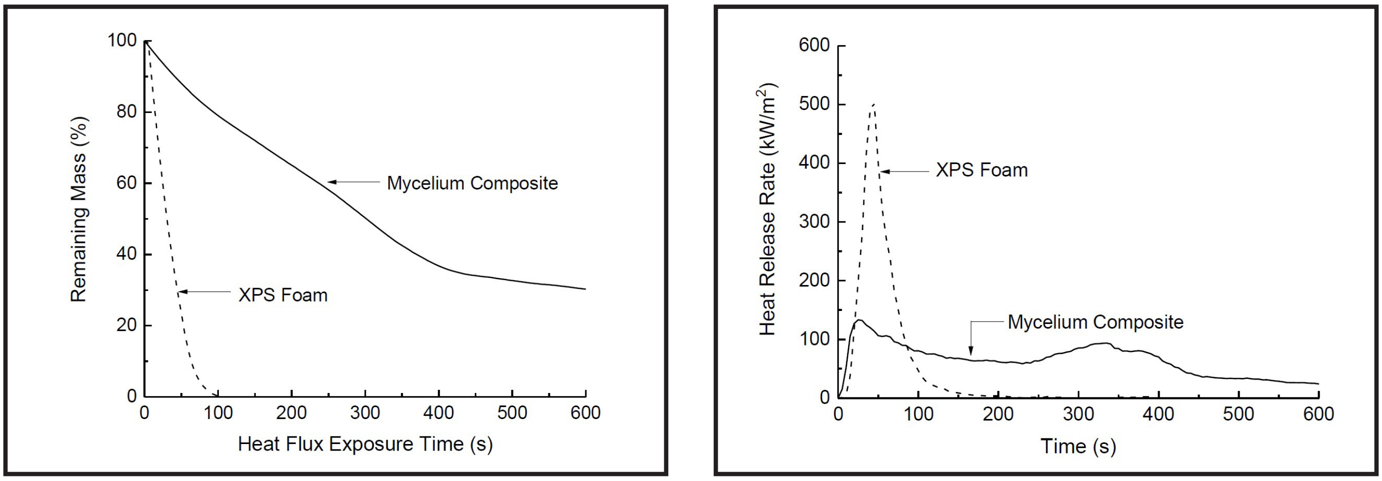



***Image 4.02**: Results from reaction to fire tests by Jones (2018)*


***Image 4.03**: Experimenting with glass additions for fire safety by Jones (2018)*

**Fire safety**
As seen in 2.6 data on MBCs' reaction to fire is limited. However, within that little data some interesting findings can be found. First of all, the acoustic panel by MOGU is interesting as it has a E.U. certified D-score (Mogu, 2019). This means that the material is suited for use in most parts of buildings. Fire escape routes, high-rises and spaces with special safety needs would need a higher B-score. In distribution centres, as discussed in chapter 3, fire safety demands are generally high, due to their valuable contents. A Euro standard B-score would therefore generate a much larger interest in the material. However currently such performance is not likely to be within reach.

Further research and optimisation are needed to increase the material resistance against fire. This would be of high priority within the industry-oriented product development approach if it wasn't for the facts that 1. Highly specialistic knowledge is required on combustion and very specific facilities are needed to perform the needed tests. And 2. Currently Australian researchers from the RMIT university led by Jones are conducting such research (Jones et al., 2017; 2018), producing promising results (Image 4.02 & 4.03). It is therefore questionable of within the possibilities of this project any contribution could be made in this area.

**Thermal conductivity**
In 3.1 several currently available insulation materials were discussed based on their usage and environmental impact. Now these materials will be compared based on their insulation performance in relation to the data found for mycelium in section 2.6. In Image 4.04 an overview can be seen of the thermal conductivity of a range of insulation materials. At the top of the image wool-like insulation materials are depicted while rigid, foam-like materials are displayed at the bottom. A distinction in colour indicates the (non)sustainable nature of the materials. Please note that the thermal conductivity of foams is in general lower, and this better, than that of wools. While most natural insulation materials, apart from MBC's and cork, are wools. Fungal foams therefore have a distinctive feature. But compared to traditional foams their performance still lacks considerable.

Optimising that behaviour would be beneficial to the attractiveness of the material. However, as quite a lot of research has been done on the subject it is unlikely that within the duration of this project significant contributions can be made to the current existing field of knowledge. Especially since the morphology of MBC's (Image 4.05) is open and in order to closed cell structure like that of PIR (Image 4.06) would be optimal.

**Structural performance**
A roof panel needs to withstand bending forces. During the during the literature review (*Appendix 2*) was found that most research in to the structural behaviour of MBC's focussed on its ability to withstand compressional and tensile forces. Some research was done into the materials bending behaviour which showed varying results. As the fungal cell structure (Image 4.05) is similar to that of bone (Image 4.07) it is expected that the material can handle such forces quite well.

However, it is unlikely that MBCs alone are able to come close to the performance of sandwich panels discussed in 3.3. It is also the composability of the material that is of interest from a circular economy perspective. In the literature two papers were found discussing composed sandwich applications with MBC cores. Surprisingly, none of these applications seemed to recognise the potential of fungal adhesion in combination with a natural solid outer component. Image 4.08 shows a composed product made with fabric and Image 4.09 shows a sandwich panel made with an MBC core glued to carbon fibre outer sheets.

No data thus exist on completely natural and fungally adhered sandwich panels. As explored earlier, such application would be interesting from both a circular as applicability level. Investigating the ability of mycelium-based sandwich panels to withstand forces under bending would thus be an interesting addition to the currently body of research.

### 4.1.3 Product Parameters
The traditional sandwich panels analysed in 3.3 and the mycelium products reviewed in Appendix 1 look completely different. The professionalism present in a mass-produced construction product has

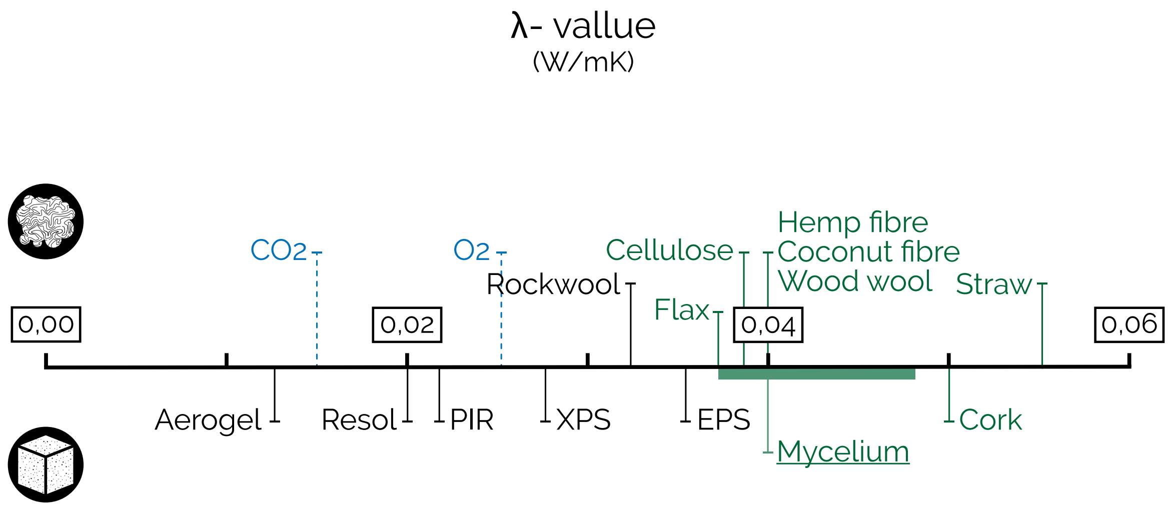



***Image 4.04:*** *Overview of thermal conductivity of various insulation materials*

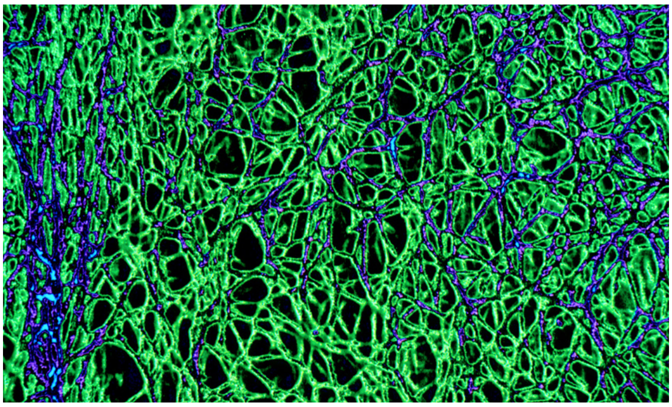


***Image 4.05:*** *SEM image of mycelium's cell structure*

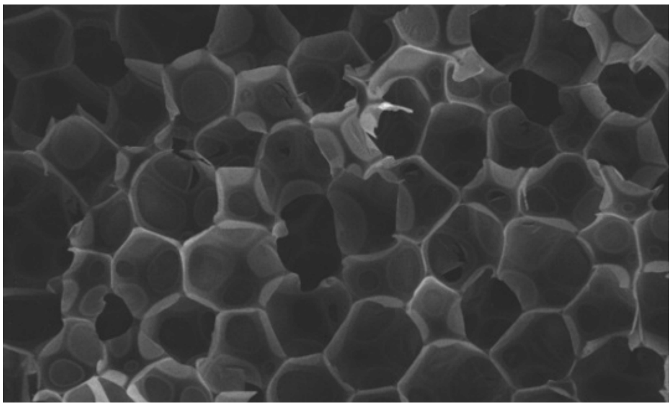


***Image 4.06:*** *SEM image of PIR's cell structure*

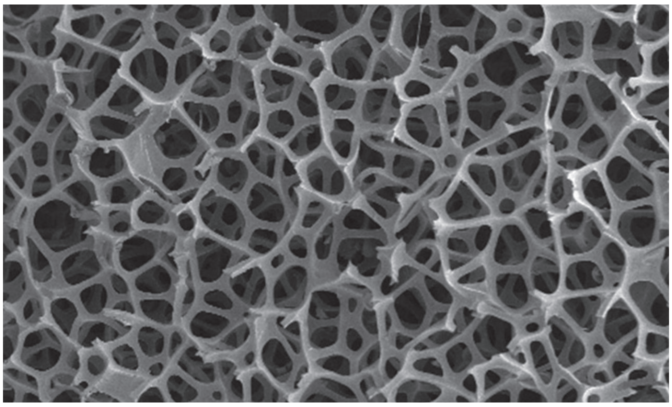


***Image 4.07:*** *SEM image of bone structure*

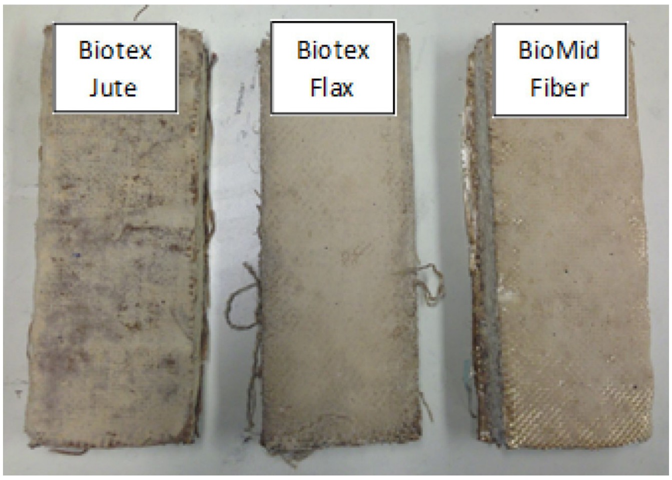



***Image 4.08:*** *Sandwich panel from canvas and MBC by Jiang (2016)*

***Image 4.09:*** *Sandwich panel from carbon fibre and MBC by Travaglini (2014)*

a completely different attitude than the often art-like projects made with mycelium so far. It seems if a large gap still has to be bridged before mycelium-based products can be applied in a distribution centre. However, in a product development process it is key to regard things for what they represent, not how they look. All previous work should be considered as prototypes containing valuable development lessons. It is important to realise which crucial lesson hasn't been learned and to explore how the most effective prototype can tell it. In this section exactly that will happen. On various level will be explored what knowledge is needed. Based on this process will be established which steps are most crucial and need to be taken first.

**Life Cycle**
The design and development of a circular product looks completely different form that of a traditional, linear project. As one faulty step, or mistake in the products life cycle can render all other treatments useless. A holistic design approach is therefore needed to consider all steps and stages from source material to the end of life scenario and beyond (Image 4.10 & 11). Specific circular design tools exist that help guide that process (Moreno et al, 2017). Using such tools early on the development process can help achieve maximum results. However, for this explorative project incorporating such step was deemed unnecessary. The use of natural materials in a circular manner was the starting point of this project. As discussed in 2.5 this insures a certain baseline circularity which is regarded as sufficient for now. When more insights are gathered in the performance and applicability of the product such steps should be considered again. It should therefore become part of future development steps.

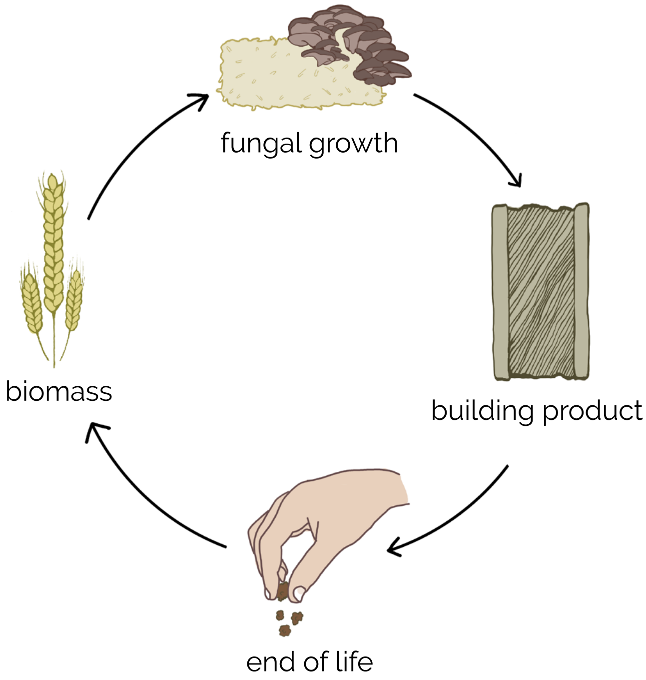
**Application**
The user phase is an important part of the products life cycle. For one as this is the period in which the product serves its use. But from a circular perspective another aspect needs to be safeguarded. The mode of application often prohibits a circular product to be properly retrieved, diminishing the circular impact. The analyses of 3.3 and ***Appendix 3.1*** have provided insights in the application methods of roods in distribution centres. Based on the prefabricated and efficiently constructed structure it would be expected that disassembly of such edifice would be easy. This would be true if it wasn't for the method of applying the waterproofing, interconnecting all separate parts. Gluing and welding large pieces of roof cover at once after all other components have been installed is very fast and lowers the risk on leakages. It is therefore understandable that the design of the Kingspan X-dek panel with a large corrugated lower sheet, but flat top takes such installation into account (Image 4.12).

As waterproofing is especially important for natural materials mitigating such issue should be a crucial part of the product development process. However, applying a waterproof material afterwards is such an effective method that most other solutions are deemed unpractical. As it is solely the irreversible nature which is the problem a brief exploration was undertaken in search of reversible option. Such an alternative was found in the form of the endlessly recyclable glue NIAGA, developed by DSM (DSM-Niaga, 2019). As this solution provided sufficient perspective for the current phase of the product development process it was decided not to incorporate further research into this topic in the rest of this project. If product performance is fully proved this solution should be investigated further.

**Composition**
With a solution at hand for the waterproofing of the sandwich panels there truly is only one aspect from a circular design perspective that needs to be investigated. A sandwich panel is an effective collaboration between light weight insulating core and two thin and strong outer sheets. MBCs are a potentially good core material. But its performance fully depends on the material it is combined with, both structurally as circularly. The selection of an outer material is thus an important, influential, step in the development process.

As the fungus needs natural compounds to attach to all synthetic and metal materials aren't eligible from a functional perspective. And, of course, also as they are not natural. Wood naturally is a potential contender as it is the most used natural construction material (Allwood & Cullen, 2015). However composed wood products such as OSB are bonded using glues that emit the toxic chemical formaldehyde (Mantanis et al., 2018). In recent year an array of formaldehyde free products has come

*__Image 4.10__: Life cycly of a mycelium sandwich panel*




| Biomass | Production | Building | End of life |
|---|---|---|---|
| - Types & origin<br>- Quality<br>- Collection<br>- Preprocessing:<br>shredding<br>pressing<br>dehydrating<br>fibre isolation | **- Substrate mixture**<br>**- Pastheurisation/ steralisa-tion**<br>**- Inoculation**<br>**- 1st Growth (colonisation)**<br>**- transfer/shaping/mould**<br>**- 2nd growth (...)**<br>**- killing/drying** | **- Prefabrication**<br>- Transportation<br>- Installation | - Dissassembly of building<br>- Reuse, refurbising, recycling<br>- Product treatment<br>- Biodegrading options:<br>composting<br>fertalising |

*__Image 4.11__: Exploration of all steps in the life cycle of a mycelium sandwich panel*

*__Image 4.12__: Kingspan X-dek 106 sandwich panel being installed*

available, as OSB-Zero and ECO-board, using a so-called MDI-based glue (Maiburg, 2018). The full name of this is compound is methylene diphenyl diisocyanate it turns out that this is the same chemical compound as PIR-Foam consists out. Solving the problem in the centre and introducing it in a mixed form in the outer layers would be odd. Therefore, using any of these products would defy the point.

A fully natural alternative is needed. The use of pure wood would could be considered but in the required lengths would make the sandwich panels priceless. A suitable material was found in the form of Ecor. This is a completely chemical free cellulose based hardboard and resembles high density cardboard. Although commercially available, this material is still under further development. For that reason, it was decided that the one major shortcoming of the material would be ignored for this stage of the research. Currently the material is only available in limited dimensions. It is sold in sheets of 1250 x 3000 mm of 2,5 mm thick (Noble Environmental Technologies, 2019). It is also available in other shapes and sizes, which indicates that it is a versatile material with further develop potential (Image 4.13). The standard material would likely be too thin for direct use in a roof plate but is perfect for a scaled exploration of the products at tests conducted with such.

## 4.2 Executive Research Plan

To conclude a brief overview will be given of the current research topics and knowledge gaps crucial to the further development of MBC products and their attractiveness to the construction industry. Based on the constraints of this project and other reason, elaborated upon in the earlier parts of the chapter,

**Further research topics within this project:**

- Structural behaviour of fully natural, mycelium-based sandwich panels under bending forces.
- How would a production facility making MBC-based sandwich panels look like and what scale can be obtained in MBC production?

**Crucial research topics outside this project:**

- Exploring possibilities to improve the reaction to fire of the material to a B-level within E.U. standards.
- Exploring possibilities to lower the thermal conductivity of MBC's.

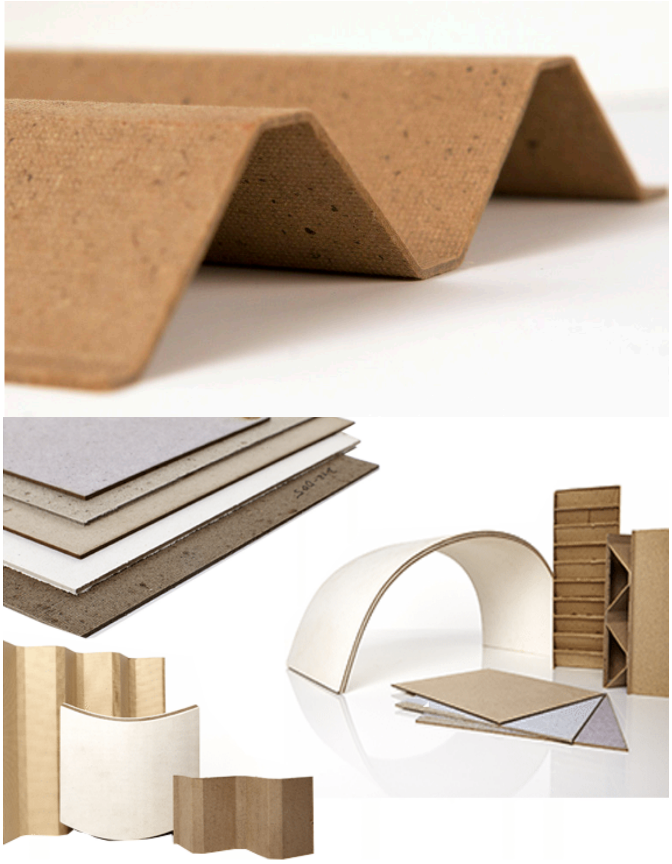


*__Image 4.13__: Overvieuw of Ecor product range*

| Data* | Metric |
|---|---|
| Density | 1067 kg/m³ |
| Modulus of Rupture | 48.5 MPa |
| Modulus of Elasticity | 6020 MPa |
| Tensile Strength | 39.1 MPa |
| Internal Bond | 0.492 MPa |
| Thickness Swell | 64.6 % |
| Linear Expansion | 0.194% |
| Fire Rating** | Class A |
| Formaldehyde and CREL Emissions | None |

*__Image 4.14__: Ecor datasheet*

# 5

# Experiments

This chapter is dedicated to the preparation, implementation and results of the mechanical tests that were carried out as part of this research project.t

## 5.1 Plan of Action

The goal of this section is to give a substantiation of the chosen test typology. An explanation of the proceedings in this chapter which evolve around this set of experiments. And a detailed description of some of the starting points for the experiments such as sample design.

**Testing typology**

As concluded in chapter 4, the structural properties of composed MBC products are the biggest unknown aspect in the structural behaviour of the material. At the same time however, it is one of its potentially biggest unique advantages. Investigating and quantifying this capacity therefore closes a hole in the available literature. But simultaneously it will provide insight in the usability of such composed products. It was therefore decided that testing this capacity was of prime importance in the industry-oriented product development approach.

The question thus is, "How is the strength of sandwich panel tested?". Most papers found and reviewed in the literature review of chapter 2 focus on the materials performance under compression. A compressional load however, case doesn't match with MBC's potential for modern industrial building methods. Compression is for the pure structural materials such as steel and concrete. Logic, and the early studies, dictate that such role isn't possible for MBC. Other parts of a structure are more and more panelised. Floors, facades all come in ready bits. The load cases for such products are almost always bending.

It isn't strange however that compressional and to a lesser extend tensional behaviour of the materials were tested so relatively extensive. They are the two fundamental structural characteristics and thus studying them makes sense from an academic point of view. In a more product-oriented approach investigating the materials behaviour under bending is more logic. Bending actually comprises of local compression on the topside and local tensioning at the bottom of the specimen, as can be seen in image 5.02. Conceptually similar to how yellow and blue create green. So, although no full understanding of mechanical material behaviour can be conducted from a bending test. It does offer a good indication of the materials applicability and is therefore in this project's explorative context very appropriate.

Bending is tested in bending tests, logically. But there are two types of bending tests, 3 point and 4 point bending tests. The highest bend stress occurs under in a three-point flexural bend test. In a four-point bend test, the maximum flexural stress is spread over the section of the beam between loading points. The concentration of force is higher in a three-point test, whereas the concentration force is spread out over a larger region in a four-point bend test. Thus, realising a more averaged indication not based on any local imperfections. Also, a four-point test tends to be the best choice if the material is not homogeneous, such as composites or wood. Therefore, in this case, a four-point bend test is the best fitting option.

**Experiment design**

The goal of a four-point bend test is two-fold. On the one hand the numerical value for the materials bending behaviour has to be derived. This property is called its modulus of elasticity and plays an important role in calculating a product's or construction's structural behaviour. As the reader will come to see in the later stages of this chapter. On the other hand, the behaviour under failure is important. This characteristic has a lot of implications on the safety of a material. A material that very abruptly breaks and loses all its structural integrity has to be dealt differently from a material that deforms before failure and keeps part of its integrity after.

In this particular case in the interest lies not only with the performance of the material but mainly at the performance of a composed product, a sandwich panel. Does the sum of the two cause characteristics that are better or more optimal than its individual parts? In order to make well founded statements about the behaviour of the product it is therefore needed that an underattendance of the separate materials also exist.

The Ecor envisioned for the outer layers is an industrialised product with a constant quality. The known materials properties (see chapter 4.1) can therefore be carelessly used in calculative processing of the

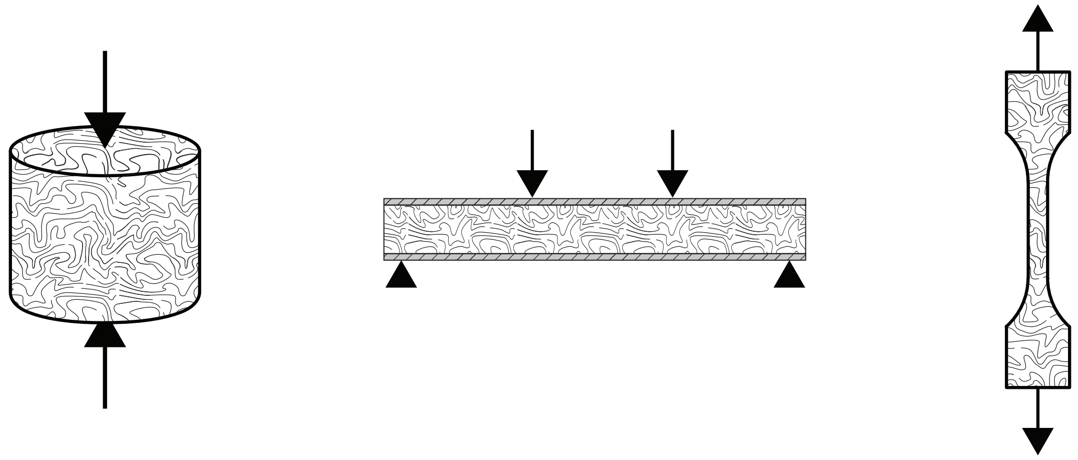


***Image 5.01**: Overview of basic material mechanics tests*

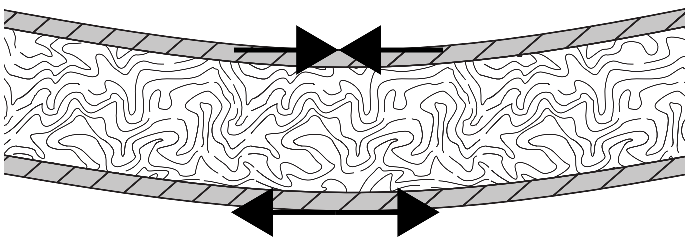
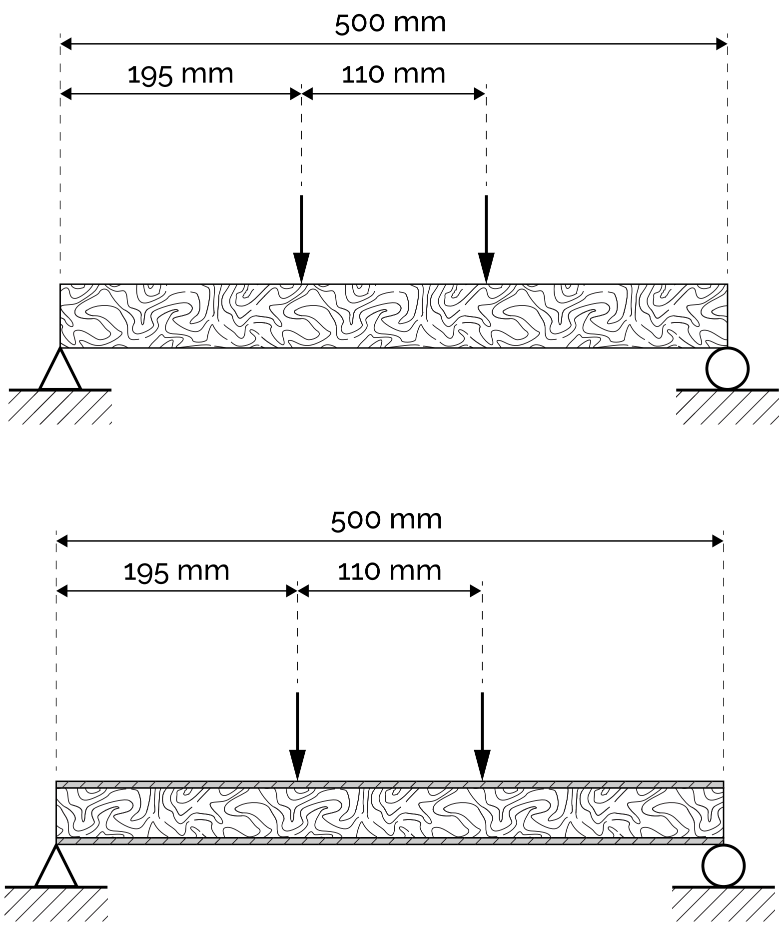


***Image 5.02**: Bending is local compression and local tension*

***Image 5.03**: Schematic representation of experiment setup*




**Dimensions**
Length: 600 mm (500 effective)
Thickness: 50mm
Width: 75 mm

**Insulation Material**
Fungi: Trametes versicolor
Substrate: 2/3 straw, 1/3 hemp

**Plate Material**
Ecor
Density: 1067 kg/m$^3$.
Size: 3000x1220mm
Thickness: 2,5 mm

test results. The MBC isn't industrially available and therefor will have to be custom made. As shown in chapter 2 the composition or recipe has tremendous influence on the performance of the material. To safeguard that a correct value for the used MBC is taken in the calculations it will be necessary to derive that value parallel to the testing of the sandwich panel. This approach was also used by Travaglini (2014) but instead of using natural outer materials and using the fungus to adhere them synthetic carbon fibre composites were glued on. This experiment will therefore for the first time give insight in the bonding capacities of the fungal threads.

In order to get proper view of both the material's and the sandwich's performance five samples of each will be tested. In this way any abnormalities of deviations will be exposed. In image 5.03 a schematic representation of these samples in the test setup can be seen. They will be bridging a gab of 500mm and will have 50mm additional length on each side to prevent them from slipping of when bending. The length of the experiment setup is important because it has direct implications on the height of the needed samples. For accurate results a height of 1/10 of the span of the samples is ideal (Tsai, 1979), in this case resulting in a height of 50mm. What should be noted is that this resulted in the MBC sections in the sandwich and pure sample not having the same thickness. The material specimen is 50mm high but the sandwich one has MBC core of 50 minus two times the 2,5mm thickness of the Ecor, resulting 45mm. The width of the samples was set on 75mm, 1,5 times the height.

For the MBC part of the samples it was decided to use recipe of 2/3 of hemp fibres of the brand Amboise and 1/3 shredded rapeseed straw particles of the Rapsody brand. The objective was to create a lightweight airy composite. Due to its loose and airy natures chopped straw was chosen to dilute the hemp and lower the overall density of the mixture. Input for this decision was the thermal conductivity data of 2.6.2, which show good results with straw and hemp. Also, as discussed in chapter 2.6 a correlation exists between density and thermal conductivity. For the fungus was opted for the Trametes Versicolor. It showed promising results in Appels (2018) and it is hoped that it demonstrates similar behaviour in a non-compressed application.

**Proceedings**

The complete process of testing, including al the pre-test steps, will be described in the next sub chapter, 2.2. With the test setup and samples designed production of the specimens could commence. This process will be elaboratively discussed in 5.2.1. In 5.2.2 will be described how the pre-experimental assessment of the samples was done. And finally, 5.2.3 gives an overview of the proceedings of the actual tests.

The results of the test will be discussing in subchapter 5.3. The tests and the resulting data don't mean anything without the proper processing and interpretation. First, in 5.3.1 an overview of the experiment's results will be given. Numeric data and visual feedback from the testing will be compared for a first impression. In 5.3.2 will be described how the numeric data was then mathematically processed and how the modulus of elasticity was found. Ultimately, in 5.3.3, the results will be interpreted. The derived values of the pure and sandwich samples will be compared with each other to make a statement about the fungus binding capacities. Additionally, a comparison with conventional construction materials and product will give an indication of its relative performance. Only then can the results of the experiments be used as feedback into the development process. In subchapter 5.5 various potential optimisations and improvements will be discussed, calculated and briefly tested in some small extra experiments.

## 5.2 Description of the method

In this section the implementation and execution of the plan of action will be discussed. A detailed as possible description of the proceedings will be given in order to insure the scientific repeatability of the tests and the created samples. As remarked before it was found by Elsacker (2019) that most of the literature on mycelium materials is lacking such sufficiently elaborated descriptions of the applied method.

This can be regarded as tragic, as it makes the interpretation of the scarce literature even harder and more doubtful. Slowing down the development and the maturity of the technology. On the other hand,

*Image 5.04: Substrate mixing*

*Image 5.05: Filled substrate bags*

*Image 5.06 & 5.07: Sealing of the substrate bags*

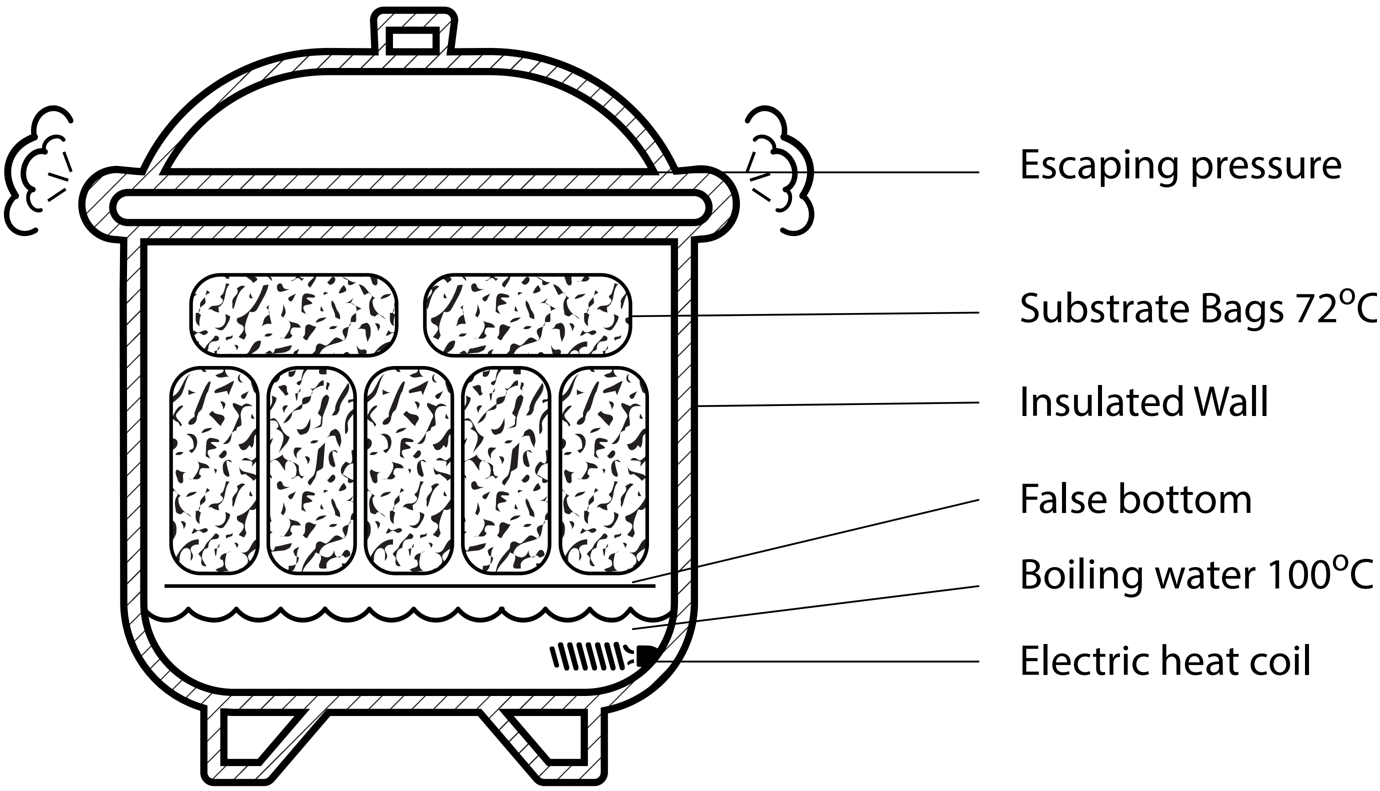



*Image 5.08: Schematic representation of pasteurisation device*

however, it has to be said that the complexity and versatility of the subject makes complete mastery of it necessary in order to produce such elaborated description. Especially surrounding the controlled or at least monitored growth of the fungus a complex array of influential aspects are at play, which for most fungi, aren't even fully understood be esteemed mycologist. It can therefore be that certain parameters of importance were unhopedly overlooked in this process. This, unfortunately, is part of the uncertain process of material and product exploration and innovation which as much a best-guess experimentation with the goal of growing understanding as it is the development of real implementable solutions.

The process will be discussed in the chronological order of sample production, sample assessment and the execution of the experiments. The results of the performed tests will be discussed in the subsequent sections.

### 5.2.1 Sample production

**The substrate**

For the mycelium-based composite the in section 5.1 stated recipe was used. The dry fractions of straw and hemp were measured based on volume and added to a concrete mixer (Image 5.01). The weight of the total mixture was measured and in accordance to it 62% if water was added. The concrete mixer was then set to mix its ingredients for 15 minutes. A few times during this period the mixer was stopped, and it was checked if any stuck 'dead zones' of dry of overly wet material continued to exist within the drum.

When the mixture was evenly mixed and the moisture absorbed, the substrate mixture was evenly distributed over special micro filter bags (Image 5.05). These were purchased from the Belgian company Sac02 and their PP75/BEH6/V37-53 model was used. The bags were then compressed to force out all the air and then sealed (Image 5.06 & 5.07). This was done to lower the insulating capacity of the mixture and thereby promoting the pasteurisation process, due next.

The bags and their contents were pasteurised in handcrafted large-scale steamer. A vessel in which a volume of water is brought to a boil with use of a plunger. The bags are placed on a permeable false bottom above the boiling water and its steam heats the bags. This was done for approximately 3 hours. A schematic depiction of the used steam vessel can be seen in image 5.08.

After the pasteurisation process the bags were taken out of the steamer and left to cool down overnight. The next morning, they were inoculated with spawn from the Belgian firm Mycelia (image 5.09). This was done inside a sterile working environment, called a laminar flow hood (image 5.10). One by one all bags were cleaned with 70% alcohol and cut open. A weight of approximately 8% in relation to the bags weight was added of the spawn. The bags were then sealed again and transferred to a growing cabinet (image 5.11). Here the bags were left for six days to let the fungus colonise the substrate. Conditions in the growing cabinet were not controllable. It can be assumed oxygen levels were normal or similar to that of the rest of the room as some parts of the tent were left open. It was made sure however that no light could enter the tent. The temperature in the tent was between 19 and 23 degrees Celsius.

**The samples**

During this six-day colonisation period the moulds for the formation growth phase were custom made. This was done using a table saw and 12mm thick concrete plywood. The bonding and finishing of this material are developed for the moulding of concrete. Its resistance against wet conditions and surface quality in releasing the set concrete were anticipated to be ideal for the goals of this project. Additionally, this construction method seemed the most economical and material efficient compared to for instance vacuum formed moulds. Especially since the required shape didn't demand the additional free formedness that thermoforming offers.

Due to the limited space in the laminar flow hood the moulds were limited to house three samples each. With the table saw all pieces were cut to size. The moulds were designed to have only three different pieces, a bottom plate, four parallel walls and six head and tail pieces. Using the table saw, incisions were made in the top of the bottom plate. These kept the vertical elements in place and enabled the absence of glue and mechanical bonders as screws. The head and tail pieces were made to snuggly

***Image 5.09:*** *Mushroom spawn*

***Image 5.10:*** *Substrate innoculation*

***Image 5.11:*** *Substrate bags pre-colonisation*

***Image 5.12:*** *Substrate bags post-colonisation*

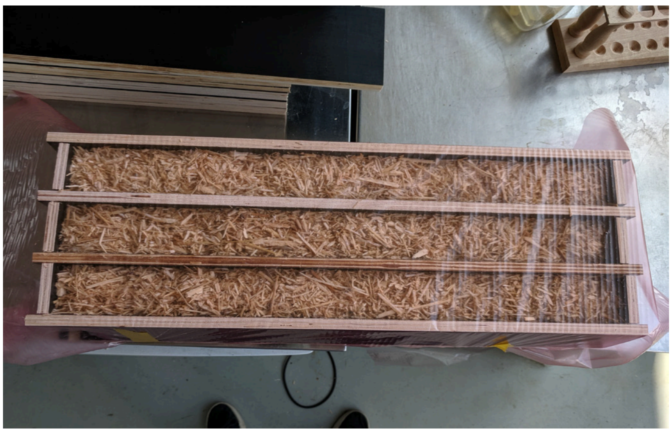


***Image 5.13:*** *Filled mould*

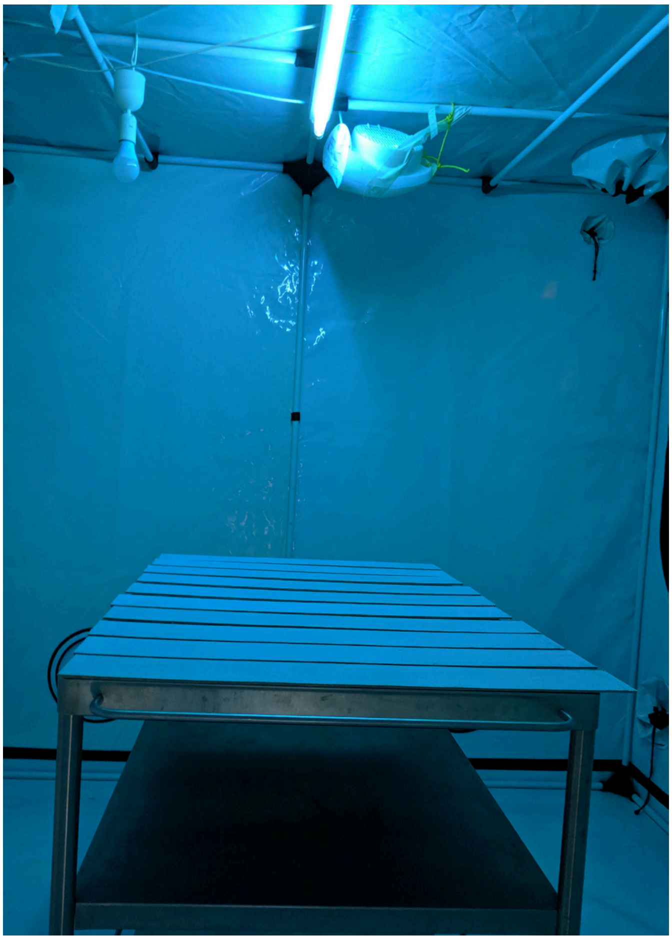


***Image 5.14:*** *UV-sterilisation of Ecor*

fit against the long vertical walls clamping them in place. The tope was intentionally left open for visual inspection of the growth and to insure enough oxygen was available for the growing fungus. During the tailoring of the elements of the moulds the sheets of Ecor needed of the sandwich specimens where also cut to size. This was also done using the table saw as a first try showed this method to have superior cut quality and precision compared to cutting with a Stanley knife.

When both the substrate and the moulds were ready, the next step in the growing phase could be initiated: the shaping phase. To start, the Ecor sheets were sterilised on both sides using UV-C sterilisation (Image 5.14). The moulds were sterilised using 70% alcohol solution and assembled inside the laminar flow hood. The substrate, still inside the sealed bags, was crumbled loose by compressing and shaking the bags. The loose colonised substrate particles were then, inside the flow hood, transferred to moulds. In case of the sandwich samples the Ecor was placed upright against the walls of the moulds before substrate was put in. The material in the filled moulds was then slightly compressed using a cut to size piece of concrete plywood. This, to equalise the surface as much as possible. Open and filled moulds were covered with a foil containing micro perforations. The filled and covered moulds were transferred back to the growth cabinet in which they were left to grow in the same conditions as in the colonisation phase for seven days.

After those seven days the mould were taken from the cabinet. On first inspection the growth seemed to have proceeded perfectly. The foil was removed from the wooden moulds. Slowly, the moulds were disassembled reveiling more and more of the grown samples. The sandwich samples were easily removed as their sides hadn't connected to the walls. The fungus in the pure MBC samples had. Using a spatula this connection was overcome (Image 5.16). Little to no damage was done by this measure. The spatula was also used to remove the samples from the bottom part.

They were then left to dry at room temperature in cabinet with metal mesh shelfs (Image 5.20). The indoor temperature was, due to the hot weather, above 25 degrees during the day and humidity was low. With a van blowing in the direction of the samples enough airflow to take away the moisture was realised. This low temp approach was chosen because of the described negative effect of higher temperature drying on the mycelium (Haneef et al., 2017). The samples were left to dry for a week. But were found to be completely dry after 3 days.

**Temperature and other growth parameters**
Unfortunately, no temperature controlled growing environment or incubation space was available for the samples to grow in. Also, no temperature dataloggers were available in order to accurately map the ambient growth temperature of the material. This was the case for both the colonisation and shaping grow phases. Samples were grown in early to medio June in the Netherlands in a semi-industrial north-facing room and building. Temperature fluctuations will therefore be slow, mild and gradually. Based on incidental readings of the thermometer in the growing rooms an ambient growth temperature between 19 and 23 degrees can be established.

Other growth parameters that are said to be of influence on the fungal growth weren't controlled or measured either. Ideally also aspects as the substrate PH value, temperature swing during pasteurisation and the chemical composition of the substrate are controlled or recorded. For now, their influence on the sample quality is unknown and potential correlation won't be able to be found. In future research these parameters should be controlled or at least recorded more precisely. At this point the approximation of the ambient growth temperature therefore seems adequate.

### 5.2.2 Sample Assessment
The pre-experiment assessment of the finished samples had two goals. Firstly, to record the samples' precise dimensions and weight, as these are essential for the proper processing of the test data and may differ from the design. Secondly, a visual inspection and documentation to assess the (growth) quality of the samples. This to establish if no mayor flaws are present in the samples compromising their comparability on forehand and to explain any potential deviant test behaviour afterwards.

For both assessments, it is crucial that all samples are equipped with a unique number. This way their dimensions and test data of individual samples can be linked during the processing and interpretation

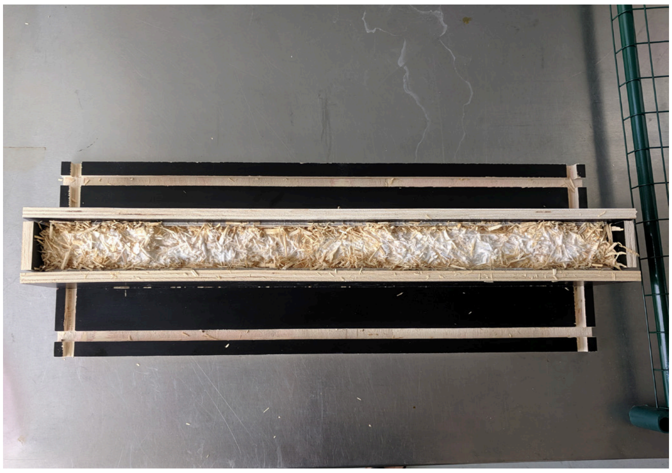


**Image 5.15**: *Fully grown sample in mould*


**Image 5.16**: *Unloading moulds*


**Image 5.17**: *Close-up of fully grown sample in mould*


**Image 5.18**: *Finished sandwich sample in mould*


**Image 5.19**: *Close-up of finished sandwich sample*


**Image 5.20**: *Drying samples*

phases while that date of various samples can be kept separated. It was here that a first methodological flaw of this projects proceedings was made. Since the fungal growth is essential to the quality of the samples, they should already have been labelled during their growth phase. This, to allow the potential discovery of importance of slightly deviant growth conditions, as with the solo growing or middle samples (image 5.18) based on deviant performance between the samples. However, labelling only was done after the drying phase after which originating the samples had become impossible. All 'normal' MBC samples were given a number 1-5 and al sandwich samples were given a code of F1-F5 (Image 5.23).

**Sample measurements**

For the measurements of the samples an electronic scale, analogue calliper and hinged ruler were used (images 5.21 & 5.24). The latter because it is has an higher accuracy than tape measurer due to its stiffness. The precision of the scale was 0.0 grams. The method of measuring was adopted from Unit D06 Diana – Laboratory experiments and accuracy of finite element analysis (Eigenraam & Veer, 2017). The dimensions (height and width) of the cross section were measured with the calliper on six increments along the samples' length, using one side of the sample as reference. The length of the specimens was measured twice using the hinged ruler, to allow for precise accurate establishment of their volume. All collected data can be seen in *Appendix 4*, of which ***table 1*** is a summary.

The goal of these measurements is to establish the accuracy of the specimens in relation to their design. The insights this provides can be used in two ways. First of all, is it of importance to have accurate and correct values for the dimensions of the samples for the processing of their test data. Secondly, these accuracy numbers tell something about the preciseness of the sample fabrication process, such a quality and suitability of the used moulds. What is important to note here is the difference between precision and accuracy, as illustrated by image 5.25. The inaccuracy of the samples can be seen in a separate column in ***table 1*** .

The irregular surface made exact establishment of the dimensions of the samples difficult. Protruding particles and the slight flexibility of the material had a negative influence of the precision of the measurements. This will also form a challenge with future samples and experiments. Larger samples could form a solution as this will lower the influence of the imprecise measurements on the accuracy of the samples in relation to their design.

An interesting insight, that can be derived from the accuracy numbers, is that there seems to be a systematic error in some of the samples, of both types. Looking at the fabrication method this seems odd. The open top moulds allow for variation in height, which translate into variating width with the samples. However, thickness varies much more between the samples. It was found that this has to do with the mould themselves. It turns out that achieving high precision with the used saw table was more difficult than expected resulting variations in the width of the moulds. As all parts of the moulds were cut at the same time the error is present in all of them.

Other points of improvement are the nonoverlapping grids on which the measurements where done compared to that on which the contact points lay. Especially for the measurements of the width this can be said. They should have been done more and especially in the middle section of the specimens, where they are likely to fail.

**Visual inspection**

Parallel to the measuring, the samples were individually put through a process of visual inspection and documentation. The full documentation corresponding to this process can be found in *Appendix 4*. No mayor defects or imperfections, that for instance pointed to contamination in the growth phase, were found during this inspection.

Based on comparison to the samples and products from the literature and projects discussed in chapter 2 it was found that the growth and sample quality of the produced samples was good. Especially when realising that the smoothest of products were all made with much finer substrate such as sawdust or cotton, were grown longer and for aesthetic purposes. As mentioned earlier, in this case the growth time and fineness of the particles was restricted in order simulate an well performing insulation material.

***Image 5.21:** Assessing thickness with analogue calliper*

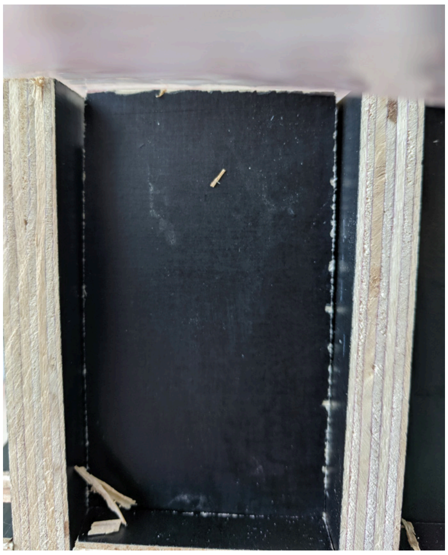


***Image 5.22:** Poorly made end of mould causing dehydration*


***Image 5.23:** Sample numbering*

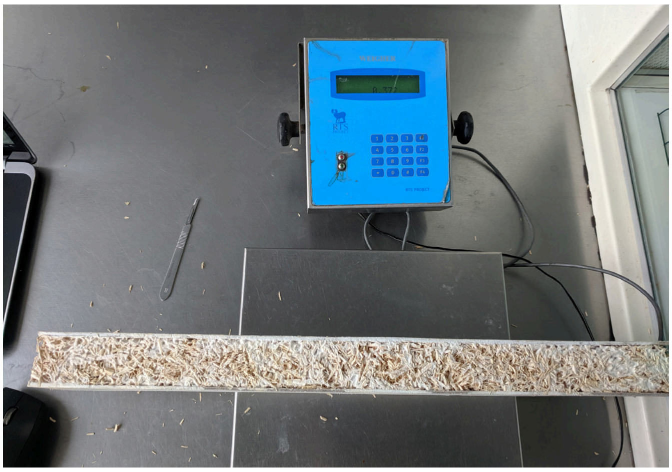


***Image 5.24:** Weighing samples on electronic scale*

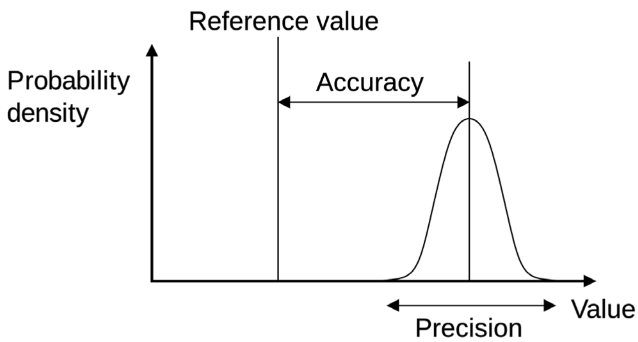



***Image 5.25:** Accuracy vs Precision*

***Table 5.01:** Overview of sample properties*

| | Shape | Length | | | Width | | | Thickness | | | Volume | Weight | Density |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mm | | | mm | | | mm | | | L | g | Kg/m3 |
| | | Av. | Av. dev. | St. dev. | Av. | Av. dev. | St. dev. | Av. | Av. dev. | St. dev. | | | |
| MBC | | | | | | | | | | | | | |
| 1 | Straight | 595,5 | 1,5 | 1,5 | 74 | 1 | 1 | 49,9 | 0,7 | 0,8 | 2,20 | 182 | 82,8 |
| 2 | Bend | 594,5 | 0,5 | 0,5 | 73,5 | 0,5 | 0,5 | 51,2 | 1,2 | 2,2 | 2,24 | 184 | 82,2 |
| 3 | Straight | 596 | 1 | 1 | 73 | 0 | 0 | 49,6 | 0,3 | 0,4 | 2,16 | 176 | 81,6 |
| 4 | Straight | 596,5 | 1,5 | 1,5 | 71,5 | 0,5 | 0,5 | 49,0 | 0,3 | 0,5 | 2,09 | 174 | 83,3 |
| 5 | Bend | 595 | 1 | 1 | 73,5 | 0,5 | 0,5 | 50,0 | 0,7 | 0,8 | 2,19 | 178 | 81,4 |
| Sandwich | | | | | | | | | | | | | |
| F1 | Warped | 596 | 0 | 0 | 74 | 0 | 0 | 50,3 | 0,5 | 0,6 | 2,22 | 374 | 168,6 |
| F2 | Warped | 596 | 0 | 0 | 75 | 0 | 0 | 50,2 | 0,3 | 0,4 | 2,24 | 390 | 173,8 |
| F3 | Straight | 596 | 0 | 0 | 74 | 0 | 0 | 49,9 | 0,4 | 0,5 | 2,20 | 372 | 169,1 |
| F4 | Straight | 596 | 0 | 0 | 74 | 0 | 0 | 49,2 | 0,5 | 0,6 | 2,17 | 372 | 171,4 |
| F5 | Warped | 596 | 0 | 0 | 74 | 0 | 0 | 49,4 | 0,6 | 0,7 | 2,18 | 366 | 168,0 |

That didn't mean that samples were all-round perfect. As mentioned above the samples' surfaces were quite rough which made measuring their dimensions difficult. This can be seen on image 5.28. This was especially the case on the sides which had been facing upwards during the growth, due to the absence of a mould on that side. Another imperfection that can likely be attributed to the mould were some slightly less grown through ends of some of the samples (image 5.30 & 5.32). This was likely caused by a crack in the mould allow moisture to evaporate and discourage fungal growth (image 5.22). As the samples will be sticking out of their support during the tests the impact on its results will likely be minimal. But better controlled circumstances will always lead to more accurate results. The presence of this phenomenon on the individual samples was noted in ***table 1***.

Similarly, the presence of curvature and twist was identified and noted (image 5.29). Not all samples were affected, and the impact of this warp was notable larger on the pure MBC samples. These are quite significant defects for samples intended for bending tests. The warp alters the shape of the sample influencing its distribution of loads. Especially in the case of the bended samples the placement (cruve up or down) will influence the results. Seeing that the samples came out of the mould in perfect straight conditions this warping has to have happened during the drying of the samples. This is a natural phenomenon that also can be seen with wood, but it is expected that the irregular metal mesh on which the samples were put to dry significantly worsened this effect.

### 5.2.3 Description of Experiments

Now a thorough description of the testing method will be given. Included are aspects such as the used machinery and settings, any feedback from the testing will be discussed in the next chapter. Normally testing procedures are dictated by a national or international standard test protocol such as NEN in the Netherlands, EN in Europe and ASTM in the USA. Such a protocol is optimised for specific material types and potential applications of such material. NEN-EN 310 for example is specifically for wood-like plate materials and NEN-EN 12089 describes the testing of insulation materials for buildings. Interestingly, and in contradiction with the principles formulated in 5.1, that latter prescribes the usage of a three-point bend test while the first prescribes using a four-point bend test (NEN, 1993; 2013). Because of the explorative nature of this project it was decided to abandon the usage of a test protocol and use a method thought to best fit the specimens at hand, a four-point bend test.

The tests have been performed using a static material testing machine from ZwickRoell, the used model was a Zwick Z010 (image 5.35). The test data was processed by accompanied software from the ZwickRoell firm. The dimensions of the experiment setup can be seen in image 5.03. The more experienced reader will note the aberrant dimensions of 110 mm of the pressing head. Normally a four-point bent test is designed in such way that the distance between the support and the first load is identical to the distance between the two applied forces. In this case no pressure head with the right dimensions or adjustable dimensions was available. This will have some minor consequences in the numerical processing of the experiment's data, but nothing unsurmountable, as will be explained in 5.3.2.

The actual testing process was initiated by the testing of the MBC samples. Starting with F1 and working up to specimen F5. This same ascending order was used with the sandwich samples. As can be seen in image 5.37 the MBC samples were provided with thin metal sheet at their support and pressure points. This was done to spread out the applied pressure preventing the samples from being locally compressed. As this potentially could have distorted the data about the materials bending behaviour. The sandwich samples didn't require such measures as the Ecor fulfilled such role.

The first sample, F1, was tested using a setting of 2 mm per minute for the machine. This is the setting for the downward movement of pressure head. As this resulted in a test time of over 15 minutes, due to the materials compliancy, all test there-after were performed using a setting of 20 mm per minute. And all tests were stopped when a deflection of 50 mm had occurred.

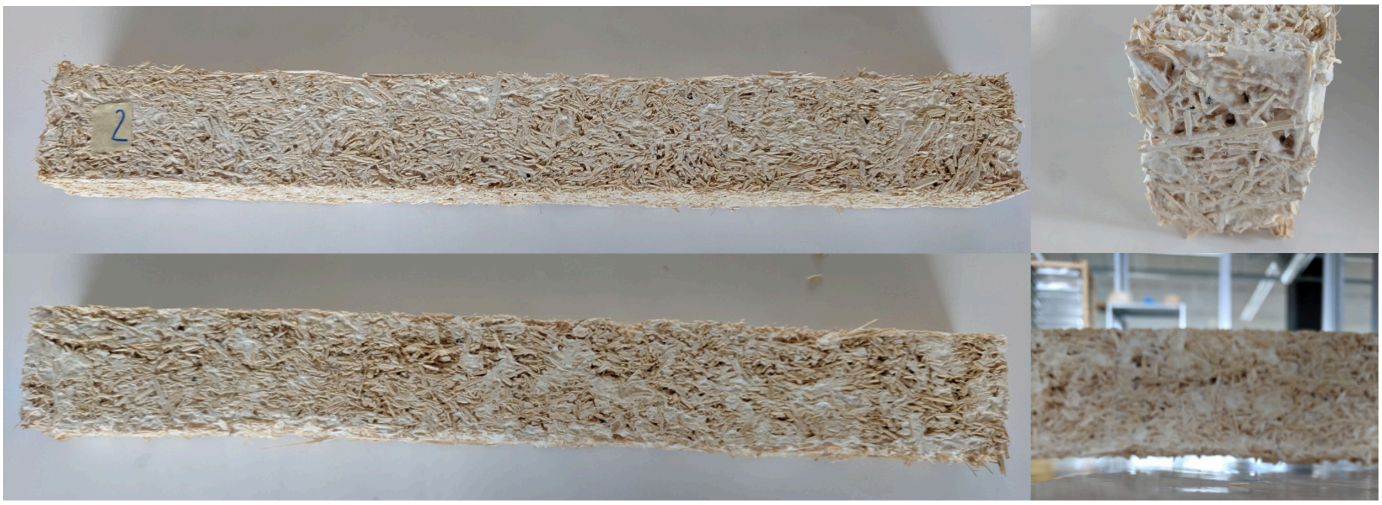



***Image 5.26-29:*** *MBC sample from various sides*


***Image 5.30-34:*** *Sandwich sample from different sides*


***Image 5.35:*** *Test device*

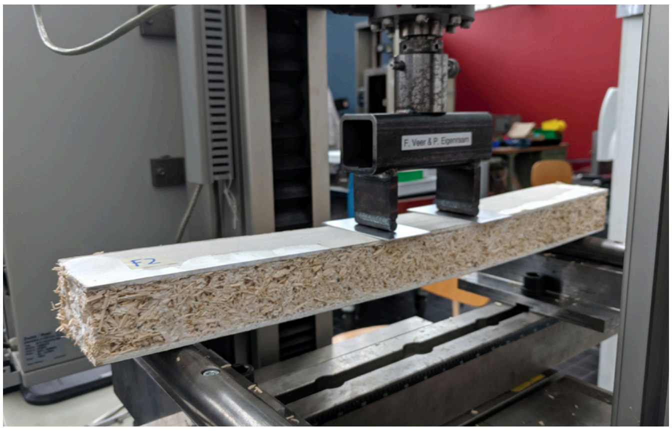


***Image 5.36:*** *Test setup*

***Image 5.37:*** *Metal sheets for load distribution*

## 5.3 The Results

As the title of this section suggests the results of the experiments described in the previous two sections will now be discussed. This will be done in the three distinctively different steps. 5.3.1 will give an overview of these results in a 'first impression-like' manner. Both visual and numeric data of the individual tests will be discussed and compared against each other. In 5.3.2 the data collected by the testing apparatus will be processed. This will go paired with a mathematical elaboration of the formulas needed to calculate the desired units. The derived insights allow for comparison of the theoretical and real performance of the sandwich panel. Finally, in 5.3.3 the processed results will be compared with other materials and products, such as the discussed in 3.3 and 4.2 and other conventional construction materials. Thereby the performance of MBC and MBC sandwich panels are brought in relation with other available solutions. This allows for a funded statement about the suitability, with which the section will conclude.

### 5.3.1 Overview of the Results

There no absolute outcome of the done experiments. Especially in an explorative research project the goals of test, such as the ones done in this chapter, are to gain as much insights as possible. It is therefore not so much the precise strength or elasticity of the material that is looked for. But rather a holistic overview of the specimens' behaviour during the tests. The feedback, or data, provided by the experiments exists largely out two components; visual data from observations and numeric data from the testing device. Both will be discussed separately and compared against each other. Since two types of samples have been tested this section is divided into two section, starting with the 'pure' mycelium-based composite.

**MBC**

All footage of the MBC sample mid and post experiment can be found in *Appendix 4*. Beside photos of all samples after the tests and of their fractures the appendix also contains a time laps of test of samples 1 & 2. The visual feedback of the procedures will now be discussed in chronological order.

**Visual Data**

On the time laps images of beam number 2 can clearly be seen that the slight twist in the specimen is quickly counteracted by the pressure piston. How this slight asymmetrical deformation influenced the results cannot be said with any certainty. The fracturing of the samples was also witnessed to be asymmetrical. This however, was behaviour that multiple, also non-warped, samples displayed. Ultimately, the cracks grew over the whole section of the beam, as can be seen on the post experiment photos (*Appendix 4*). Also visible is that all samples kept some of the integrity after the tests. Only sample 5 that was dropped after the tests is displayed in two parts. Moreover, the images also show how after the pressure of the piston was released the samples partially flexed back. With specimen 2 this behaviour was significantly more than with sample 1. The flexibility of material is an interesting structural characteristic and the difference between the two sample is remarkable. However, as this behaviour was not measured no statements can be made concerning it.

The last visually notable finding from the experiments was that with some of the samples the contact between one of the two pressure pistons was lost. Effectively a four-point bend test became a three-point bend test. On inspection of the samples it was found that this was caused by the eccentrical fracture number 1 and 4. The distance between the beam's centre and the centre of the crack were measured post experiment (***table 5.02***). Samples 2,3 & 5 turned out have perfect central failure. Sample two had a minor deflection and sample four a rather significant one. The size of this deflection in sample 4 is remarkable as its centre lies outside of the centre 110mm of the pistons. The specimens have to have had a weak spot in that location causing the fracture to occur there. The fail behaviour of the sample turned out be even more deviant than thought. On first impression it had seemed as if all samples had a single fracture. On closer inspection however, sample 4 showed a smaller second fracture.

**Numeric Data**

The numeric feedback from the testing machine can be seen in image 5.43. On first display the results appear to be randomly scattered and not very corresponding. However, a first similarity between the

| Sample | Centre to crack centre | Length of crack | Times own weight |
|---|---|---|---|
| | mm | mm | |
| 1 | 23 | 45 | 8,97 |
| 2 | 3 | 45 | 8,23 |
| 3 | 3 | 15 | 8,55 |
| 4 | 73 | 35 | 8,25 |
| 5 | 3 | 25 | 9,38 |

***Table 5.02:*** *MBC sample failure details*

***Image 5.38:*** *MBC being tested*

***Image 5.39:*** *Asymmetrical crack in sample 4*

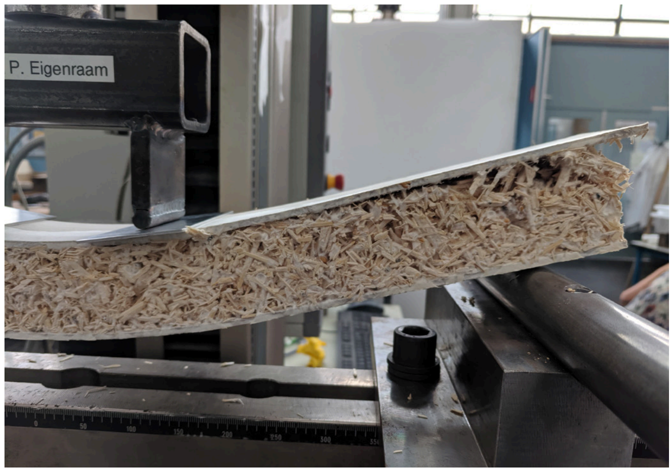



***Image 5.40:*** *Delamination showing at end of sample*

***Image 5.41:*** *Cavity between core and bottom sheet*

***Image 5.42:*** *Mirrored delamination*

behaviour of all samples is their non-linearity. The declining slope of the curves mean that the stiffness of the samples varies depending on the deformation and applied force. The steepness of the curve indicates the samples stiffness, as will be further discussed in section 5.3.2. The variance between the samples indicates inequality, which probably finds it origin in the non-homogeneity and natural origin of the composite. The further into to the test the variance increases, and the influence of their divergence enlarged.

Nevertheless, some similarities can be spotted. When looking at the beginning of graph, samples 4 and 5 clearly display similar and stiffer behaviour. Briefly, there seem to be a division between the samples into two groups. In a search for an explanation for this divergence production and dimensions were considered. It was found that the width of samples 2 and 5 were significant wider that the others. However, this does not, or only partially, explain the superior behaviour of samples 4 & 5. As number 2 in that case should have demonstrated more stiffness as well.

Further along the X-axis the differences between the samples become larger and larger. A subdivision in two groups can no longer be made. When looking at the fail behaviour, the declining course of the lines after their max, there are similarities though. Samples 1, 3 and 5 show abrupt failure and a steep decline of supportable force where sample 4 shows a much more graduate course. The latter, as discussed above, likely has to do with the acentric fracture of the sample. Sample 2 seems to be a hybrid between the two groups, first displaying quick declination but recovering slightly along the line of sample 4. These mixed behavioural types during the course of the experiment results in an apparent random scattering of the data. Some conformity can be found but overall the samples appear to be unpredictable. It must be concluded that the samples were not uniform. This can be attributed to the variety in particle size of the substrate, the uncontrolled growth condition and the quality of the moulds. In further research these aspects need to be fixed or circumvented.

**Sandwich**
All footage of the sandwich samples mid and post experiment can be found in *Appendix 4*. Beside photos of all samples after the tests and of their fractures the appendix also contains a time laps of test of sample F1. The visual feedback of the procedures will now be discussed in chronological order.

**Visual data**
As to be expected, but noteworthy nonetheless, was the significantly difference in behaviour of the sandwich samples during the test opposed to the MBC ones. The sandwich beams seemed to withstand the applied force with more ease. Not by withstanding so much force but by smooth deformation. Failure occurred very gradually and almost stayed unnoticed. Ultimately cracks appeared in the MBC but the Ecor in all samples stayed intact. The primary fail modus turned out to be delamination of the Ecor outer layers and MBC core. This in congruousness with the results of Travaglini (2014). The main expression of this delamination was the pultruding, and thereby notable slipping, Ecor sheets at the end of the samples as can be seen on image 5.40. Although in some instance's small cavities between the MBC core and the bottom Ecor sheet could be seen (image 5.41). Apparently, the bending behaviour of the delaminated Ecor was significantly more fluid and that the Ecor-MBC top, resulting in the distance between them. Opposed to the MBC tests no pressure points got detached form the samples during the tests. This is more optimal behaviour and can probably attributed to the more flexible Ecor.

Studying the samples post experiment an interesting finding was done. The delamination behaviour turned out the differ between them. An overview of the findings can be seen in ***table 5.03***. Remarkably, some of the samples delaminated on top and bottom while others only laminated on their bottom. None of the sample solely delaminated on their top. This likely has to do with the larger radius of the curve in which the bottom is pushed, compared to the top sheet. Another noteworthy observation about the delamination is that all samples always only delaminated unto halfway, or to the samples centre. Never did full delamination occur. Also, in the case of the two-sided delaminated of F1, F2 and F4 was the delamination of the top always on the opposing side of the bottom delamination (image 5.42). The prominent delamination and only minor tearing of the samples indicates that the fungal attachment of the MBC to the Ecor is probably the weakest link of the product. The opposite parallel movement of the layers demonstrates the work of shear force. Presumably the attachment is predominantly weak in this direction.

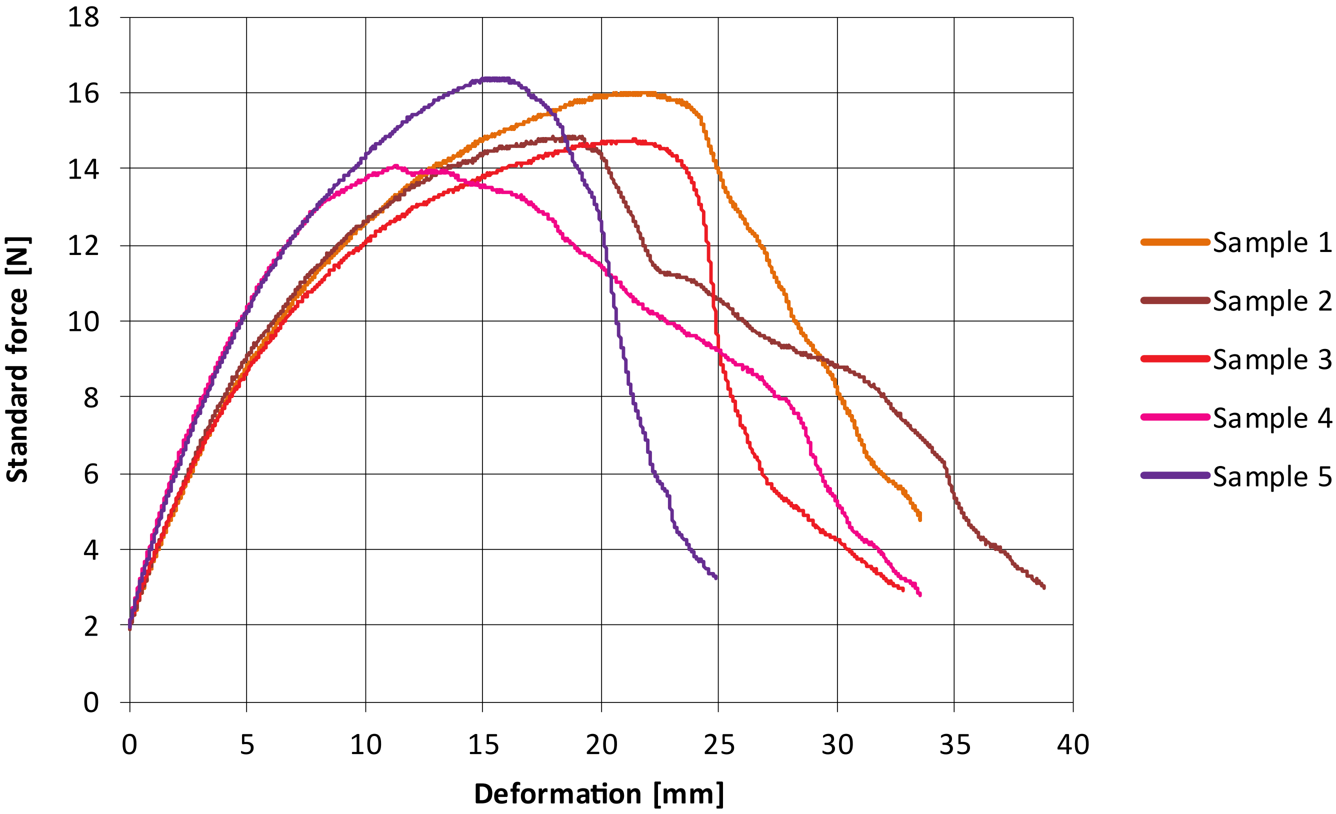



***Image 5.43***: *Graph of numeric test results MBC samples*

| Sample | Delamination | | Centre to crack centre | Times own weight |
|---|---|---|---|---|
| | type | location | mm | |
| F1 | 2-sided | mirrored | 60 | 13,2 |
| F2 | 2-sided | mirrored | 30 | 12,7 |
| F3 | 1-sided | bottom | 0 | 10,8 |
| F4 | 2-sided | mirrored | 40 | 12,4 |
| F5 | 1-sided | bottom | 10 | 11,8 |

***Table 5.03***: *Overview of failure and delamination behaviour sandwich samples*

**Numeric Data:**
The numeric feedback from the testing machine can be seen in image 5.44. On first display the results seem less random than was the case with the MBC samples. Although less entangled the surface occupied by the lines in the graph tells behaviour from sample to sample is significantly different.

At the beginning of the graph can be seen that specimens F1 and F3 are displaying a steeper, meaning stiffer, line. F2, F4 and F5 are more ductile, deforming more under similar loading. Like the MBC samples they show varying, gradually shifting, stiffness along their elongation. With F2 this apparent flexibility leads to the absence of a clear point of failure. At most, its dip around 14 mm of deformation could be described as such. All other samples do show clear failure. F1, 3 & 5 clearly reach their maximum after which their strength falls back. With F4 this failure was premature although a reason or signs of this could not be found the sample post experiment.

All samples show, in some degree, behaviour of recovering and improving after failure. The clear lower limit come from the Ecor which stays intact. Roughly, the samples keep 50 percent of their load bearing capacity. Such a fall-back mechanism with in structure can be deemed a safety feature. However, it also demonstrates that the product doesn't reach its full structural potential. Increased bind strength could improve performance. This is proven in the second part of the graph where the samples display improving behaviour after failure. This phenomenon is probably caused by the increasing friction between the MBC and Ecor sheets that comes with increased bending.

From a structural point of view the behaviour of samples F1, F3 and F5 should be preferred. As they demonstrate a clear moment of failure but still preserve certain strength. How then does this correspond to their delamination behaviour described above? As can be seen in Table X samples F3 & F5 delaminated on a single side. While F1, F2 & F4 delaminated on two sides. This is remarkable as the numeric data of F1 would appear to point toward the superior single delamination. However, in closer inspection of the footage of the test of F1 it was found that the sample shows singular delamination up to a very late stage of the test.

### 5.3.2 Processing of the Results

With the first impression of the results discussed it is time to dive a little deeper into the test data. As elaborated upon in 5.1 the main goal of the experiments was to investigate the strength of the fungus unique binding capacity. To do that correctly it was necessary to test both pure MBC and sandwich samples. As not failure but delamination determined the sandwich samples behaviour it is expected that the full potential of the composed beam was not reached. However, this can also be factually be established using the data derived from the tests. In order to process this data first the right formula needs to be derived.

Therefore, this section is built up as follows; To start the formula derivation and needed mathematical wizardry will be discussed. After which the needed data processing steps will be made and elaborated up. Finally, a comparison will be made between the theoretical and real performance of the sandwich panel.

**Algebraic preparations**
As discussed, the testing device measured two different aspects; the applied force (F) and the vertical movement of the pressure pistons, and thus the deformation of the specimens, (delta-x). The measured values of these quantities determine the course of the curves in the graphs discussed in the previous section. The steepness of the curves is the product of these two quantities and indicates the samples bending stiffness (K), as seen in Formula 1. The bending stiffness is a quality the sample derives from beam and material specific properties, namely the materials elastic modulus and the beam's moment of inertia. These can respectively be derived by rewriting the formulas 3.1A & 3.1B, and calculated using Formula 4, as will be demonstrated below.

For the experiment setup as used in this project (image 5.45 & 5.46) the deflection can be calculated with formulas 3.1A & 3.1B. The first formula is used for the deflection on a point between R and P. And the second formula is used for a point between the pressure pistons P1 and P2. As said, the deflection and applied force were measured by the testing device. The machine controls and measures these

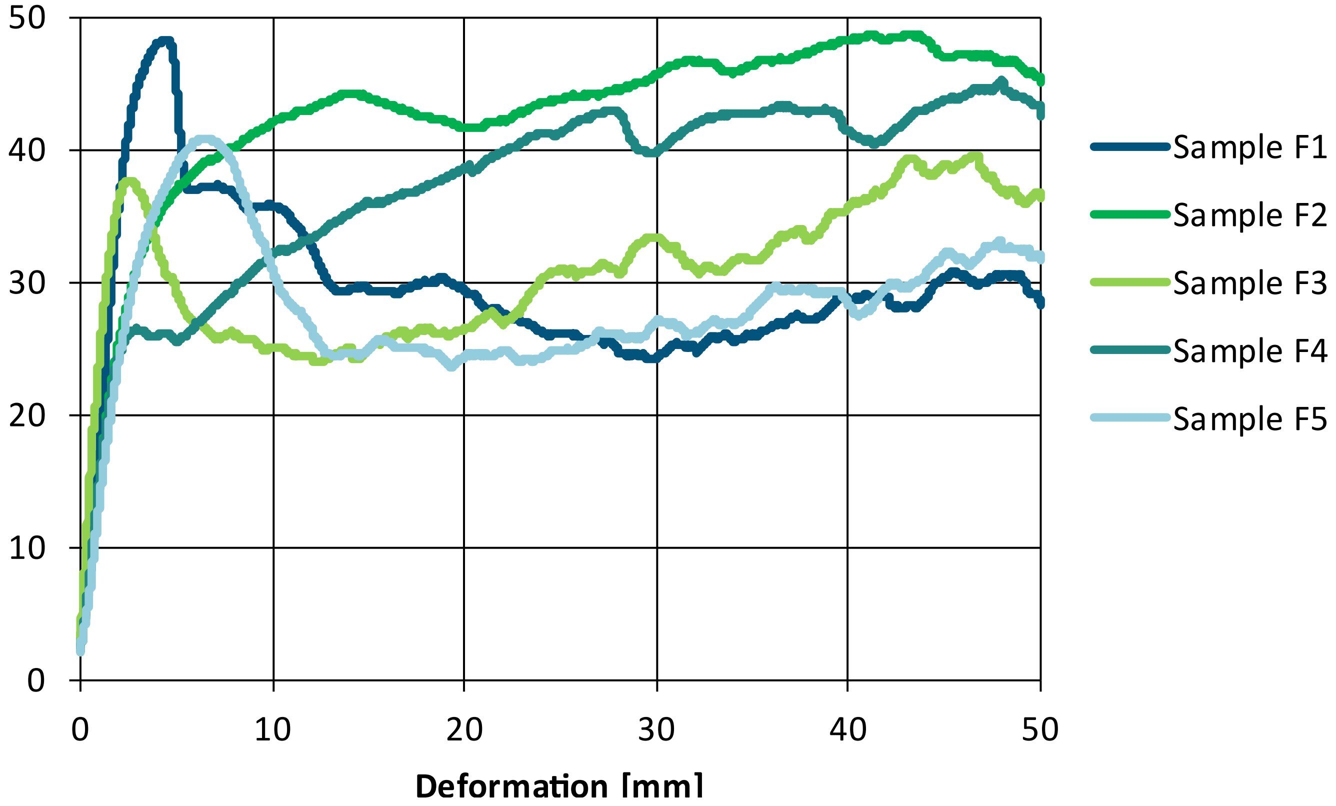



***Image 5.44:*** *Graph of numeric test results sandwich samples*

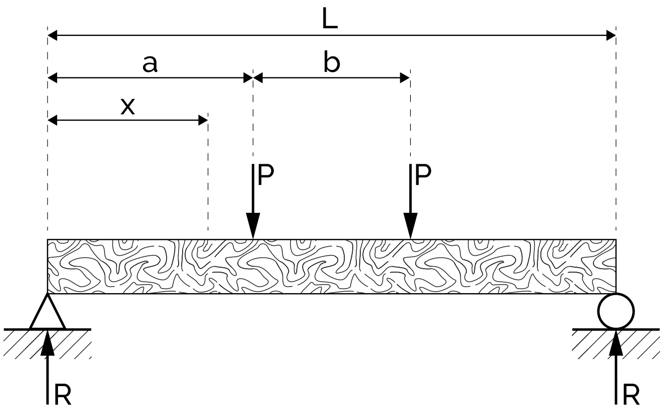



***Image 5.45:*** *Experiment setup MBC*

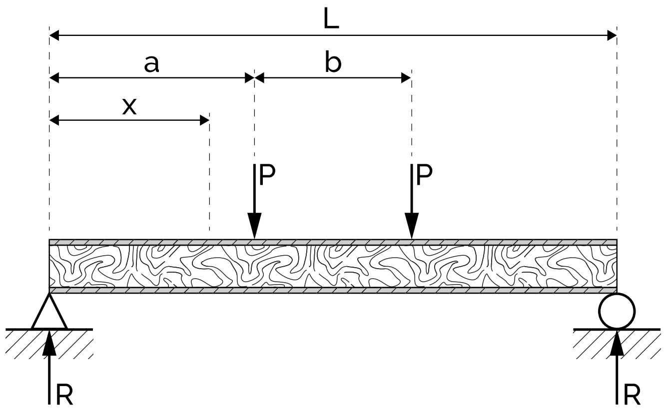



***Image 5.46:*** *Experiment setup sanwich samples*

values through the pressure pistons P1 and P2. The first consequence of this is that the force through P1 and P2 is half of the measured force F (Formula 2). As second consequence this has that x equals a (x = a) in the test setup. x being the distance from which the deflection is calculated and a being the distance between R and P. By implementing this in formula 3.1A or B, formula 3.2A is obtained. Formula 3.2A can be simplified, first of all by writing -3a2- a2 between the brackets as -4a2, to get formula 3.2B. And secondly, by getting the shared a from within the brackets out of them, resulting in formula 3.2C. As said, it is not the deflection but the elastic modulus (E) that is sought-after. By multiplying both side of the equation with E and dividing both sides through delta x Formula 3.3A is obtained. If both sides are also multiplied by I, Formula 3.3B is the result.

The reason for externalising I as well has to do with the nature of this unit. I represents the second moment of area, also known as the area moment of inertia. This value is specific for the area of the section of the sample beams. It is calculated using their dimensions and as they were measured in 5.2.2, I can be calculated. For a beam with a rectangular section the formula for I is simple and can be seen to the right as Formula 4.1. For a composed beam this becomes a little more complex as its section now contains of two materials with different elastic moduli. This requires separate calculation of EI, as explained by Formula 5. As the elastic modulus of the Ecor is known, the elastic modulus of the MBC-core can be calculated and compared with the Elastic modulus of the MBC beams, as will be done below. First however the area moments of inertia have to be calculated for bot the MBC-core and the outer Ecor sheets. This can be done using Formula 4.2, where both the full section and the section of the MBC-core are rectangular and therefore can be calculated with Formula 4.1.

Most units in Formula 3, right of the equal sign are rather straight forward as their representation can easily derived from Image 5.03. Obtaining the right values for delta x and P does need some additional explanation. As can be recalled from 5.3.1 the deflection of the specimens varied significantly throughout the experiment. The value for delta x therefore will heavily depend on which point of the graph it is taken. As it is not the performance of the beams after their failure that is sought after it makes sense to abstract delta x from before the failure point. In image 5.47 can be seen how the deformation value be obtained correctly. And how this stands in direct correspondence with the value for F. As F is the amount force needed to result in the deflection x. Remember that P is a half F (Formula 2). Image 5.47 shows a straight line up till the point of failure. In reality however most curves of the tested specimens resembled the curve depicted in image 5.48. Drawing a straight line for the determination of delta x and P will be impossible and would misrepresent the behaviour of the beam. A result of this fluid behaviour of the specimens is that no one elastic modulus for them exist. Their flexural behaviour alters as they deflect. As a consequence, multiple elastic moduli need to be determined for the various ranges of deflection. The number and size of these ranges will be determined below during the processing of the test data.

Besides the elastic modulus also the maximum bend strength ( ) is material property of importance. As it indicates the maximum amount of force the material can withstand. It is calculated using Formula 6. The value taken for F in the is the maximum found in the calculated of the E-modulus above. Additionally, to the material properties of elastic modulus and bending strength also the specimen specific properties of shear force and bending moments are aspects of interest. For the load case of a four-point bend test the shear force diagram (SFD) and bending moment diagram (BMD) have an obvious course (image 5.49). The magnitude of the shear force and bending moment depend on the performance of the specimens. The shear force is equal to force P and reactive and opposite force R in the support points. Understandably, since the shear force is the transportation of force from the pressure point to the support point. Looking at the SFD the resemblance with the delamination of the sandwich panels samples is striking. On the upper side on the one side and on the bottom on the other. This behaviour clearly indicates that shear force caused the delamination. As can be seen in the BMD the maximum bending moment occurs and is steady between the two pressure pistons. This maximum bending moment is calculated with M = P*a. Between the support point and pressure point the bending moment increases linear. There the bending moment is calculated using M=P*x.

Formula 1: $$K = \frac{F}{\Delta x}$$

---

Formula 2: $$P = \frac{F}{2}$$

---

Formula 3.1A: $$\Delta x\ (x < a) = \frac{Px}{6EI}(3La - 3a^2 - x^2)$$

Formula 3.1B: $$\Delta x\ (a < x\ < (L - a)) = \frac{Pa}{6EI}(3Lx - 3x^2 - a^2)$$

Formula 3.2A: $$\Delta x\ (x = a) = \frac{Pa}{6EI}(3La - 3a^2 - a^2)$$

Formula 3.2B: $$\Delta x\ (x = a) = \frac{Pa}{6EI}(3La - 4a^2)$$

Formula 3.2C: $$\Delta x\ (x = a) = \frac{Pa^2}{6EI}(3L - 4a)$$

Formula 3.3A: $$E = \frac{Pa^2}{6\ I\ \Delta x}(3L - 4a)$$

Formula 3.3B: $$EI = \frac{Pa^2}{6\Delta x}(3L - 4a)$$

---

Formula 4.1: $$I = \frac{1}{12}bh^3$$

Formula 4.2: $$I_{beam} = I_{MBC-core} + I_{Ecor}$$

---

Formula 5 $$EI_{beam} = (EI)_{MBC-core} + (EI)_{Ecor}$$

---

Formula 6 $$\sigma = \frac{3F_{max}}{2bh^2}(L - b)$$

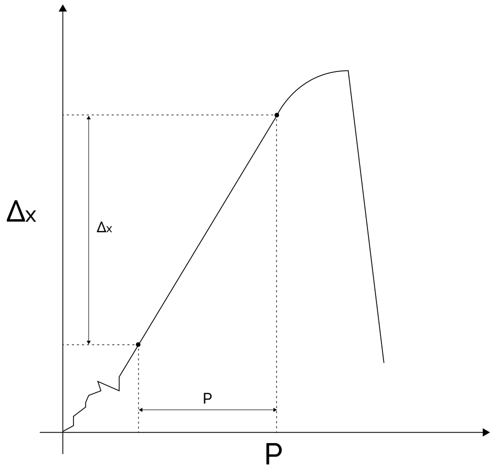



***Table 5.47**: Determining delta x - straight*

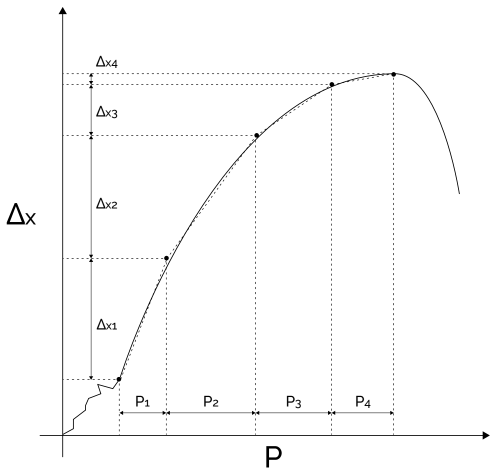



***Table 5.48**: Determining delta x - curved*

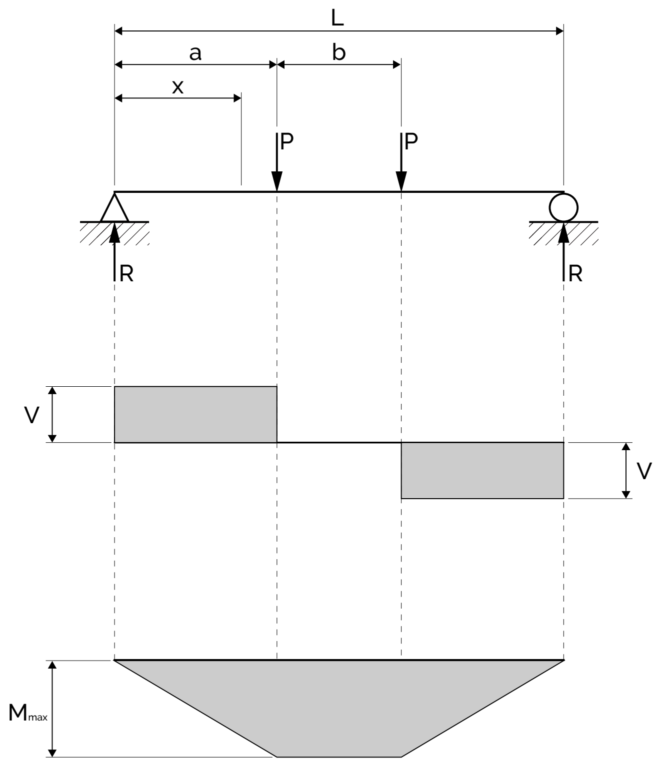



***Table 5.49**: Free Body Diagram - Shear Force Diagram - Bending Moment Diagram*

**Processing - MBC**
All the above-mentioned quantities were calculated using the described methods, the results of which can be viewed to the right in ***table 5.04***. For the calculation of the specimens' elastic moduli Formula 3.1 was used. An overview of the chosen increments for the derivation of delta x and F can be found in *Appendix 5.1*. In order to come to comparable elastic moduli, the decision was made to approach the camber of the curves using three set increments for all MBC samples. These increments are based on their deformation because it is ultimately that quantity that will determine the functionality and safety of a material, as will be discussed in 5.3.3. The increments range from 0 to 5 mm, 5 to 10 mm and 10 to maximum elongation as can be seen in ***table 5.04***. In order to go beyond the individual results of the specimens both the averages and normal distribution were calculated for all values.

**Processing – Sandwich panels**
The process of processing the data of the sandwich panel test data was a little more complex compared to that of the MBC samples. Not only because of the additional calculating step described above, necessary to deal with the two materials with different properties, but also because more aspects of the sandwich beams are of interest. All the processed data can be seen in to the right in ***table 5.05***.

First of all, the beam specific qualities of maximum bend strength, shear force and bending moment were calculated. Also, the E-modulus of the beams (E-beam) was calculated, using Formula 3.3A. This quantity is specific for the beam with its exact dimensions and proportions. It is therefore not a quite scalable and useful aspect of the beam to establish. However, it does perfectly give insight in the performance of the sandwich panel samples compared to the MBC samples, as can be seen in 5.3.3.

This required the derivation of delta x and F, also needed for further analysation of the E-moduli of the separate materials in play discussed below. In contrary to the proceedings with the MBC samples it was decided to only calculate the E-modulus for the sandwich panels once. This as the deflection of in the course of most sandwich panel curves was significantly less (compare image 5.43 with image 4.44). Additionally, as it was established that the failure of the samples was largely caused by delamination this would result in the establishing of the E-modulus of a partially delaminated, and thus partially failed, sandwich panel. As this is an explorative study it is enough to establish the underperformance of the panels and quantify it. The increment of 0,5 to 2 mm elongation (delta x) was chosen as the samples demonstrated their most linear behaviour in that range. An overview of the chosen increment for the derivation of delta x and F can be found in *Appendix 5.2*.

As explained above, further processing of the composed beam requires the use of Formula 3.3B and Formula 5 instead of Formula 3.3A. EI-beam is thus calculated and using the known E-modulus of Ecor (6020 Mpa) and the just derived E-modulus MBC the performance of the sandwich panel can be calculated, as will be done in 5.3.3. This also requires both the moments of Inertia of the Ecor sheets as the MBC core are needed, which can be found in ***table 5.05*** as well. Also note that moment of Inertia is stated for a single layer of Ecor. This as it will be used in 5.3.3 to establish the difference between the sandwich panel and the sum of its individual components.

### 5.3.3 Interpretation of the Results
Now the samples behaviour has been analysed and the results of the experiment have been processed the findings can be interpreted. Un till now the results were just numbers. This allowed for comparison between the samples, but no frame of reference has been put into place to give meaning to the results. Exactly that is the goal of this coming section. Hopefully, at its end it will be possible to come to a conclusion about the applicability of mycelium-based composites and sandwich panels made of it. First however, the frame of reference has to be applied. This will be mainly done through comparison and calculation.

To start, the results of the, MBC, material will be interpreted. This will be done by first looking at tested properties and compare them with the properties of other mycelium-based composites found in the literature. And second, by comparing the results with properties other rigid insulating materials both 'circular' as traditional. A main instrument in this review will be the ASHBY-chart.

The material comparison will be followed by a study into the performance of the tested sandwich

*Image 5.50: Zoomed graph force - deformation of sandwich samples*

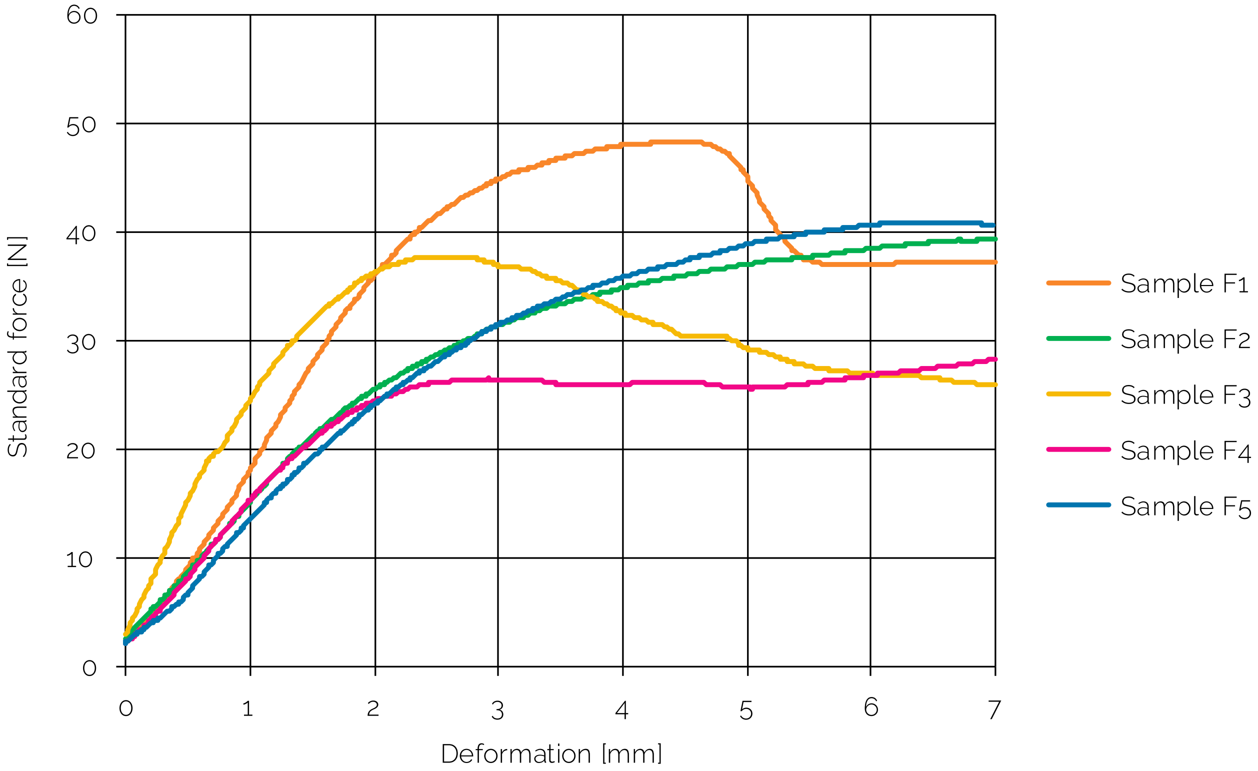



*Table 5.04: Overview of MBC results*

| Samples | Max Bend Strength | Elastic Modulus | | | Moment of Inertia | Max Force | | Shear Force | Bending Moment |
|---|---|---|---|---|---|---|---|---|---|
| | F-max | E (0-5) | E (5-10) | E (10-max) | I | F-max | P-max | V-max | M-max |
| | N/mm2 | N/mm2 | N/mm2 | N/mm2 | mm^4 | N | N | N | Nm |
| **1** | 0,050 | 4,07 | 2,26 | 0,86 | 764902 | 16,02 | 8,01 | 8,01 | 1,56 |
| **2** | 0,046 | 3,96 | 1,94 | 0,69 | 824150 | 14,87 | 7,44 | 7,44 | 1,45 |
| **3** | 0,049 | 4,09 | 2,09 | 0,73 | 741351 | 14,76 | 7,38 | 7,38 | 1,44 |
| **4** | 0,048 | 5,45 | 2,18 | 0,93 | 699766 | 14,09 | 7,05 | 7,05 | 1,37 |
| **5** | 0,052 | 4,92 | 2,41 | 1,20 | 766938 | 16,38 | 8,19 | 8,19 | 1,60 |
| **Average** | 0,05 | 4,50 | 2,17 | 0,88 | 759421 | 15,22 | 7,61 | 7,61 | 1,48 |
| **Standard Deviation** | 0,00 | 0,59 | 0,16 | 0,18 | 40402 | 0,85 | 0,42 | 0,42 | 0,08 |

*Table 5.05: Overview of sandwich results*

| Samples | Max Bend Strength | Elastic Modulus | $EI_{beam}$ | Moment of Inertia | | | Max Force | | Shear Force | Bending Moment |
|---|---|---|---|---|---|---|---|---|---|---|
| | F-max | $E_{beam}$ | 0,5 - 2mm | $I_{core}$ | $I_{edge}$ | $I_{1sheet}$ | F-max | P-max | V-max | M-max |
| | N/mm2 | N/mm2 | Nmm2 | mm^4 | mm^4 | mm^4 | N | N | N | Nm |
| **F1** | 0,149 | 51,819 | 40666789 | 573251 | 211540 | 96,4 | 48,32 | 24,16 | 24,16 | 4,71 |
| **F2** | 0,153 | 32,195 | 25477047 | 577706 | 213632 | 97,7 | 48,72 | 24,36 | 24,36 | 4,75 |
| **F3** | 0,125 | 41,524 | 31775452 | 557401 | 207830 | 96,4 | 39,59 | 19,79 | 19,79 | 3,86 |
| **F4** | 0,148 | 33,831 | 24845915 | 532497 | 201925 | 96,4 | 45,15 | 22,58 | 22,58 | 4,40 |
| **F5** | 0,137 | 35,363 | 26300453 | 540019 | 203719 | 96,4 | 40,84 | 20,42 | 20,42 | 3,98 |
| **Average** | 0,14 | 38,95 | 29813131 | 556175 | 207729 | 97 | 44,52 | 22,26 | 22,26 | 4,34 |
| **Standard Deviation** | 0,01 | 7,17 | 5957623 | 17767 | 4453 | 1 | 3,75 | 1,88 | 1,88 | 0,37 |

panels. With the data from the MBC material processed and analysed it will be possible to compare the theoretical and real performance of the sandwich panel. As not failure but delamination determined the sandwich samples behaviour it is expected that the full potential of the composed beam was not reached. Calculation will show if this hypothesis is correct.

Finally, the section will be finished by a comparison on the product level. The properties of the tested sandwich panels will be compared with the industry available panels from Kingspan and Brucha. This will provide insights in the feasibility to develop sandwich panels that are capable of meeting industry standards, ultimately, this projects objective.

**Material comparison**
During the course of this project there have been multiple instances in which other materials have been encountered. Although their relation to the MBC tested here has been varying, they all shared some sort of similarity to the material. Examples are the traditional insulation foams currently available and used within the construction industry and the other MBC's encountered in the literature study of 2.6. The results of the experiments done in the project will now be brought in relation to the properties of those encountered materials. As established in chapter 4, this will show how the tested MBC performance on the qualitative parameter of structural behaviour.

To start, the other MBC materials are regarded, their mechanical properties under bending load are collected in ***table 5.06***. As 'material 0' the average of all MBC-results from this report were added to the table. Keep in mind that all of the results in ***table 5.06*** were made, at least, in collaboration with a commercial fungal material grower. As shown in the previous section, the processing of the results allows for interpretation. It could be possible that the results in the literature are optimal representations of the materials.

In a first impression the values for the three quantities in the table seem to lay in a continues range or spectrum. Also, immediately, some exceptions spring to the eye. The bend strength of the samples form Appels & Travaglini significantly, 4 to 15 times, higher. In the case of Travaglini this comes paired with very high density, already discussed in 2.6, and phenomenally high elastic modulus. An E-modulus of similar proportion has been found with the sample from Mogu. This raises the question if the material actually performed so well or other causes can be attributed for these values. Has a mistake been made with the decimals or has a similar distorting testing method been used?

Considering the values that seem to fit the spectrum of possibilities it appears that the material grown for this project achieves similar, slightly below average, when compared to the other MBC materials. Keeping in mind that this project's MBC is 20% lighter than the next lightest materials, this is remarkable. This above average performance strength and stiffness to weight ratio indicates that the growth quality of the samples was probably good, as visual confirmed. When compared to Appels' TNR, which has a comparable fungus, substrate and density, it is interesting to see how a much higher bend strength is achieved while Elastic modulus is lower. Of course, the Elastic modulus of this report MBC is the optimal E (0-5). Nevertheless, this illustrates that better understanding of the material and its production process is needed to master the parameters of influence.

The values of the MBC's compare surprisingly well with those of other rigid insulation materials, displayed in ***table 5.07***. The MBC tested in this project has only a third of the bending strength, but the E-modulus is comparable with that of EPS and PF foam. Considering that other MBC materials displayed better mechanical behaviour it seems as MBC's can become structurally comparable with rigid insulating foams. A big side note here is that all foams have densities of half the weight or more of the fungal foams. This could turn out to be problematic in structures as the own weight will increase significantly.

Using the CES material database, the results of the experiment were also compared with a large group of material and material types. Two graphs comparing materials based on their Elastic modulus, density and thermal conductivity can be seen to the right (images 5.51 & 5.52). In both images not only an array of materials can be recognised by the coloured dots, but they are also clustered in their material typology, Foams (light green) and Natural materials (dark green) can be seen. What was interesting

| | Info | | | Ingredients | | Mechanical Properties | | |
|---|---|---|---|---|---|---|---|---|
| Nr | Name | Manufacturer | Data origin | Substrate | Fungus | Density | Bend strength | Elastic modulus |
| | | | | | | kg/m3 | n/mm2 | n/mm2 |
| 0 | MBC avarage | - | - | Rapeseed straw + Hemp | Trametes versicolor | 83 | 0,05 | 4,50 |
| 1 | MycoCom- posite 029 | Ecovative | Ecovative (2019) | Hemp | - | 110 | 0,10 - 0,20 | 7,20- 13,0 |
| 2 | MycoCom- posite 570 | Ecovative | Ecovative (2019) | Aspen Chips | - | 190 | 0,12 - 0,21 | 10,0- 16,0 |
| 3 | MycoCom- posite 584 | Ecovative | Ecovative (2019) | Aspen Shavings | - | 140 | 0,076 - 0,11 | 5,5 - 9,7 |
| 4 | Mogu - P01 | Mogu | Mogu (2019) | Cotton | - | 200 | 0,05 | 150 |
| 5 | Appels - TRN | Mogu | Appels (2019) | Rapeseed Straw | Trametes multicolor | 100 | 0,22 | 3 |
| 6 | Appels - TBN | Mogu | Appels (2019) | Beech Sawdust | Trametes multicolor | 170 | 0,29 | 9 |
| 7 | Appels - PRN | Mogu | Appels (2019) | Rapeseed straw | Pleurotes ostreatus | 130 | 0,06 | 1 |
| 8 | Travalingi - MBC | MycoWorks | Travalingi (2014) | Northern Red Oak | Ganoderma lucidum | 318 | 1,4 | 168 |

***Table 5.06**: Comparison of bending capacities of test and literature results*

| Info | | | Mechanical Properties | | | |
|---|---|---|---|---|---|---|
| **Name** | **Material** | **Data origin** | **Density** | **Bend strength** | **Elastic modulus** | **Thermal conductivity** |
| | | | **kg/m3** | **n/mm2** | **n/mm2** | **(W/mK)** |
| **Biofoam** | Poly Lactic Acid | Biofoam (2017) | 40 | 0,3 | 3,1 | 0,034 |
| **PIR** | Polyisocyanurate | Kingspan 2019 | 30 | - | - | 0,022 |
| **PUR** | Polyurethane | CES EduPack 2019 | 59 - 64 | 0,14 - 0,26 | 9,2 - 12,8 | 0,028 |
| **EPS** | Polystyrene | CES EduPack 2019 | 18 - 22 | 0,15 - 0,39 | 3,4 - 7,0 | 0,033 |
| **PF / Resol** | Phenolic formaldehyde | CES EduPack 2019 | 32-38 | 0,14-0,21 | 4,0 - 7,0 | 0,19 - 0,20 |

***Table 5.07**: Comparison of bending capacities of insulating foams*

to find was that of the materials most similar to the tested MBC most had applications in sandwich panels. Apparently higher density doesn't always have to be a bad thing in construction. Based on these insights it can be concluded that the MBC has properties that lay within a range where also other usable products are. It is therefore safe to say that the material is not useless. However, real statements about the materials applicability can't be made as this also influenced by more practical aspects such as production and cost. Chapter 6 will provide some insights in the dynamics behind those parameters. First however the applicability of the material in sandwich panels will be further investigated from a mechanical point of view.

**Sandwich performance**

The sandwich panel is expected to outperform the MBC beam discussed above. Based on basic structural mechanics this can not otherwise be assumed. Also, the first interpretation of the numeric data sketched this image. The goal however is to quantify by how much exactly the performance of the beam improves. The elastic modulus of the beam, calculated with Formula 3.3A, is a direct product of F, delta x and the beams dimensions, and thus provides and easy and comparable number. For further mechanical analyses in the service of product development this value doesn't hold much substance as it only represents mycelium-based sandwich panel with these exact proportions between MBC and Ecor. With an increase in maximum bend strength of an approximate three-fold and an increase of the E-modulus with a factor of ten the Sandwich panel is clearly stronger and stiffer. However, compared to the properties of the added Ecor this improvement seems only minor. As the elastic modulus of the material is with 6020 Mpa over 100 times higher than that of the sandwich beam (Noble Environmental Technologies, 2019). If this seemingly minor improvement is indicative of the sandwich beam not reaching its full potential cannot said that easily and requires a little more elaboration.

In order to truly establish and quantify by how much exactly the performance of the beam improves a comparison needs to be made between the real and theoretical performance of the sandwich panels. The latter can now be done as both the e-modulus of the Ecor and MBC are known. This calculation quantifies the ideal situation based on the properties of the individual components. It is expected that the samples did not reach this full, theoretical potential due tot the observed delamination. Therefore, it was decided to compare the test data with a second theoretical case; the sum of the three-individual components of the panel. This provides a theoretical lower limit and thereby establishing a numeric range in which the performance of the samples can be graded, this concept is illustrated in image 5.53.

The comparison is best made using the combined product of the elastic modulus and moment of Inertia, EI. An overview of the values of all aspects at play can be seen to the right in ***table 5.08***. In a first glance at this table the large differences immediately become clear. The tested sample average is approximately a ten-fold higher than that of the, lower limit, sum of components. More drastic though is the rough 43 times the theoretical upper limit is higher than the measure value. This dispersion has two causes but only one true origin. The variance in E-modulus between the Ecor and MBC have already been discussed above and although significant is not directly normative in this situation. Rather, it is the influence of the moment of Inertia that is biggest in this instance. This is best illustrated by the difference in this quantity between the single sheet and the two outer sheets of Ecor, a difference of over 2000 times. When looking at Formula 4.1 the cause of this dispersion becomes clear. The third power to which the height of the panel is multiplied causes the enormous differences in moment of Inertia. This multiplied with Ecor's relatively high E-modulus is the predominant source of the high theoretical EI value of the sandwich panel, as can be seen in ***table 5.08***.

This whole comparison also perfectly illustrates the effectiveness of the sandwich panel principle. It is not about the use of the strongest materials but about creating two layers as far apart as possible. Even though the MBC core has double the moment of Inertia it has nine times the surface in a section of the panel. Even if the core material was as strong as the traditional foams discussed earlier it's added value to the overall performance of the beam would be minor. Essential in enabling this full potential in the rigid connection between all components. As soon as an individual component can move relative to the others it starts to behave as its much weaker isolated self. Such delamination is exactly what the tested samples showed (image 5.40). It therefore needs to be concluded that the tested samples did not reach

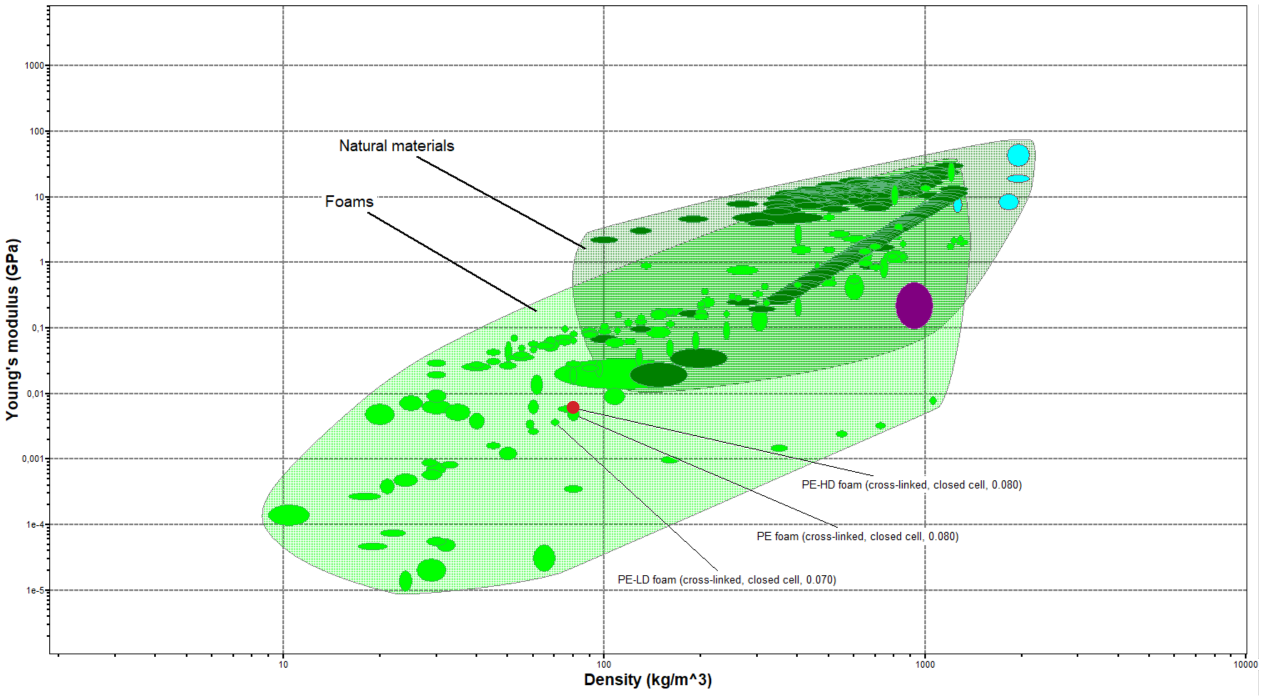



***Image 5.51:*** *Ashby chart of foams, natural materials and the MBC test results*

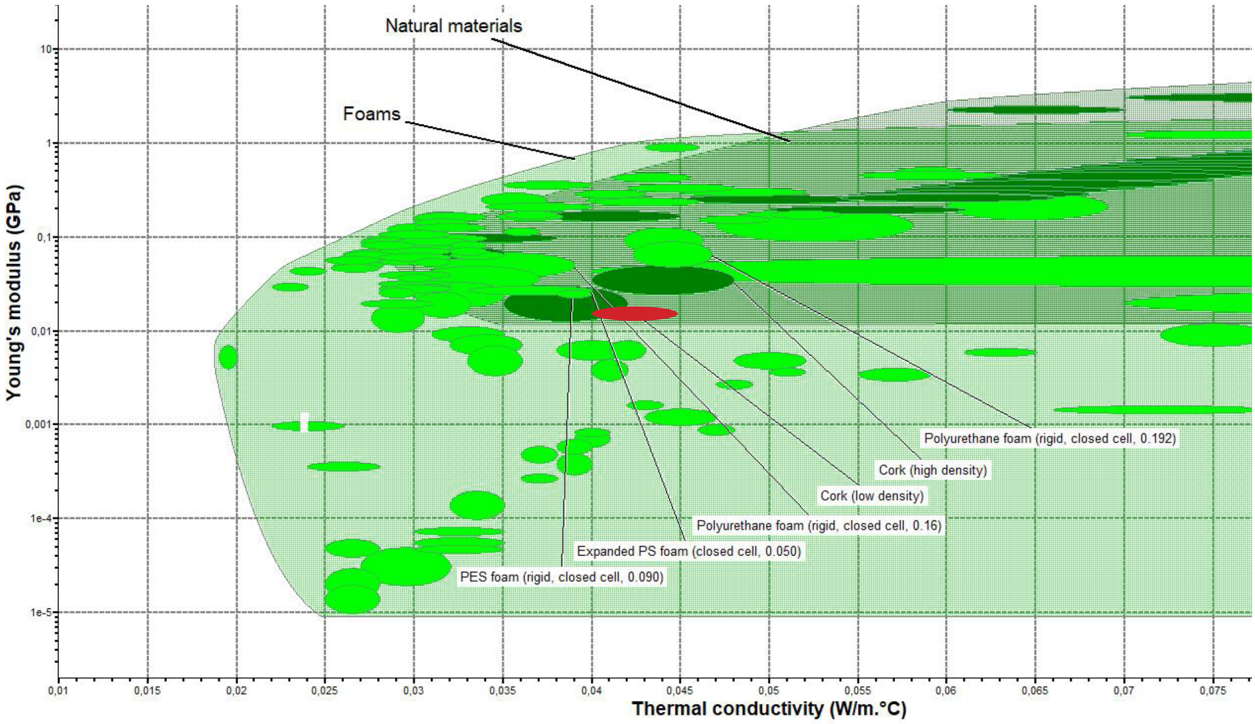



***Image 5.52:*** *Graph of Young's modulus and thermal conductivity of foams, natural materials and MBC*


***Image 5.53:*** *Upper and lower theoratical limit sandwich performance*

their full potential and that the fungal bond between the components was the weakest link of the total. Looking at the position of the sample performance within the created theoretical range it also has to be concluded that the fungal bond, as implemented in this research, is highly inadequate for its purpose. Thinking back to the fail behaviour of the sandwich samples it is now understandable that most of the recovered after their failure. As the further deformation forces the separated components back against each other and the friction was apparently enough to restore part of the sandwich behaviour improving the performance. How this inadequate bonding can be overcome or improved upon will be explored in the next subchapter, 5.4.

**Product comparison**
Finally, this subchapter is concluded with a comparison of the tested MBC-based sandwich against more traditional sandwich panels. This turned out to be significantly more challenging than the material comparison above. A number of assumptions and simplification had to be made to come to comparable results. These considerations will be discussed first after which the comparison will be made and finally a conclusion about the applicability of the MBC-sandwich panels is given.

It was identified that insufficient bonding between the layers prevented to MBC sandwich panels from reaching their potential in the tests. As the deviation between the tested and theoretical performance was so big it is unlikely that the beam as tested will be comparable with traditional panels. Therefore, it was decided to only use the ideal performance in this comparison. Because insufficient data on the panels analysed in 3.3 was found also their ideal performance was calculated. Although not realistic per se, this provides an honest insight in the differences originating from the other composition. Thereby this comparison is not between two different products, also considering their specific design, but purely between sandwich panels composed of traditional and natural materials. All product specific design features were therefore left out of the comparison, the impact of such features will be discussed in 5.4.3.

In image 5.54 a representation of the calculated scenario can be seen. A span of 6 meters was chosen as this is a normal, slightly conservative distance for an industrial hall. A load case with two loads was used; 0,6 kN/m2, with a safety factor of 1,5, representing a normal maximum snow load and the own weight of the panel with a safety factor of 1,2. For the calculations two sections with different dimension were used, as can be seen in image 5.55. The firs, bulkier, section was obtained by enlarging the section of the tested sandwich panels by 4-fold. An insulating core of 180 mm corresponds with a thickness fitting thermal building regulations. For the traditional sandwich panel, a composition of PUR and aluminium was chosen, similar as used in the Kingspan panels. A second section was designed using the dimensions of the Kingspan X-dek panel, stripped of its profiled bottom (for the influence of a corrugated outer layer see 5.4.3). An overview of all data used in the calculation can be seen in ***table 5.09***.

The results of the calculation can be seen in ***table 5.09*** under deformation. The fungal panel outperforms the thin panel with traditional composition. This is hardly a fair comparison as the traditional panel is half the height and weighs a sixth of the fungal panel. The superior E-modulus of the Aluminium, compared to Ecor, can't make up for the much lower moment of inertia. This shows though that the Kingspan panel is highly dependant on its corrugated bottom. The same can be said for the fungal sandwich as a deformation of 24 mm is much more than is acceptable (max 3mm). The superior performance of the PUR-aluminium composition is made shown by the last calculation. The thick traditional panel, with a section matching the fungal panel, deforms only a tenth, staying within regulations. Of course, two layers of a centimetre-thick aluminium aren't a very realistic. But it illustrates how much stronger the traditional composition is and shows that fungal sandwich relays on a still rather thick outer Ecor panel.

With these insights in the performance of the panel it can be concluded that this simple composition of flat ecor sheets and an MBC core, even with perfect adhesion, won't suffice as roof panel for industrial halls. Improvements in binding and design have to be looked after in order to make a structurally acceptable sandwich panel. If such improvements won't suffice, other better suited materials will be needed for the construction of fully bio-based, biodegradable roof panels.

| Panels | E*I | Elastic Modulus | Moment of Inertia | Area | Thickness | Width |
|---|---|---|---|---|---|---|
| | Nm2 | N/mm2 | mm^4 | mm2 | mm | mm |
| **Sample Avarage** | **29,81** | 38,9 | 758.655 | 3648 | 49,9 | 73,1 |
| **Sandwich optimal** | **1277,11** | 1365 | 781.250 | 3750 | 50 | 75 |
| MBC-core | 2,56 | 4,5 | 569.531 | 3375 | 45 | 75 |
| Ecor-outer sheets | 1274,55 | 6020 | 211.719 | 375 | 5 | 75 |
| **Sum of components** | **3,15** | 5,5 | 569.727 | 3750 | 50 | 75 |
| MBC-core | 2,56 | 4,5 | 569.531 | 3375 | 45 | 75 |
| Ecor-single sheet | 0,59 | 6020 | 98 | 187,5 | 2,5 | 75 |

***Table 5.08:*** *Comparison of test and calculation outcomes of sandwich performance*

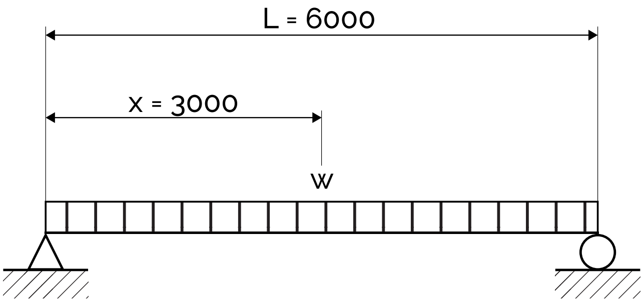



***Image 5.54:*** *Loadcase for calculations*

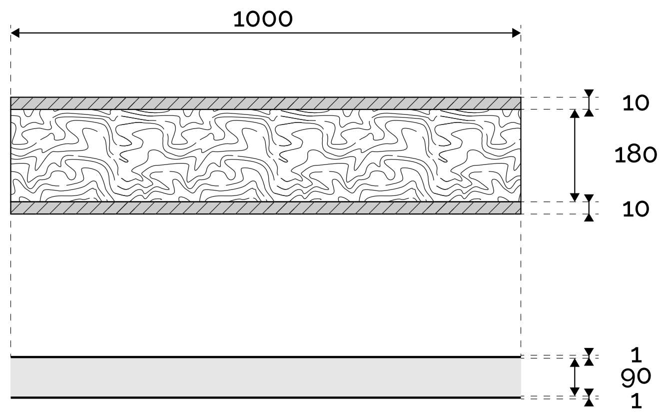



***Image 5.55:*** *Sections used in calculations*

| | Deformation | Load | | | Weight | Span | Elastic Modulus | Moment of Inertia | Density | Width | Height |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Snow | Own | | | | | | | |
| **Panel Type** | | w | | | | L | E | I | | b | h |
| | mm | N/mm2 | | | g/mm2 | mm | N/mm2 | mm^4 | kg/m3 | mm | mm |
| **Fungal Panel** | **24,64** | 1,591 | 0,9 | 0,691 | 57,62 | 6000 | | | | 1000 | 200 |
| MBC- core (180mm) | | | | | 14,94 | 6000 | 4,5 | $4860 \cdot 10^5$ | 83 | 1000 | 180 |
| Ecor-sheets (10mm) | | | | | 21,34 | 6000 | 6020 | $1807 \cdot 10^5$ | 1067 | 1000 | 10 |
| **Traditional Thin** | **59,82** | 1,030 | 0,9 | 0,130 | 10,8 | 6000 | | | | 1000 | 92 |
| PUR-core (90mm) | | | | | 5,4 | 6000 | 10 | $608 \cdot 10^5$ | 60 | 1000 | 90 |
| Aluminim sheets (1mm) | | | | | 5,4 | 6000 | 70000 | $41,41 \cdot 10^5$ | 2700 | 1000 | 1 |
| **Traditional Thick** | **2,24** | 1,678 | 0,9 | 0,778 | 64,8 | 6000 | | | | 1000 | 200 |
| PUR-core (180 mm) | | | | | 10,8 | 6000 | 10 | $4860 \cdot 10^5$ | 60 | 1000 | 180 |
| Aluminim sheets (10mm) | | | | | 54 | 6000 | 70000 | $1807 \cdot 10^5$ | 2700 | 1000 | 10 |

***Table 5.09:*** *Comparison of calculation outcomes traditional and MBC sandwich panel performance*

## 5.4 Improving the results

The processing and interpreting of the results of chapter 5.3 gave a good insight in the deficient mechanical properties of the MBC and the sandwich panel samples. As shown in 5.3.3 significant improvements are needed to meet industry standards. If it is concluded, based on the collective insights of this full report, that nevertheless continuing research into this materials combination and application is still of interest improving upon the results of this project should be one of the focus points. If such is the case the insights from this first explorative research can be of tremendous value. It was therefore decided to explore the possibilities of improvement, with the results and their insights fresh in the mind. Four different levels were identified on which such improvements can be sought after, namely: a stronger composite, higher bond strength, smarter product design and more effective building application. Possibilities for optimisation on these four levels will be discussed below.

### 5.4.1 Stronger Material

First of all, as shown in 5.3.3, improving the properties out of which the sandwich panel comprises would be an ineffective way to make it better. But as MBC's are also applicable in a range of other products it is a research that is probable to be initiated. Also, if the more impactful issue of delamination has been addressed it will likely be that the MBC turns out to be the second weakest link in the equation. As Ecor is a developed, commercially available product it will be left out of consideration. The question is thus, how can the mycelium-based composite (MBC) be made stronger and how much stronger does it need to be?

Three parameters of influence were identified; the growth process, the matrix (fungus) and the fibre (substrate). But before discussing them in that order the required improvement in strength and stiffness will briefly be addressed. As seen in 5.3.3 the MBC grown for this project clearly had inferior properties compared to other rigid insulation foams (***Table 5.07***). Levelling with a material such as PUR would drastically increase its applicability. This would require an improvement a doubling or tripling of the materials properties. If this is within the range of possibilities will require a better understanding of the material functioning. Nevertheless, methods of improvement were explored.

Optimisation of the fungal growth will require full control of the parameters at play. This means a much more thorough work method including specialistic facilities are needed to start understanding the processes at play. The complex interplay of aspects like fungal activity, growth time, nutrient composition, moisture levels, temperature and PH of the mixture have to be mastered. Controlling and studying one, will mean nothing as long as all other parameters aren't monitored either. The significance of all that work however needs to be questioned. As it is hard to say if these optimisations are just mere optimisations or will bring drastic improvements.

Similar considerations should be held by a quest for a stronger and more optimal fungus. The kingdom of fungi is enormous, and it is likely that a better performing fungus than the used Trametes versicolor exist. However, how likely is it that a better fungus provides a drastic improvement instead of a minor optimisation? Better understanding of the chemical compounds and cell strength of the fungus is needed to make any useful statements about that. Before reviewing hundreds or even thousands of strains such an understanding should be established.

An on forehand less complicated approach to improving the MBCs strength would be altering the substrate out of which it comprises. Besides the interaction between fungus and substrate, which shouldn't be neglected, the logic is as simple as more and stronger particles likely result in a stronger composite. Increasing the fibre density will make a stronger material but also a heavier one. As discussed in chapter 4 this will likely have an undesirable effect on the insulating properties of the material. This while the MBC used for the experiment already had more than double the weight of PIR foam and half the insulating capacity. A density of 83kg/m3 and thermal conductivity of 0,042 W/mK for MBC against 30kg/m3 and 0,022 W/mK for PIR.  Because of PIR superior performance this translate to a mycelium insulation package of 3 to 5 times higher than that of PIR. Heavier thus doesn't seem to be a feasible method of improving the materials strength.

Stronger and lighter, or at least not heavier, seems to be the direction. Holt (2012) found that liquid

| Substrate type | Wheat straw | Hemp | Cacao shells | Reed fine | Reed rough | Wood shavings | Cellulose |
|---|---|---|---|---|---|---|---|
| Density (Kg/m3) | 87 | 126 | 120 | 129 | 117 | 61 | 40 - 65 |

***Image 5.56 & table 5.10:*** *Eight types of suitable biomass and their densities*

***Image 5.57:*** *Mycelium Tectonics, before and after growth*

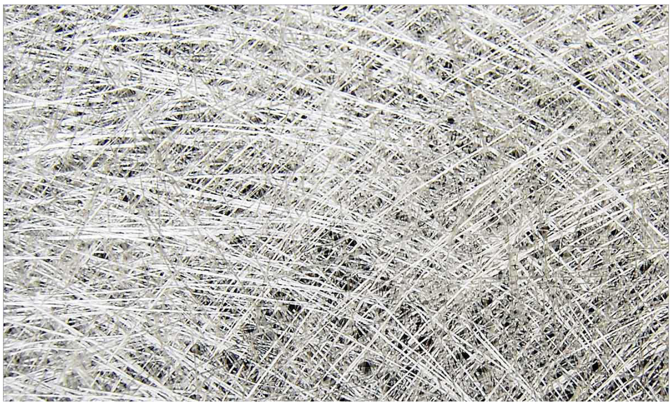


***Image 5.58:*** *Glass fibre mat, undirectional*

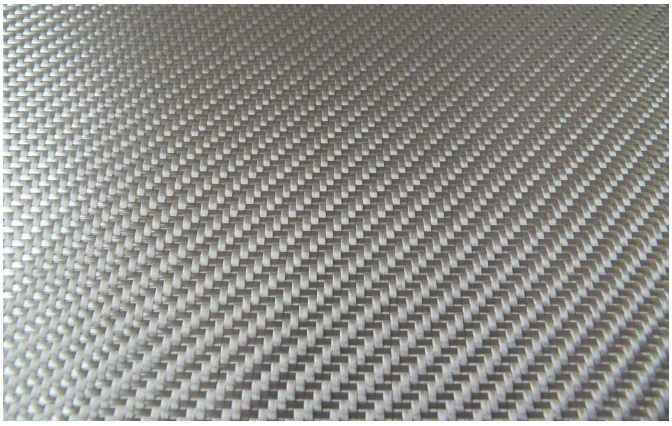


***Image 5.59:*** *Glass fibre mat, woven*

***Image 5.60:*** *Natural fibres*

inoculation results in lower density. This has the simple cause of the bird seed/millet substrate of the spawn having a higher density than the substrate of the insulation material. The nutrient rich liquid spawn will largely evaporate or be metabolised by the fungus. A quick scan of some available substrates shows a large difference in density (***Table 5.10***). Both the source materials as its morphology turn out to be important. Wood shavings have half the density of hemp and fine reed. 60kg/m3 of the wood shavings was the lightest substrate found. In (Everuse, 2019) it was found that cellulose insulation can be lighter. And since fungi also grown on cellulose this could be an option to further reduce the weight of substrate (De Bruin, 2019). Ultimately, further studies into the processing of the substrate and its morphology could potentially result in sub 60kg/m3 densities.

Density data has to be combined with insights into the strength of natural fibres. Although such data wasn't available to this project it is very likely that within the bio-based building community expertise on this topic can be found. For instance, in the field of more traditional bio-resin bio-based composites. Also, other traditional composite insights can be used in the pursuit of a stronger substrate for a MBC. In FRP's for instance various fibre typologies are available *(Images 5.58 & 5.59)*. Random, woven and directional fibre patterns result in composites with varying properties of which the first is considered the weakest (Edwards, 1998). The particle organisation in the samples made for the experiments in the project can be considered as short and random. Future research should look at how production methods can be adapted to allow for the use of longer and directional fibres. The implementation of such insights is not new and has been used by Gianluca Tabellini in his 2015 work Mycelium Tectonics *(Image 5.57)*. It would be interesting to see in what magnitude this would improve or worsen the performance of this experiment's samples; mechanically, in density and thermal conductivity.

### 5.4.2 Bond Strength

One of the core conclusions of the analysis of the experiments' results was that the preliminary delamination of the outer Ecor sheets from the MBC core prevented the sandwich samples from reaching their full mechanical potential. Therefore, the most effective method to increasing the performance of the sandwich panel is thus improving the bond strength the Ecor and MBC. The current and necessary increase in bond strength can be calculated using the test data. However, this would require a deeper under in the delamination phenomenon. As shear force is currently identified as the main cause for delamination more understanding is needed of the resistance of the fungal bond against these forces. This could be done with the experiment setup displayed in Image 0. As such surpass the focus of this project this section will be restricted to the discussion of potential methods of improvement. ***Image 5.61*** shows there is currently more then enough potential for it.

An obvious method would be somehow promoting the fungal growth at the Ecor surface leading to an improved adhesion. This could for instance be done by locally providing additional nutrients for the fungus. A shorter colonisation and longer formation phase could also be considered. In the preparation of this project's samples the fungus grew for 14 days on the substrate but was only in contact with the Ecor during the last 7. The last days are much more significant as fungal growth occurs more or less exponentially. But nevertheless, a forward and surely and backward elongation of the formation phase timewise could result in improved fungal adhesion.

A simpler method to increase the bond strength would be to not necessarily improve the strength of the bond per surface area, as described above. But just to simple increase the bonding area. A design solution with a profiled upper and or lower plate as seen in chapter 3.3 with both the Kingspan and Burcha sandwich panels. Such panels also have another advantage which will be discussed below under 5.4.3 Product Design. For now, it suffices to establish that a profiled sheet has a larger surface than a flat sheet, as illustrated in ***image 5.62***. An identical bond strength but multiplied with a larger surface will still result in a stronger bond between the core and the outer layers.

The same logic of surface increase can be applied on a micro level. By mechanically treating the Ecor, with for instance a steel brush, its surface can be roughened. This will lead to the increase of the Ecor's surface on a micro scale. Effectively reversing the effect shown in Image 2 for the sanding, and smoothening, of a wooden surface. Although the relief is minor its constant meandering results in drastic surface increase. Roughening of surfaces is for that reason common practice in a lot of gluing and adhering processes (Lord Corporation, unknown).

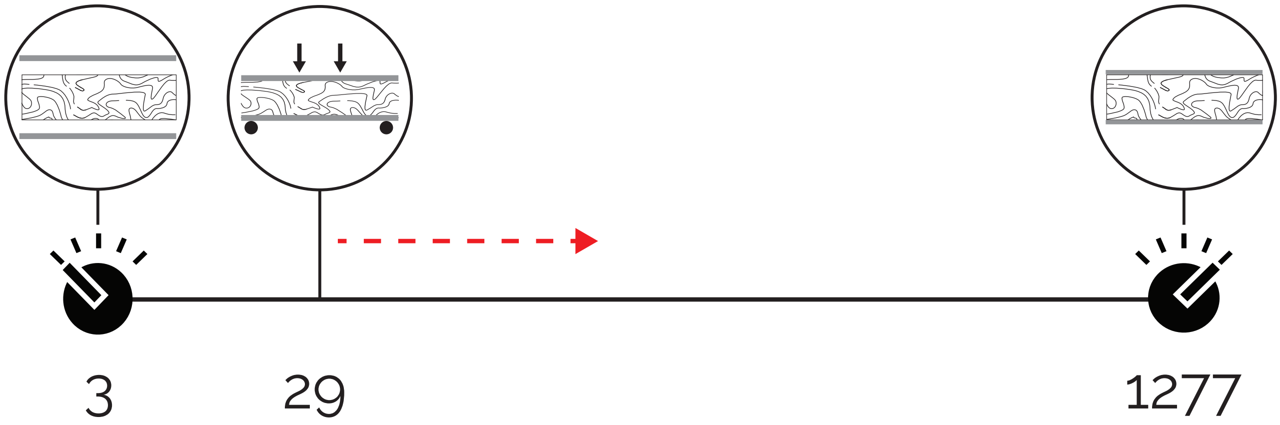



*__Image 5.61__: Improving bond strength is critical in achieving stronger panel*

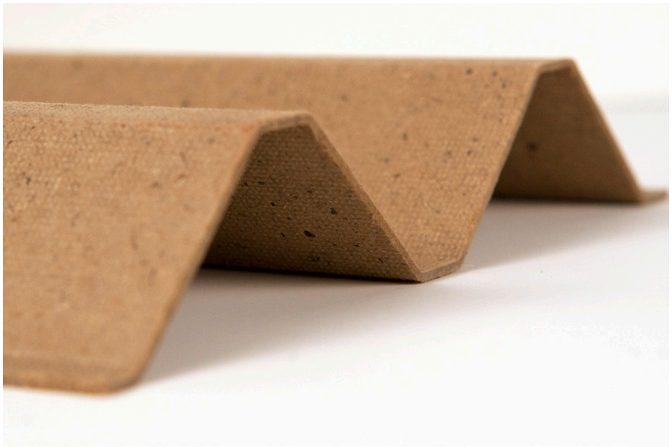


*__Image 5.62__: Corrugated Ecor*

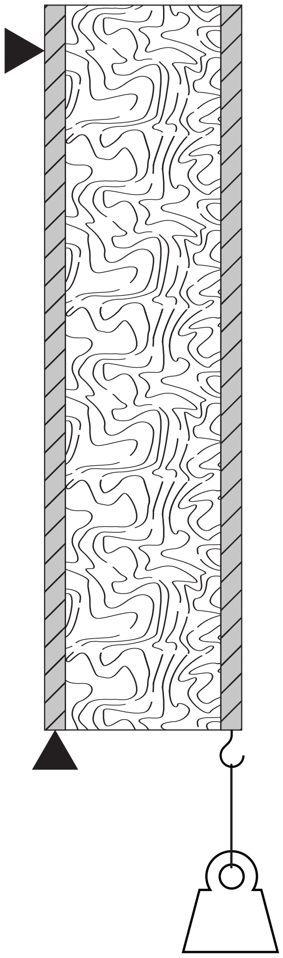


*__Image 5.63__ Shear force bond strength test setup*

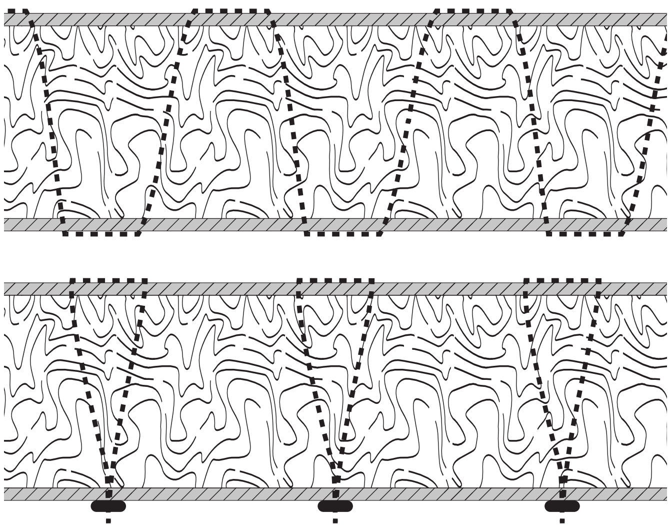


*__Image 5.64__: Internal tensioning*

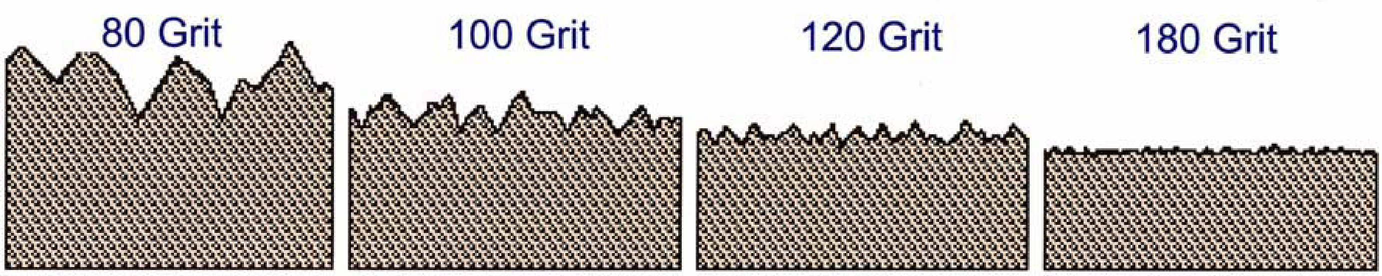



*__Image 5.65__: Roughness per sanding grit, rougher means more surface area*

A third and final imagined method of improving the bonding between Ecor and MBC is by the application of pressure on the outer layers during the growth phase. The reasoning behind this strategy is that the pressure results in a local compression of particles and Ecor. This tighter packed region is assumed to have higher fungal activity. Thus, locally growing more fungus and thereby creating a stronger bond. Theoretically this densification should only occur at the edges where MBC and Ecor meet, without compromising the lightness and thermal conductive capacities of the rest of the material. The mode in which this pressure is applied, and the magnitude will probably have a lot of influence on the success of this method. External pressure can be applied on the Ecor by an external upper or lower press.

Another possibility that wouldn't require an enormous press would be the use of a mechanism that pulls together the two outer layers; internal mechanical pressure. As illustrated in *image 5.64* a method can be adopted from the upholstering of the famous Chesterfield couches. Such method, and other rope and sowing-like methods form a hybrid between material and product improvements. Ultimately, to a certain extend a connection is made between the two outer layers. This is a potentially valid line of improvement, but it steps away from the sandwich panel typology. This type of solutions will be discussed next.

### 5.4.3 Product Design

Now a certain understanding in the material and product have been obtained these insights can be used in alterations to the panels design. As will be shown the influence this can have is quite substantial. During the processing of the results two key issues were identified for which solutions will be explored. First of all, as seen in the elaborations above the weakest link in the tested sandwich panels is the binding between the core and the outer sheets. Countering the shear forces that cause this delamination will thus be key. Additionally, it has been calculated that even if the connection was perfect, the panels theoretical maximum strength would not be enough for the envisioned application. Based on the quantities at play in this equation the only real option, besides the selection of other materials, is improving the second moment of Inertia. This will thus be the second aspect of the exploration in this section.

**Internal connecting beams**

The adhering function of the fungus is not strong enough, this has been established. Improving this bond through better controlled growth parameters could further improve this but the question remains, by how much? Based on the overview of *Image 5.61* it is unlikely that this will be enough to enable the full potential of the sandwich panel. A solution on a product level, already touched upon in the previous section, is connecting the top and bottom Ecor sheet in a different way that fungal adhesion. The most obvious way to do this would be implementing two or more beams through the sandwich panel (*image 5.65*). This would ensure the panel reaches its full capacity (*image 5.67*) and, depending on the material used for the beams, increase the moment of inertia by a certain degree. Natural materials that would be suitable for this application would be wooden or Ecor beams. The latter currently don't exist, but as cardboard profiles do (*image 5.66*), it is likely that these could be produced.

This solution does however introduce two separate problems. The beams will only withstand the shear forces if the connection between them and the Ecor are strong enough. No real natural alternatives for the fungus exist. Non-natural solutions would therefore be needed. Glues would be irretrievable after the products lifespan. Industrial staples would probably be the best solution a magnet could get them from a shredded heap of panel. The second issue is more fundamental. The beams would turn the sandwich panel in more of a timber frame panel. The beams would interfere with the continuous layer of insulation the sandwich panels would provide, introducing a cold bridge. Although, the thermal conductivity of wood and cardboard aren't that high this would have a measurable effect, certainly over the enormous surface of a distribution centre. Adding beams with staples would be a very easy thing to do but also goes against some of the fundamentals in of the MBC-sandwich panel.

**Hollow core slab**

A more elegant solution, from a design perspective, would aim to solve the problem of shear force and delamination directly without compromising the core insulating and circular principles of the product.

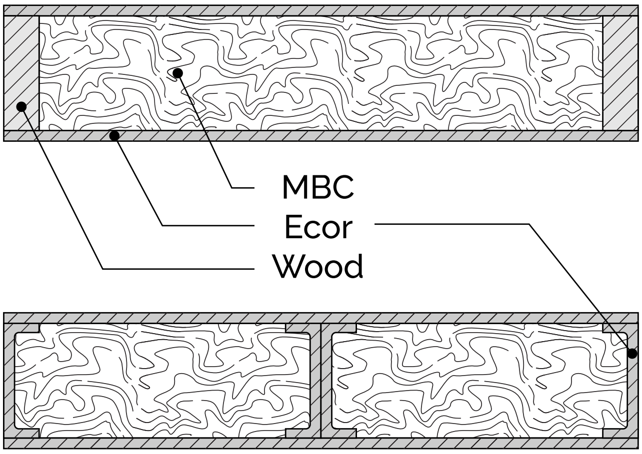



**Image 5.65**: *Two potential sections with internal beams*

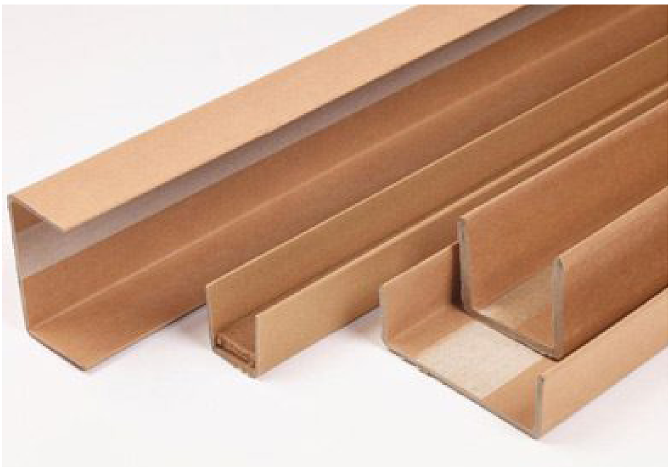


**Image 5.66**: *Cardboard profiles*

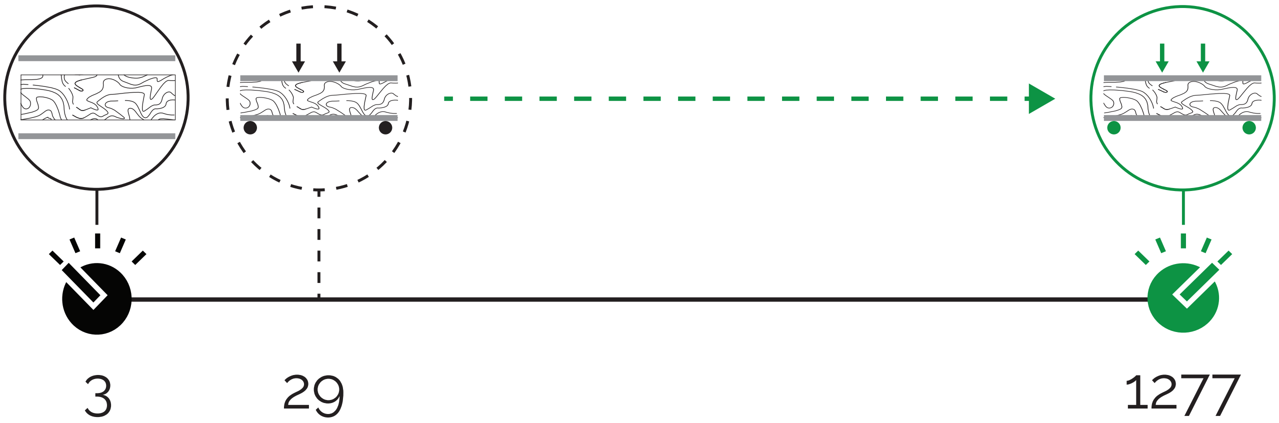



**Image 5.67**: *Reachin the sandwich panels full potential*

**Images 5.68 - 5.70**: *Prototyping a hollow core slap using TL-bulps*

This could be done with a hollow core slab, similar to hollow concrete floors (*image 5.71*). It would require making tubular cavities in the panel, for reasons that will be discussed in chapter 6, this is also beneficial for the production process. In *images 5.68 - 5.70* can be seen how the possibility to do so was investigated through prototyping.

The hollow cores don't have any mechanical functioning themselves. The moment of inertia will even decrease slightly due to the absence of material. But as this is the weaker MBC, located in the middle of the panels section the effect will be minor. The hollow cores do however allow for the placement of cables through them. These cables could be made from steel but also rope from natural fibre like hemp. By applying a special fitting pieces for the beginning and end of the panels these cables can be tensioned (*image 5.74*). This tension helps to counteract the shear forces that will be caused through loads on the panel (*image 5.73*).

This solution also doesn't come with side effects. Tensioning the cables will put a lot of force on the two Ecor sheets. This will likely cause them to buckle. These forces are needed to counter the shear forces but when these are not present the tension will have the unwanted effect of outward delamination (*image 5.73*). This can be overcome by again placing a beam in the middle of the panel, preventing this buckling behaviour. Or, by selecting an outer sheet with a higher buckling length, a stiffer element. Such a sheet doesn't need to be made from a different material but can be made by corrugation. Solutions based on corrugated Ecor are the topic of the next section.

**Corrugated Ecor**
In the industry product analyses of 3.3 it was found that both analysed products had one non-flat side. The Brucha panel had outside ridges and the Kingspan panel had a large corrugated sheet on the inside of the panel. Clearly these provide some sort of function for the rigidity of the panels. Regarding the panel comparative calculations of 5.3, it becomes clear that an improvement of some sort is needed as also the traditional panel doesn't achieve proper stiffness (*Table 5.09*). The corrugated outer sheets help by improving the moment of inertia. As discussed in 5.3 the height of the section of the beam has with a third order effect a large influence on this value (*Formula 4.1*). This is largely the same effect that gives sandwich panels their strength, just another method of achieving it. For the best effect, as seen in the traditional panels, these methods are combined.

Calculating the second moment of inertia for a sandwich panel with one or more corrugated sheets is a little more complex as that of a rectangle. This won't completely be discussed here but the logic behind it is similar to that in *Formula 4.2*. By calculating the value for the full enclosing rectangle of the section and subtracting the missing pieces the value can be obtained. In *image 5.76* can be seen how the second moment of inertia changes between a flat, single corrugated and double corrugated panel. But the irregularly shaped panel brings additional complexities. As discussed in chapter 3.3 and 4.1 the Kingspan panel has a flat top to allow for continuous roofing to be applied. The double corrugated panels can only be applied on sloped roof, like a farm barn, as otherwise water will collect in the lower ridges.

Finally, as discussed in 3.4.2 the use of a corrugated plate also has a beneficial effect on the binding of the core and outer sheets. As shown in *image 5.75* the surface area of non-flat sheet is much large thus providing more binding area.

### 5.4.4 Building Application
Finally, alterations can be made to the way panels are applied during construction that positively influence their applicability. This is not a method of improving the strength of the panels but of dealing with their inadequate mechanical performance. It is as simple as adding an additional point of support. As can be seen in *image 5.77* besides the support on either end of the panel a third is added in the middle of the panel. Not only does this effectively half the span width the extra support acts as a kind of scale. Interestingly, this effect is also beneficial when the complete beam or panel is charged with an evenly distributed load. The bending moment of the load on the one side of the middle support counteracts the one on the other, befitting the capacity of the beam.

This effect can be calculated for the tested beams but is best explained using the formulas for a double

*Image 5.71: Hollow core slaps floors being installed*

*Image 5.72: Delamination causing peltruding ends*

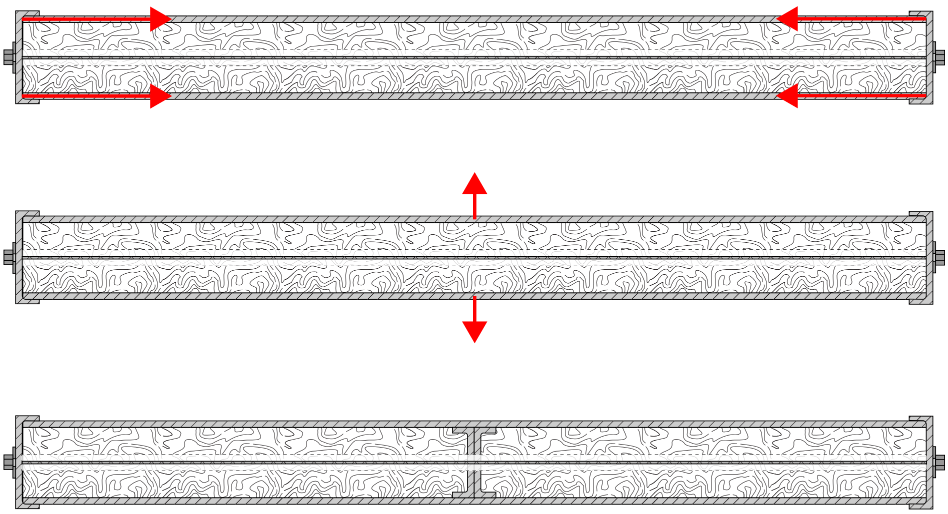


*Image 5.73: Functioning of a tensioned panel*

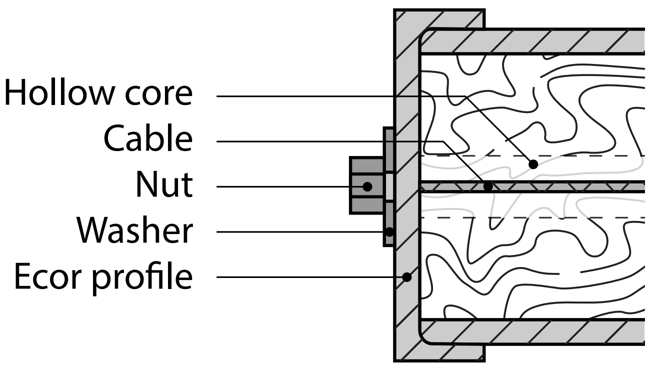



*Image 5.74: Detail of a tensioned hollow core slap*

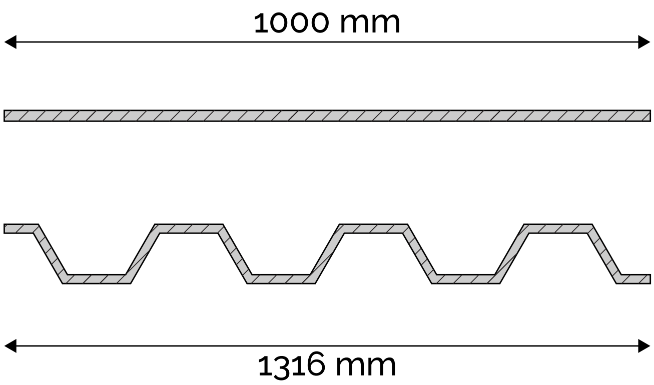



*Image 5.75: Surface increase of corrugated sheet*

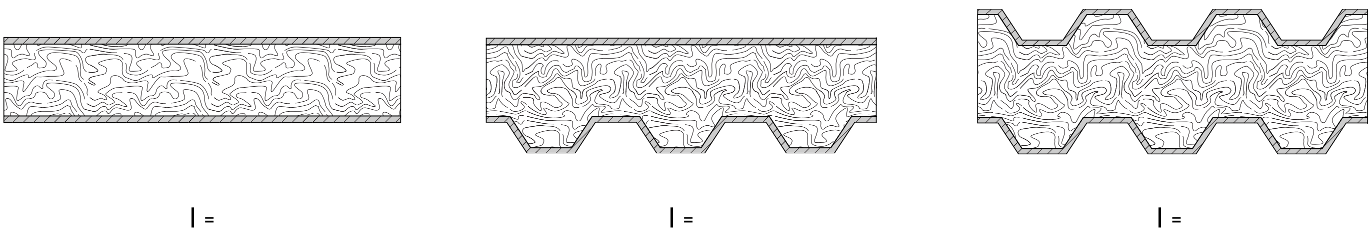



*Image 5.76: Second moment of Inertia for flat, one-sided and two-sided corrugated sheets*

and triple supported beam. To the right the Free Body Diagram, Shear Force Diagram and Bending Moment Diagram can be see together with the corresponding formula for delta max, or deformation in the most extreme point. The two formulas look quite similar and have contain the same quantities. L is the length of the span; E and I are the E-modulus of the material and I the moment of inertia and w is the equally spread force on the panel. When these are kept the same, requiring the panel with 3 supports to be double as long, they cause any difference in the outcome of the formula. The difference in outcome is cause between ***Formula 7A & 7B*** are the numbers in them. If these are isolated, they become ordinary numbers which can be compared. It turns out that with the same span and same amount of force applied the deformation in the panel with triple support is 2,4 times lower.

During the analysis of chapter 3.3 the significance of this measure was found on inspection of the data sheet of Kingspan's X-Dek panel. ***table 5.11*** shows part of that data sheet. A clear pattern can be seen in the gradient in which the max variable load decreases as the span width increases. With a two-sided support the declination is much steeper compared to the triple supported panel. A downside is that the panels have to be twice as long. In case of a short distance between the support points this is manageable. But in the likely case of support points as far as possible outward this will cause problems. Challenges are most likely be faced in production or transportation of the panels. It is however an application that is fairly common. A triple support structure has an additional safety advantage for the roof structure as a whole. By applying the panels in a stretcher bond-like pattern, as shown in ***image 5.78***, an interwoven roof slap is created. This enables stresses to flow away and spread throughout the roof. This makes it as whole much less susceptible for the local failure of one row. Application in this manner was also advised by Kingspan for their panels (***Appendix 3.2***).

A second, and even simpler way of dealing with the inferior performance of the panel is by shortening its span width. For instance, to 3 or 1,25 metres respectfully the full length or width of an Ecor panel. The effect of this on the deformation of the panels is quite significant. The reason for this is the forth order influence the length (L) has on the deformation, as can be seen in ***Formula 7A***. In most cases, and certainly in distribution centres beam distance can't be altered. In that case a secondary row of beams needs to be laid on top of the primary beams to shorten the span. These building level solutions should however not be regarded as stand-alone solutions. As with most of the solutions mentioned in this section it is likely that a combination of them will be needed to get to an applicable MBC sandwich panel.

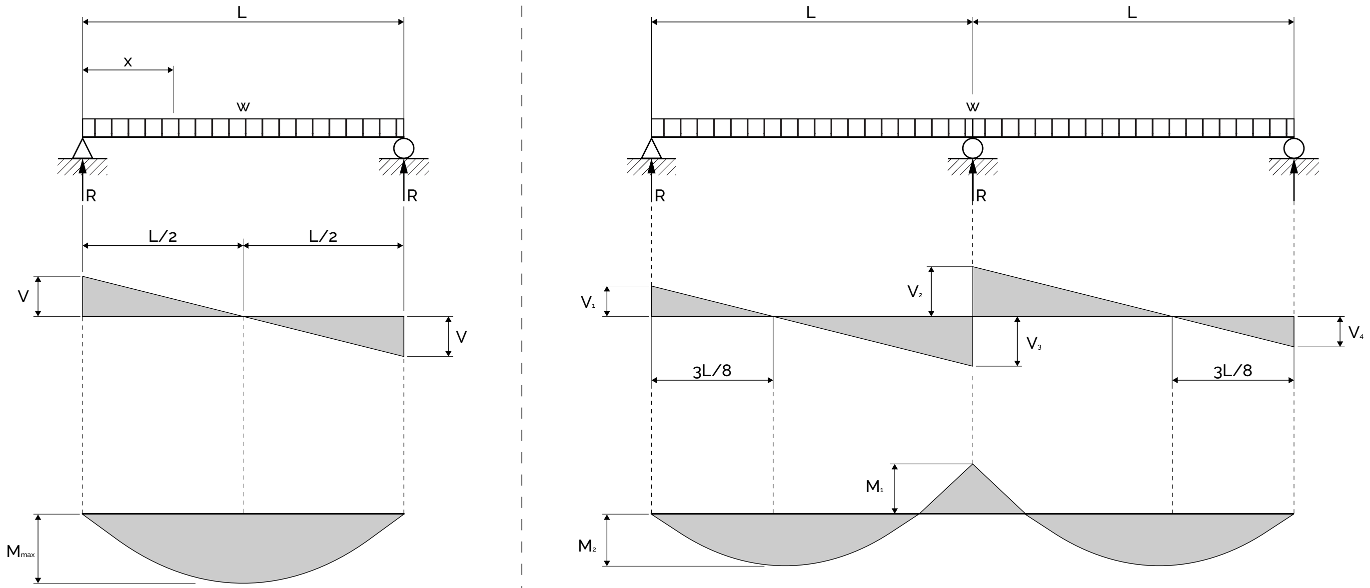
## 5.5 Discussion of the Method

As assumed in 5.1, with the selection of the testing method, the experiments have provided valuable mechanical insights on both a material and product level. However, both the process as the approach weren't free of flaws. An important part of an explorative research projects is learning by doing. If it turns out that the investigated concept is in some form viable the insight gathered from the first explorative research run can be of tremendous value. This subchapter will therefore reflect on both the mistakes that were made as on the alterations in approach that would be considered based on the insights that the process of doing has provided. First the process as described above will be regarded. And second, the whole approach of using the used methodology and potential changes that could be made in that.

#### 5.5.1 The process

The right amount of experience with the production of fungal materials was present to make samples of sufficient quality. Also, the facilities were enough for the goals of this project. However, when research would progress additional preparation should be taking to allow for the production of better samples. Especially in the process of improving and optimising it will be essential to have controlled growing conditions. Otherwise the repeatability and thus the scientificness and even usability of the results will be at stake.

Another point on which the tools used during the production of the samples could be improved is the quality of the moulds. As seen during the discussion of the assessment of the samples it turned out that some irregularities and systemic defects were present in the moulds (***images 5.79 & 5.81***). These were cause by the production method of the moulds. The use of more expensive but more precise




**Formula 7A**

$$\Delta_{max} = \frac{5wL^4}{384EI}$$

$$\frac{5}{384} = 0{,}0130$$

**Formula 7B**

$$\Delta_{max} = \frac{wL^4}{185EI}$$

$$\frac{1}{185} = 0{,}005$$

***Image 5.77**: Loadcase, shear force, bending moment and deformation formula for double and tripple support*

Variabele belasting (kN/m²), CC2, enkelvelds
Staaldikte: Buitenplaat 0,7 mm, binnenplaat 1,1 mm

| Kerndikte (mm) | Belasting Type | Overspanning (m) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 3,00 | 3,50 | 4,00 | 4,50 | 5,00 | 5,50 | 6,00 | 6,50 | 7,00 |
| 80 | Druk | 6,51 | 5,56 | 4,31 | 3,07 | 2,23 | 1,64 | 1,21 | 0,90 | 0,67 |
| | Zuiging | 6,80 | 5,84 | 5,13 | 4,32 | 3,27 | 2,53 | 2,00 | 1,61 | 1,32 |
| 100 | Druk | 6,72 | 5,74 | 4,87 | 3,54 | 2,62 | 1,97 | 1,49 | 1,13 | 0,86 |
| | Zuiging | 7,02 | 6,04 | 5,30 | 4,73 | 3,78 | 2,97 | 2,37 | 1,92 | 1,58 |
| 140 | Druk | 6,72 | 5,74 | 4,87 | 3,54 | 2,62 | 1,97 | 1,49 | 1,13 | 0,86 |
| | Zuiging | 7,02 | 6,04 | 5,30 | 4,73 | 3,78 | 2,97 | 2,37 | 1,92 | 1,58 |

Variabele belasting (kN/m²), CC2, tweevelds
Staaldikte: Buitenplaat 0,7 mm, binnenplaat 1,1 mm

| Kerndikte (mm) | Belasting Type | Overspanning (m) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 3,00 | 3,50 | 4,00 | 4,50 | 5,00 | 5,50 | 6,00 | 6,50 | 7,00 |
| 80 | Druk | 3,93 | 3,37 | 2,95 | 2,63 | 2,36 | 2,15 | 1,96 | 1,81 | 1,57 |
| | Zuiging | 4,51 | 3,93 | 3,49 | 3,14 | 2,86 | 2,64 | 2,45 | 2,28 | 2,14 |
| 100 | Druk | 4,16 | 3,56 | 3,12 | 2,77 | 2,49 | 2,26 | 2,07 | 1,90 | 1,76 |
| | Zuiging | 4,77 | 4,14 | 3,67 | 3,31 | 3,01 | 2,77 | 2,57 | 2,40 | 2,25 |
| 140 | Druk | 4,16 | 3,56 | 3,12 | 2,77 | 2,49 | 2,26 | 2,07 | 1,90 | 1,76 |
| | Zuiging | 4,77 | 4,14 | 3,67 | 3,31 | 3,01 | 2,77 | 2,57 | 2,40 | 2,25 |

***Table 5.11**: X-dek span table double & tripple support*


***Image 5.78**: Half brick bond application pattern*

mould could improve this. It has to be added that also the use of a controlled, but primarily flat, drying environment would also help preventing deformation in the samples.

In the literature fears were encountered that the mould could also have another unwanted effect on the samples. Travaglini (2014) states that as a reaction on the mould a layer forms on the surface of the sample. In order to prevent disruption of the results based on the behaviour of this layer it best practice to remove the layer and cut out the tested samples. For the experiments in this project this was not done because it was feared that cutting the samples would have more of a damaging and disrupting effect. Especially since the density of the samples here was much lower than the dense material of 318kg/m tested in that case. However, the formation of a top layer is an existing phenomenon with fungal materials (*image 5.80*). For future research it is something that must be considered and potentially can be ruled out as of influence on the test results.

Other than cutting away the top layer this effect could also be diminished by the usage of larger moulds. This would also lower the inaccuracy of the sample assessment that was caused by the irregular surface of the samples. It was experienced that protruding particles and the slight flexibility of the material had a negative influence of the precision of the measurements (*image 5.81*). Larger samples could form a solution as this will lower the influence of the imprecise measurements on the accuracy of the samples in relation to their design. The influences of which can be quite significant, especially for the height of the samples, as this influence the moment of Inertia by the third power (Formula 4.1).

The method of assessing the samples should also be improved. The intervals in which measurements were done didn't overlap with the grid on which the contacts point of the experiment setup lay (Image 4). The measurements done could also have been more numerous, especially for the width of the samples. It could also be advisable to condense the measurements in the middle part of the samples, where it is likely to fail. Of course, these improvements would be rendered useless when samples could be made to higher precision.

Also, the testing of the samples could be improved. Although the irregular and non linear behaviour of the samples could have partially been predicted based on the results found in the literature, not all measures were taking to register the needed data to explain the deviations between the samples. During the overview of the results, discussed in 5.3.1, it turned out to be crucial to have visual data from the entire course of the experiments. As the video of sample F1 proved crucial in understand its delamination process. By recording all the experiments this could be overcome. With two cameras on standards filming in different angels and detail most overlooked occurrences could be registered. A hand-held camera could be used additionally to record some of the local failures in more detail.

Another aspect of the testing that could be improved is the extensiveness of the tests. Doing more experiments always helps in establishing a better image of the average behaviour and the width of the range in which the performance lays. It is however not the extensiveness of tests that were done that is of importance here, as the quantity suits the graduation context of the project. Rather, it are the tests that weren't done that are of more crucial here.

As it was established that the delamination of the sandwich panels, due to the occurring shear forces, was the main cause of the panels not meeting their full, theoretical, potential. This is very likely so, but due to the planning and design of this project it can't be ruled out that other phenomena are at play too. And certainly, the magnitude of their influence can't be quantified. A prominent possibility is that the theoretical potential of the sandwich panel isn't indicative for the performance of the real samples. As it can't be ruled out that the E-modulus provided by the Ecor company wasn't accurate for the material used in the experiments. By incorporating some additional steps further research would obviate this and gain substantive insights in the effects at play. This could be easily done by firstly testing some pure Ecor samples as well to establish the correctness of the value provided by the company (*image 5.83*). And secondly, by making some additional sandwich panels, removing their Ecor sheets and testing them. This to see if the production process, for example the fungal growth of sterilisation, weakens the Ecor, and thus also the maximum obtainable strength and stiffness (*image 5.82*).

As encountered in this project, hence the extensiveness of this chapter, testing a bioengineered

*Image 5.79: Sample ends grew less due to dehydration*

*Image 5.80: Thick mycelium layer on top*

*Image 5.81: Irregular top of sample, due to mould*

*Image 5.82: Fungal growth on Ecor*

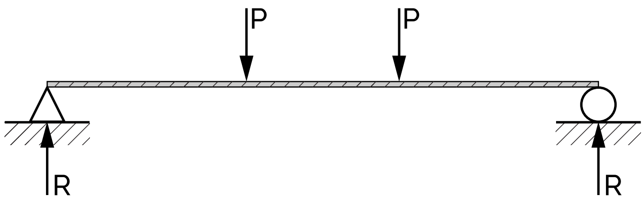



*Image 5.83: Test setup with only Ecor*

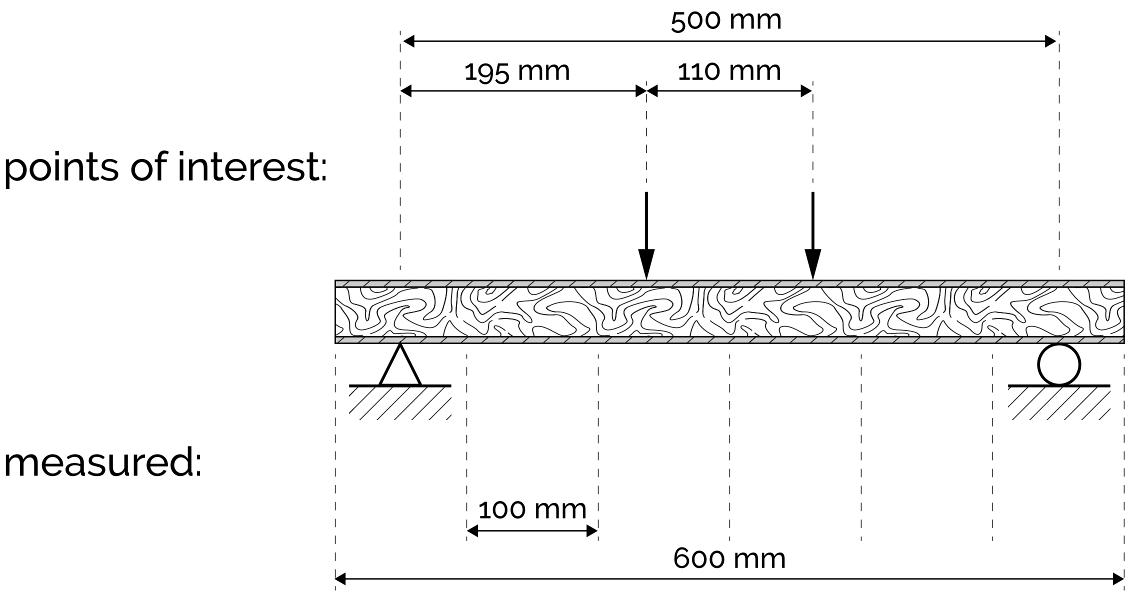



*Image 5.84: Non corresponding measurement and point of interest grid*

composite material is a complex undertaking. The number of parameters that are of influence on the result is very large. Not only aspects of the growth and production process have this impact but also choices made in the testing and processing. This makes interpretation of the work of others in the field difficult as their exact methodology remains unclear. While in order to make the quick progress essential in subject, as pointed out in chapter 1, the comparability and exchangeability of the results from various research group is crucial.

As discussed in 5.1 and 5.2 the available testing protocols were found to be inadequate. Currently no standardised testing method for mycelium-based composites exists. A challenge acknowledged by multiple scientific authors of work reviewed in the literature. For instance, Travaglini (2013) who states "Tests were completed according to ASTM D3574 -11, which provided the most applicable testing methodologies, as no testing standards currently exist specifically for natural composite foams. For that reason, various methodologies are used resulting in hard to compare data.

An aspect that was found to specifically challenging was the method for establishing the E-modulus. Even if the material will be improved the chances are high it will still behave in the non-linear way as it did in the performed test. Seeing that MBC from the literature had similar behaviour (Travaglini et al., 2014). The selection of delta x & F has large influence on the E modulus. As this probably isn't a unique phenomenon the literature needs to be studied to see how this should be correctly dealt with.

A uniform testing protocol seems to be a solution solving this problem on all levels. Potentially beneficial in establishing this could be the involvement of testing authorities as the EN-committee. As it likely that besides mycelium-based composites also other nature based and biotechnological materials will surface in the near future. Maybe it would therefore be wise for these organisations to expand their focus to the field of bioengineering and biomaterials.

### 5.5.2 The approach

As discussed at the beginning of this subchapter, is this explorative research project a perfect opportunity to learn about the used method. As shown above, there are plenty of way this method can be improved upon. In this section the focus will be slightly different. Instead of regarding the quality of the implementation it will be the adequacy of research strategy that will be discussed. Can future research be more effective or better by doing things differently?

At the beginning of this chapter a case has been made for the use of a four-point bend test in this project. The two main arguments were the resemblance of the test to the actual roof panel application and the combination of tensile and compressive forces at play in a binding load case. These arguments suit the explorative nature of this project but lose their validity in a more comprehensive project. As a bending loadcase contains both tensile and compressive forces it will be even more important to understand the reaction of the material to these forces. Also testing the tensile and compressive behaviour of the material (*image 5.86*) will provide a better understanding of its weaknesses and help making better and more focussed development choices.

Apart from this chapter's conclusion that the weakest link in the sandwich panels was the fungal binding, it seems logical that research into the improvement of the materials performance would be conducted. This as a better performing material is automatically more appealing and useful. Gaining a better understanding of the phenomenon at play will be crucial in this undertaking. To truly build an understanding of the relation between material morphology and its properties it would be advisable to study the theory of foams, or cellular solids, more closely. Interesting theories, as the cell wall strength theory (*image 5.87*) exist that give entry to the mastering of the realm of foams. Travaglini (2013) briefly touches upon this subject as she compares the mechanical behaviour of her tests with various foam typologies; elastomeric, elastic-plastic and elastic-brittle (*image 5.88*). Scanning Electron Microscope (SEM) imaging could help better understanding the mechanical behaviour of MBC on a cellular level. It is only in such a comprehensive approach that a true mastery of mycelium-based composites can be achieved.

The above-mentioned approach would mean a lot of work. Most of the activities and tested variables would be based on hunches and trial and error. It is naïf to think that developing a new range of materials

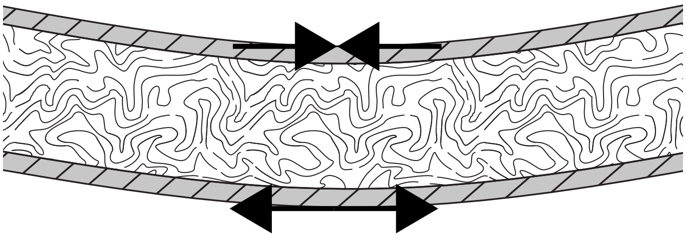


***Image 5.85:*** *Bending consist of local compression and tension*

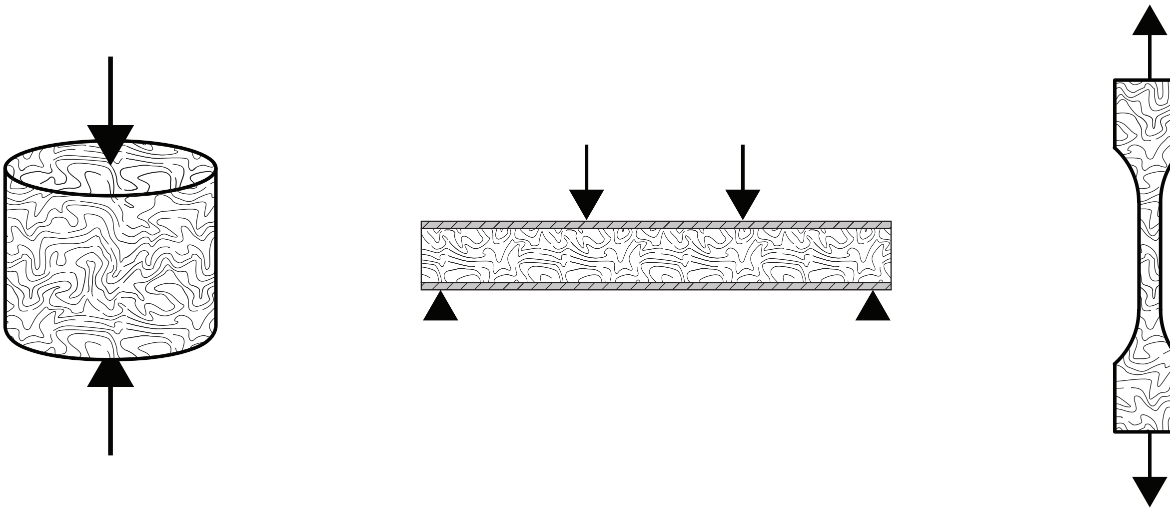


***Image 5.86:*** *Compression, bending and tensile tests all are needed to achieve a full understanding of the material*

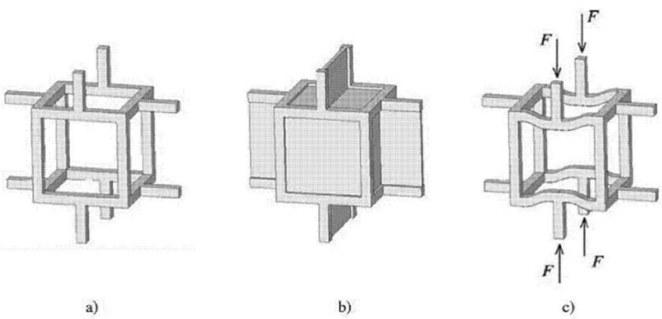



***Image 5.87:*** *Closed and open cell foam models*

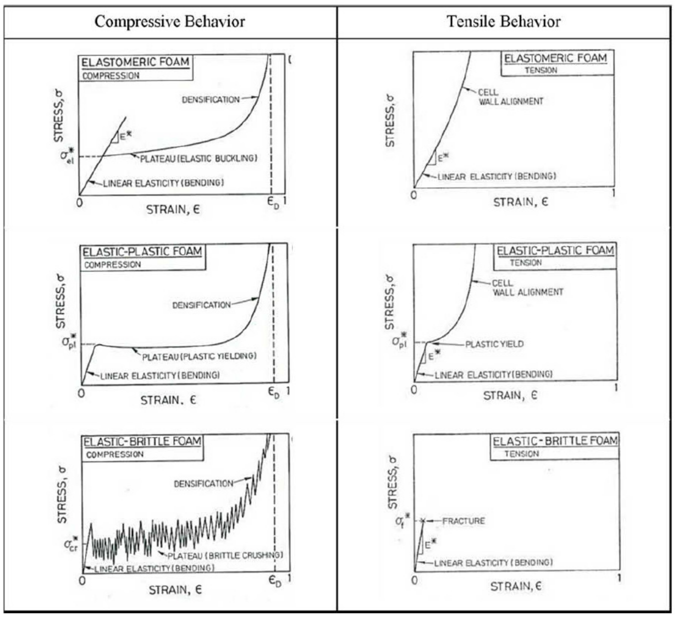



***Image 5.88:*** *Behavioral patterns for different foam types*

using biotechnology can be easy. However, it makes sense to explore if more effective approach exists. During the exploration of the existing literature on the topic two studies were encountered that may offer such a method. Islam (2017; 2018) shows it is possible to simulate and predict the materials behaviour by computer calculations (***image 5.89***). As far as understood, this will offer a basis on which with much higher speed and accuracy an indication can be made about the reachable limits of the material's structural characteristics. One of the recommendations of this research is to investigate the likelihood and suitedness of this technique to substitute parts of the mechanical research as it will be a lot less, labour and capital intensive.

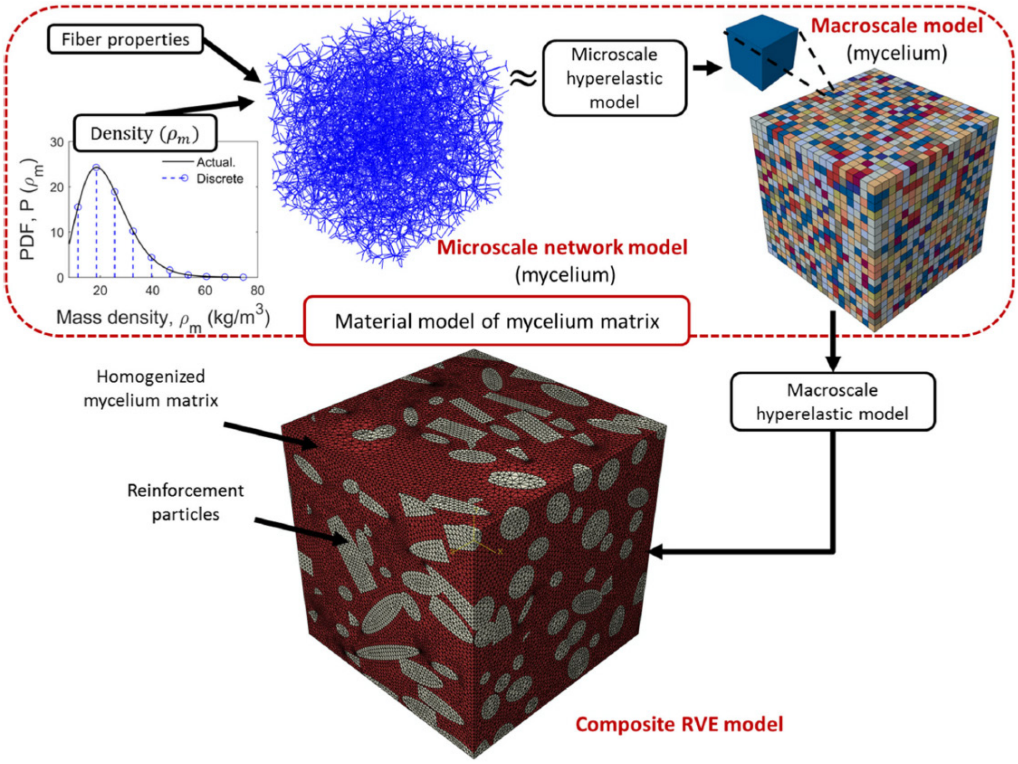



***Image 5.89:*** *Conceptual model for computational approximation of material behaviour by Islam (2018)*

# 6

# Production Development

This chapter explores the potential production of mycelium-based sandwich panels. Ultimately the goal is to investigate if it is feasible to produce this product in the right quality and with right quantity. Often production is regarded as a way to make large quantities of a premade design. In this project however, a thourough believe is held in the relation that the production process has to both the quantity in which a product can or has to be made and the quality with which this happens. In order to regard these quantitative and qualitive questions in the appropriate manner an analysis of the industrial processes of comparable sectors will be made (6.1). Together with points of attention gathered throughout this project the gained insights of these analyses will be combined in a list of production challenges (6.2). In 6.3 a number of solutions will be developed and presented based on the formulated challenges. In 6.4 the focus will shift towards scale. Based on the numbers of supply and demand from chapters 3 and the analysis of 6.1 the scale of a potential production process will be established. It is also here that the feasibility of that scale be questioned. Ultimately, the chapter will finish with the design of conceptual production line that could be scaled to the appropriate capacity in 6.5.

## 6.1 Production Exploration

This subchapter is dedicated to the establishment of the crucial principles behind the production of mycelium composited based sandwich panels. The substantiation of the exact process is the subject of this entire chapter and will be presented in 6.5. First, the outlines, challenges and missing pieces of knowledge of the process must be identified, as will be done in this section. Although continuing on the principle steps in making MBC's, discussed in 2.4, this section will differ significantly. Mainly, because it is not the production of a material that is the topic, but the large-scale production of a circular product. The additionally needed production steps and consequences of scaled production will be established here. This will be done through the analysis of the production process of two product categories adjacent. As captured in image 6.01 the production of mycelium composite based sandwich panels is, simply put, nothing more than the aggregation of mushroom and foam sandwich panel production principles. Therefore, it was decided to analyse the production of these two industries looking for product and scale-based boundary conditions.

### 6.1.1 Mushroom Industry

The principle processes of the production of most mushrooms is very similar to that of making mycelium-based composites. All production steps of interest have therefore already been explained in subchapters 2.4 and 5.2. No third elaboration to these individual steps will be given. Most of the imagery on which this analysis is based has been used in one of these two prevailing sections. A complete overview of all footage, including clear video source explaining all individual steps can be found in ***Appendix 6.1***. All points of interest, or concern, that came out of the analysis will be discussed according to the overview of mushroom production steps (image 6.02), and in linear order from top to bottom.

The first stage of production is mixing of right substrate recipe. The recipe of the mixture for MBC's will likely differ from that used for mushroom production. This however, is not expected to result in drastic alterations in the process. The scalability also doesn't seem to be a real issue as mixing installations can easily be enlarged in volume or expended in number. Proper monitoring of ingredient quality and mixing homogeneity can become challenging at larger volumes but not in a surmountable manner. The most challenging aspect of this first step is expected to be the supply chain management that will be involved. As large quantities of biomass are needed year-round while these mainly come available in a limited harvesting window. Storage needs to be voluminous and stable.

The second, and potentially more challenging issue of concerns all stages of the production but starts at the end of the mixing phase. Due to the required procedure of pasteurisation or sterilisation mushroom production is done in batches. This in itself is not problematic as for instance also concrete production is done in batches. It does however significantly influence or characterise the production and must be reckoned with. What is more challenging is the relatively small size of these batches. In the large production unit regarded for this analysis approximately 5 cubic meters of substrate could be sterilised at a time. Also limiting is the use of special plastic grow bags. These contain between 5 to 10 litres and are intended to provide a sterile and controlled grow environment while the fungus is still able the breath through the special microfilters (Sac02, 2019). Working with bags of these volumes will make the process extremely labour intensive. Especially the filling the mould will be challenging as a sandwich panel could be over 2 cubic meters in volume. All these bags and batches require a lot of individual handling. As said, this is labour intensive but also requires a lot of space and infrastructure. Although this can be relatively simple as rolling carts, all batches have to be physically taken through the various stages of production. In some cases, as with inoculation, even all lose bags have to be dealt with.

This seems like a case of simple work but from pasteurisation onward this has to happen in a sterile working environment to prevent contamination. It is practically making a Styrofoam alternative in laboratory environment. This requires a specially trained labour force, increasing. But all these handlings are also potential sources of contamination, risking the continuity of the operation. An advantage of the use of the small bags is that contamination can be kept contained and doesn't directly threaten the whole batch. More automation, less human handling and larger batches do seem to be preferable.

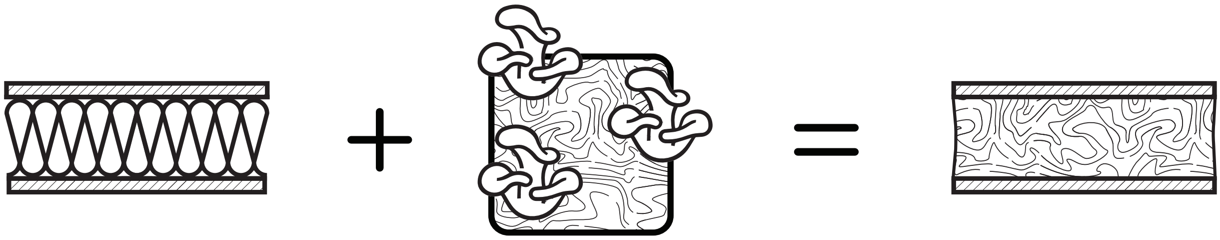
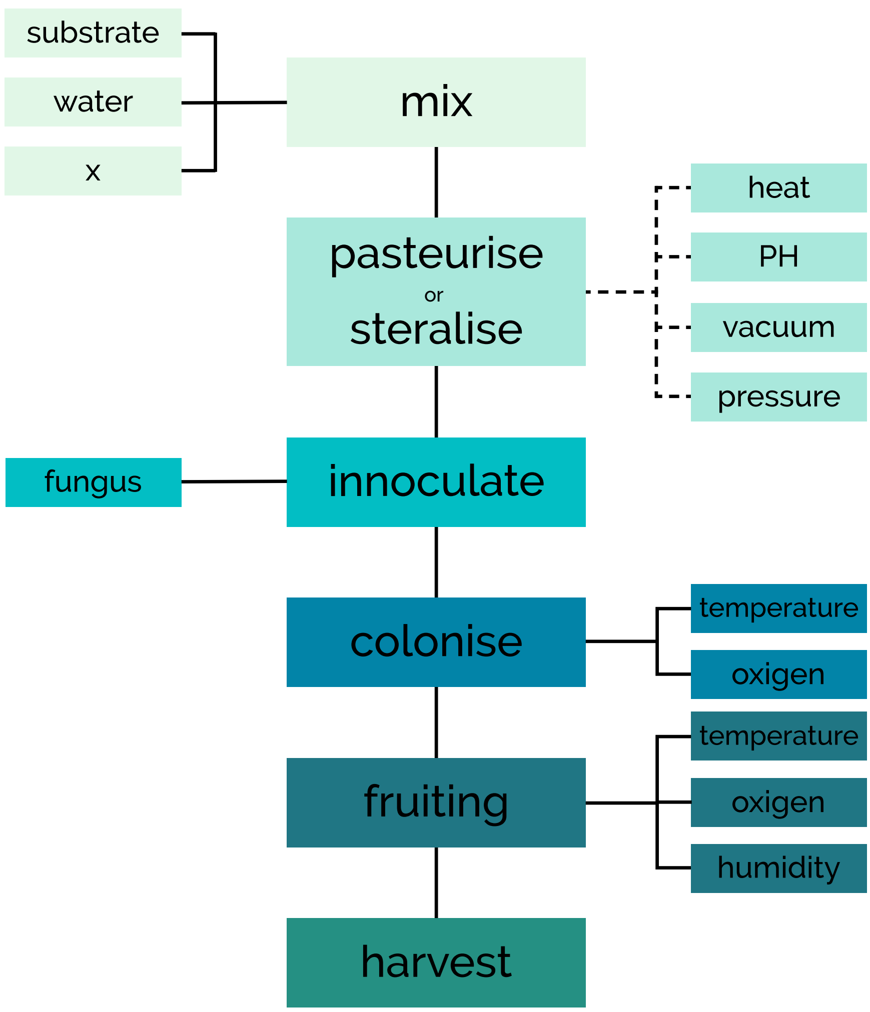


***Image 6.01:*** *Sandwich plus mushroom production equals MBC production*

***Image 6.02:*** *Overview of the mushroom cultivation process*



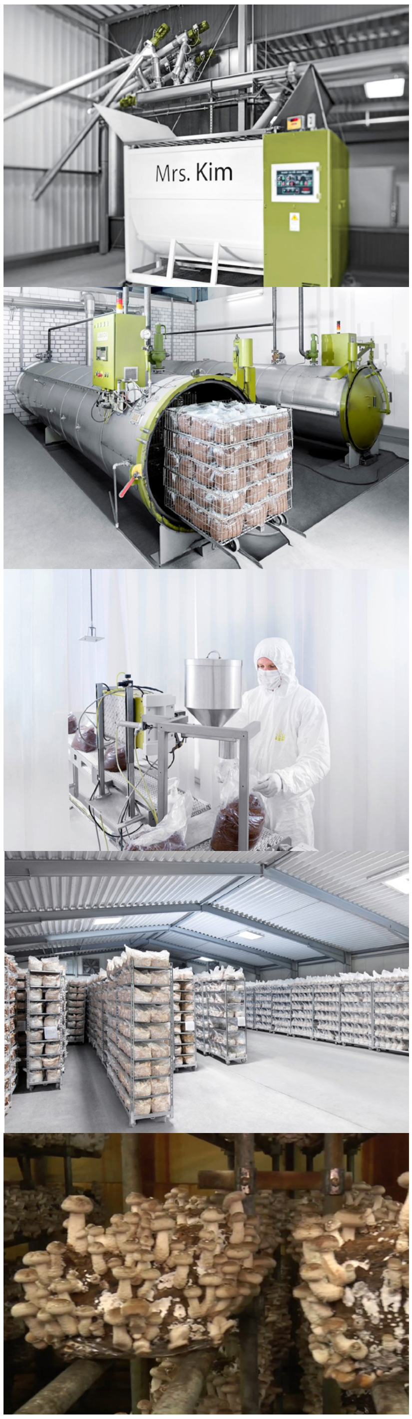




***Image 6.03:*** *A collage of photos from appendix 6.1*

One of the main reasons identified in the mushroom production for the usage of these small volumes is the handleability. Especially the last two stages of the process demand the mycelium blocks to be of manageable size. In the fruiting stage all bags are removed, and the blocks are placed on growing racks where ultimately the mushrooms can be harvested. In the case of MBC production these steps are not relevant potentially allowing other optimisation in other stages of the process. Interestingly, this occurs in the production of a very well known, mass produced, mushroom: the button mushroom. The Button mushroom fungus, Agaricus bisporus, is not suitable for MBC production as it grows on nutrient rich earth and not on a substrate. But its growth speed and strength allow for cultivation on a much bigger scale (Image 6.05). One of the reasons for its wide availability and low price. In 6.4 will be explored how button mushroom practices could benefit the production scale of MBC-based sandwich panels.

### 6.1.2 Foam and Sandwich industry

An analysis of these two industries was made based on promotion videos of various manufactures showing their processes, an overview of all videos can be found in ***Appendix 6.2***. The notion that they are two separate, distinct industries with differing production processes was found to be false. As it turns out the sandwich panel production is just a more elaborated version of foam production with additional pre and post foam processes. It is thus more of a niche adaptation of a larger industry. For that reason, the findings about the foam production process are first discussed. Before will be reviewed how the process of making sandwich panels alters and complicates this process.

Various types of rigid foams are made using production lines similar to that is shown in image 6.06. These are continuous processes where on one side a chemical liquid is being dispersed and on the other finished foam blocks are sawn to size. For people not familiar with large scale production processes it can seem like baking a cake, and while it can cut on one side fresh batter is continuously being added on the other. That metaphor expands even more of the process. The foaming liquid is pulled through the production line between sheets of looks a lot like baking paper. At the end these sheets are peeled of, automatically, and the blocks of foam are cut the required size. Image 6.07 shows the start of the process and image 6.08 the end. From start to finish takes under 30 minutes.

The process of making traditional sandwich panels is in principle nothing more that replacing the baking paper with metal sheets and adding less liquid for a thinner foam layer. The most prominent additional step in the production of a sandwich panel is the cold rolling of the metal sheets into the corrugated sheets extensively discussed in chapter 5. The used metal enters the factory on large rolls of metal sheet and is being shaped in the same process as the foam. This is remarkable as often different production steps are kept separate but the added value of a continues and effective process clearly outweighs the negatives.

Keeping the fungal sandwich panel and the MBC production in mind during this analyses a couple of challenges or conflicting aspects came to mind. These mainly have to do with the continuous nature of the production process. As the formation of the MBC is not a chemical but a biological process it raises that question of such process could run continuous. As the fungus is a living organism it could very well be that it changes its growing behaviour if placed in an endless volume. Also, the speed of the foam production is much faster than the week of formation time needed for the MBC. Creating a continuous process would have to be very slow and thus have little output or be extremely long. An additional problem would be caused by the Ecor. As it is not that bendable, it doesn't come on a roll. Even if the currently limited production dimensions of 1250 by 3000 mm would be increased this would still undermine the usefulness of a continuous process.

## 6.2 Production Challenges

The two analyses of production processes above combined with a number of insights gained throughout this project resulted in the formation of a list of production challenges. In this subchapter they will be analysed and discussed, in the next several solutions will be presented. The assessment of the production challenges showed that the potential problems were not step or phase specific. Although nuances were found for individual steps, they all seemed to fall under several overarching themes. In the following sections the identified production challenges will be discussed based on these themes.

***Image 6.04:*** *Fruiting room of shiitake*

***Image 6.05:*** *Fruiting room of button mushroom*

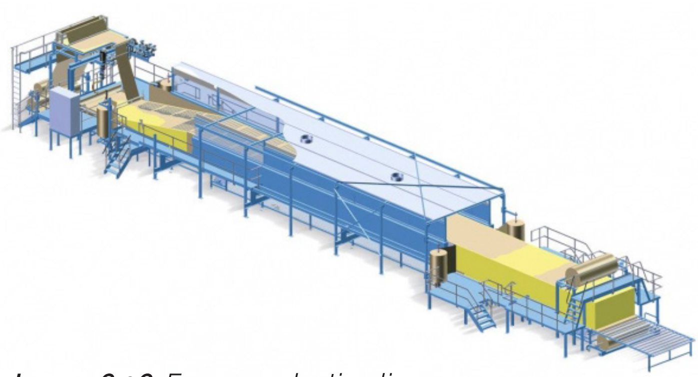


***Image 6.06:*** *Foam production line*

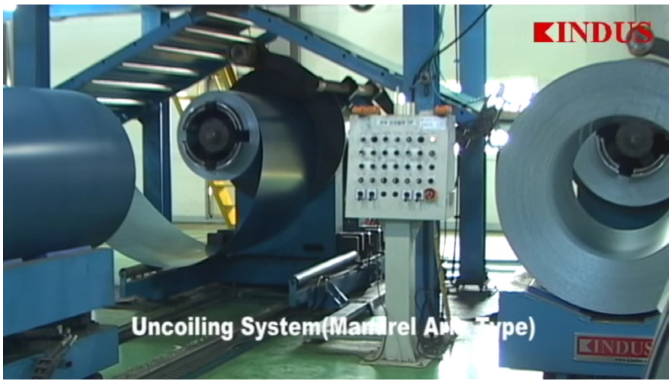



***Image 6.09:*** *Rolls of metal*

***Image 6.07:*** *Start of foam production line: liquid*

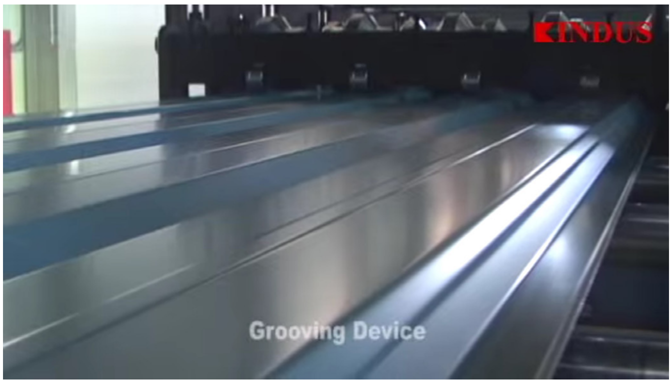



***Image 6.10:*** *Cold rolling of sheet metal*


***Image 6.08:*** *End of foam production line: foam blocks*

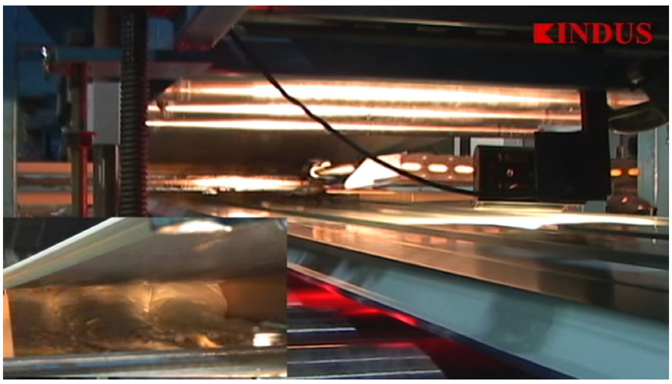



***Image 6.11:*** *Curing foam within two sheets of metal*

Present in all challenges is the recurring, earlier discussed, tension field between quality and quantity. Both these aspects were found to manifest themselves in two facets of the production process, as illustrated in image 6.12. Balancing all four in every steps of the process is crucial in designing an effective process. In order to come up with sound solutions that ultimately results in that effective production setup it is important to first understand how these four pillars are present in the faced challenges. This will be discussed now.

### 6.2.1 A Controlled Growth Environment

In the various chapters of this report the need for control over the process has been a constant theme. This section will be specifically focussed on the needed control over the production environment. The order in the various aspects in which this need for control is manifested will be discussed from large to small, from a macro to a micro level.

The production of MBC's can be described as making a Styrofoam alternative in a laboratory environment. For an industrial size production however, this laboratory environment needs to be rather large. In contrast to most construction materials the requirements the production process in this case has on the facility in which it is housed are much higher. A large industrial hall with a high ceiling and columns far apart, isn't enough. As encountered in 2.4, 5,1 and the above analysis of the mushroom industry the most important aspects of the product process that need to be controlled are temperature, sterility, relative humidity and oxygen levels.

How the control of these facets is guaranteed throughout all production steps is a challenge that needs to be addressed. It is questionable if newly construction an enormous production hall with laboratory grade specifications is the most effective method of solving it. As seen in the mushroom industry analysis working with plastic bags allowed for very local implementation of sterile working environment. Although plastic bags are likely not the most optimal way for a sandwich panel production scale such interventions are needed for an effective and attractive process. The schematic depiction of Ecovative's, now closed, production process for mushroom packaging (Image 6.11) is a perfect example of such process (Holt et al., 2012). Although not very detailed, probably because of competitive considerations, such depiction helps making the changing requirements between steps clear and tangible.

When the conditions of the working environment are in order, the focus can be shifter towards a type of control needed for optimisation of the production process and product. As seen in both several sections of this report as the literature, controlling the specific growth parameters can be beneficial for growth speed and quality. Jiang (2013, 2014, 2016) for instance reports on a growth time of between five and seven days. Although it remains unclear if he addresses the formation or complete growth phase this would at least indicate a shortening of the process by 15%. According to Travaglini (2014) proper aeration is needed during the growth phase as it allows for the gaseous exchange of oxygen and carbon dioxide, crucial in the fungus metabolism. An aspect that gave AFJD's honeycomb mycelium benches its hollow core (Image 6.14). It was found that from a thickness of over 50 centimetres a lack of oxygen diminishes the fungal growth at allows rot and other contamination to occur (Dahmen & Frid-Jimenez, 2018). Although the thickness of the MBC-based sandwich panel is not expected to exceed 25 centimetres this should be considered as the Ecor sheets on both side of the panel probably limit the amount of gaseous exchange that can occur. Also, for the quick and even drying of the panels aeration is crucial, preventing phenomena such as warping.

An additional challenge facing aeration, that has to be addressed, is contamination. Travaglini states that "Aeration has proven the most common source of infection with competing species, despite the need for free exchange needed for growth" (Travaglini et al., 2014). Also, during this reports analysis of the mushroom industry was noted that an increase in handling steps or mangling with the process increases the risk on contamination. Local, targeted but controlled and sterilised aeration will thus be key for the realisation of a fast production process with high quality output.

### 6.2.2 Handling Large Volumes

The analysis of the foam and sandwich production showed a truly optimised and efficient process that can deal with large volumes. Although subchapter 6.4 will go into further detail regarding the required

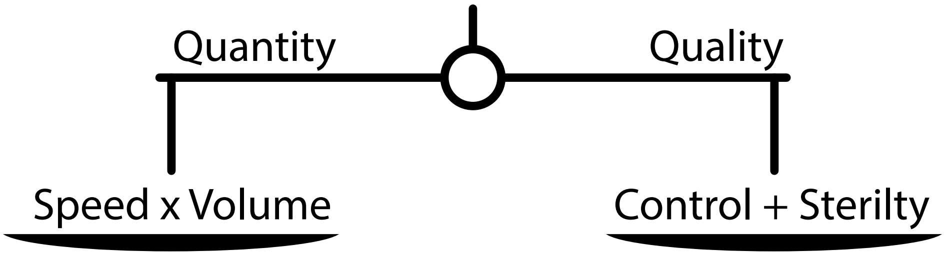



*Image 6.12: The overarching production challange*

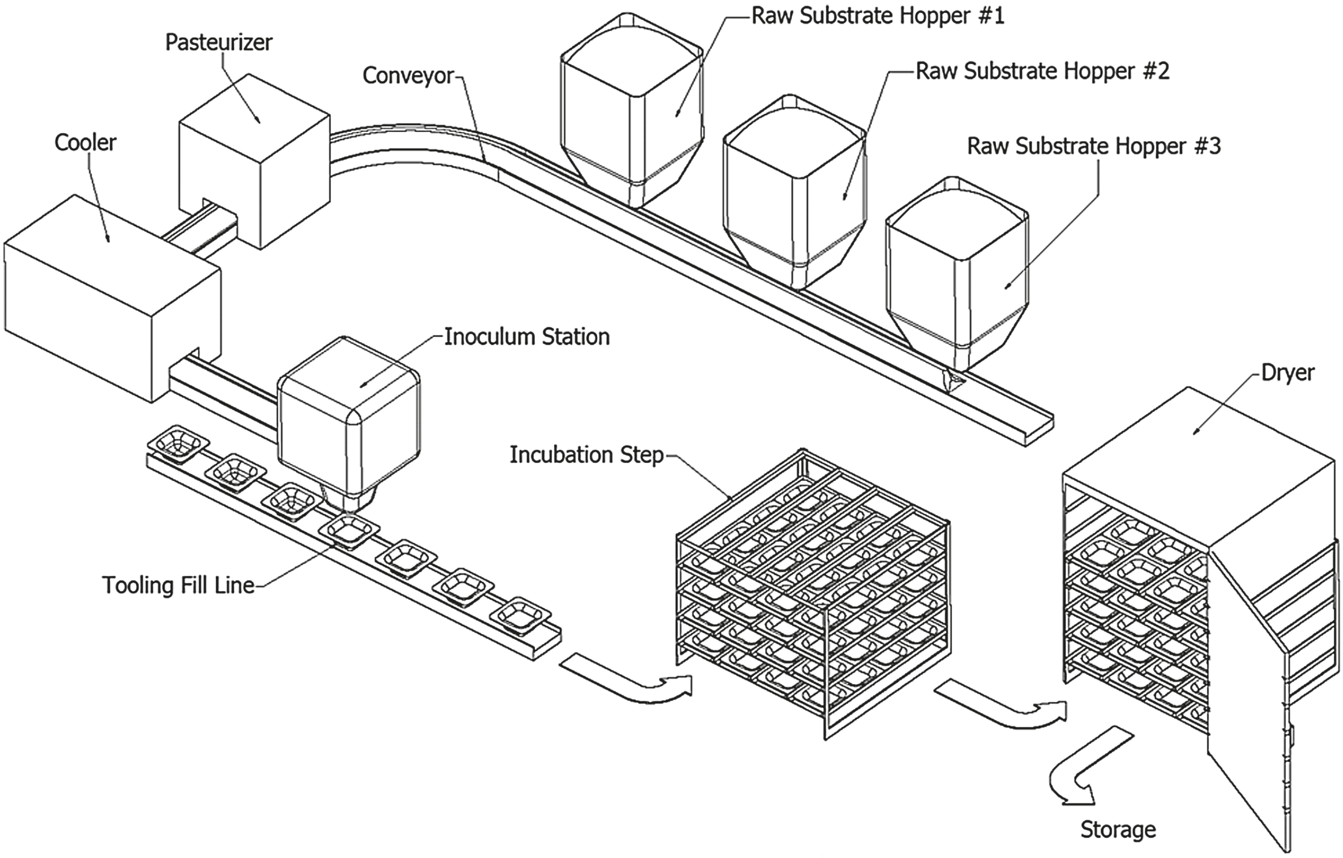



*Image 6.13: Schematic depiction of Ecovative's pilot*

*Image 6.14: 'They grow without us" honeycomb benches by AFJD*

scale of the operation it is can be assumed that practices as seen in the mushroom industry analysis of 6.1 won't suffice. But although the traditional production of sandwich panels can be seen as inspiration it is important to remember that it is an uncircular industry creating monstrous hybrids. It therefore must be accepted that new practices have to be invented and thought through for the production of MBC-based sandwich panels regarding and respecting the characteristics of the materials involved. In order to do that the challenges faced in dealing with larger volumes of MBC in its production process will now be discussed.

These challenges touch on the essence of the production typology. In the case of the traditional foam and sandwich production a continuous process is most optimal (Image 6.15). However, the materials in the MBC-sandwich panel differ in their morphology and handling from the foam and metal used in traditional panels. In the mushroom production small manageable volumes are used that are taken through a journey of various environments (Image 6.16). As identified during the analysis of that production there are number of steps in that process that seem unfit for the scale in which sandwich panels are produced. In both the mixing, inoculation and colonisation phase working with the plastic bags seems to require an already enormous quantity of handlings and logistics. It is questionable of such approach is fit for further scaling. Especially when considering that all handling adds to the risk of contamination. Also, the use of enormous amounts of plastic bags seems odd in the production of a sustainable, circular construction product.

The question seems to be if larger, preferably in reusable, production volumes and a higher level of automation is possible. Aeration, as discussed above, would form a challenge anyway but also the handling of large volumes could become challenging. Although MBC's are considered light when finished, during the growth phase its weight comprises for 60% out of water. The transportation of larger volumes, especially the growing panels, will thus be challenging. In contrast to foam that is easily transported and spread out as liquid and then just expands, the inoculated MBC substrate acts much more as concrete, just hardening out over time. How do these material specific handling characteristics influence the various stages of the production process and in what way are they best be handled?

### 6.2.3 Product challenges

All challenges discussed in this section have relation to the additional steps needed to go from an MBC sheet to a sandwich panel. The part of production that is similar to the extra steps that are part of the traditional sandwich production compared to that of foam. Logically, these difficulties mainly surround the use of Ecor. As seen in with the production of the sandwich samples in chapter 5, the sterilisation of the Ecor was not a challenge. The UV method was very effective, although it is not yet investigated if this process had any effect on the material performance. A more challenging aspect of the sandwich panel production, also discussed in chapter 5, is the binding between the MBC and Ecor. The experiments have shown that in order to make a usable product this aspect need to be improved and this researched further. It remains to be seen which of these methods proves to be most effective and how it will influence the production process.

The only real issue faced regarding the use of Ecor is the size in which it is available. Currently the material is sold in sheets of 1250 by 3000 mm Based on the insights provided by the product analysis in chapter 3.2 a clear standardised width of 1000 mm exists for roofing elements exists. This could correspond with the narrow side the Ecor sheet. This would result in a maximum width of 3 meter which would clearly not be enough, as this is the smallest size Kingspan offers (Kingspan, 2018). A solution should thus be formulated on how MBC-based sandwich panel could be made into larger sizes.

A challenge that is complicated by the absence of a set or standardised size for roofing panels. As panel widths are set, alternating lengths makes for a versatile construction method. In the interviews with industry experts (***Appendix 3.2***) it was stated that there currently is very little standardization, much less than you would expect according to Diederik de Jonge of Habeon Architects. A solution would therefore have the capacity to solve the variance in lengths.

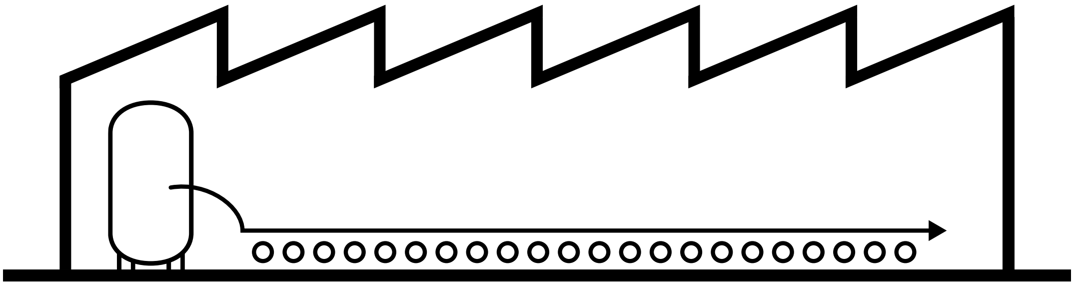


*Image 6.15: Foam production typology: continuous*

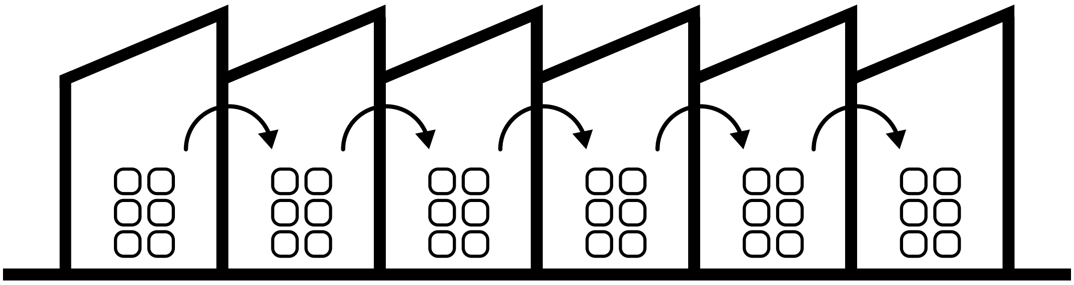


*Image 6.16: Mushroom production typology: batch production*

*Image 6.17: Mixing liquid chemicals for foam production*

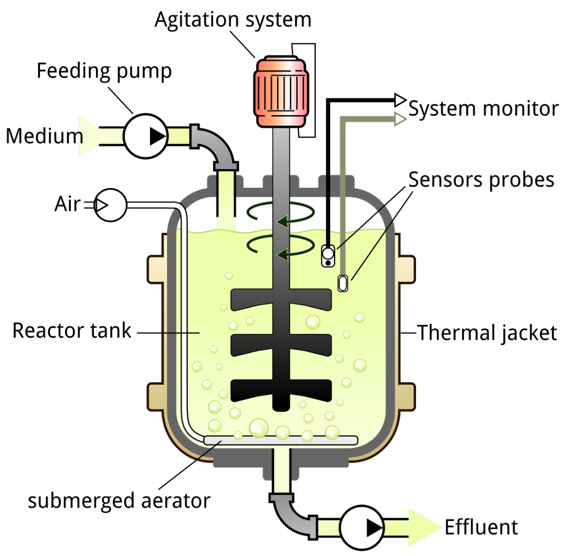




*Image 6.19: Liquid bioreactor: easy to control*

## 6.3 Production Solutions

Several product and process design solutions to the production challenges discussed in 6.2 will now presented. In contrary to the covered challenges the solutions are specific to the various parts of the process where they are designed for. For the structure of this subchapter they divided into two phases. The material phase, dealing with all production steps from mixing to colonisation. And the product phase, focussing on the formation, drying and product specific steps. These will now be discussed in this order.

### 6.3.1 The material phase

**Bioreactor**

Mushroom production can be regarded as simple version of a biotechnological process called Solid State Fermentation (SFF) (Letti et al., 2018). The plastic bags in which the fungus is grown act as small static bioreactors. Gaseous exchange occurs through the filters, but moisture is left inside, and other microorganisms are kept out. One of the questions that raised during the analysis of the mushroom production was if these bags couldn't be bigger or other reusable volumes could be used in order to scale production. During the exploration of the research step it was discovered that the actual question asked was, is a large SSF bioreactor could be made?

Realising that this would become a high-tech bulky device its consequences for the production were considered. In foam production the base chemicals are mixed before they are dispersed in the production line (Image 6.17). Could, in a similar fashion, all production steps up to the formation phase take place in one volume? If so, the amount of handling steps and risk on contamination would be lowered drastically. Fully colonised substrate could be made in batches and be transferred to moulds for the formation phase. Very much like a cement mixer and a concrete formwork.

The possibility of such controlled, multi stage, growth vessel was investigated. But although ideal it had to be concluded that suitable installations currently don't exist. This could somewhat be expected as otherwise they would likely be deployed in every large-scale mushroom cultivating operation. However, although not commercially available the fair share of research into such devices has been done. In order to elaborated on some the difficulties faced in the development of a solid-state bioreactor it is necessary to explain some biotechnological basics. It was found that in biotechnology roughly three types of fermentation reactors exist; liquid (Image 6.19), submerged and solid-state reactors. The later, and of interest to this project, turns out to be the most complex (Mitchell et al., 2006).

Fungal growth is a biological process. The fungus needs oxygen for growth and converts in carbon dioxide. In this metabolic process heat is produced (Lelievelt et al., 2015). In a bioreactor, larger than the mushroom bags, it is therefore necessary to refresh oxygen levels and subtract heat (Mitchell et al., 2006). In submerged and liquid fermentation heat can easily be removed through the reactors walls as the liquid conducts heat. In the case of solid-state fermentation this has to be done through ventilation. This immediately restores the oxygen levels but to also dehydrates the mixture. As all these parameters should constantly be kept stable while in a dynamic interplay.

The complexity of this method has had a discouraging effect on development and commercial application. Since the rise of more complex computer software and the possibility has arisen to simulate these processes. Together with renewed public interest in fermented foods like kimchi and tempeh it is expected that solid state fermenters will become more common (Mitchell et al., 2006). Further research should explore the current state of affairs of this development and explore its suitability for application in the mycelium-based composite production process. It could very well be that breakthroughs bioreactor development will spark the widespread use of MBC products as it would become significantly easier to produce large volumes in a high quality.

**Substrate Blower**

The successful development of an SSF bioreactor for MBC substrate would lower de number of proceedings in the material phase drastically. However, the heavy and complex tanks would likely be unable to move and be installed statically somewhere in the facility. In contrast with the small plastic bags from the mushroom production this would create a logistic problem. How would fully

***Image 6.20:*** *Pouring concrete*

***Image 6.21:*** *Concrete pump wagon*

***Image 6.21:*** *Filling cavities with cellulose insulation*


***Image 6.22:*** *Cellulose blower and cellulose packages*

***Image 6.23:*** *Semi-automatic substrate bag filler*


***Image 6.24:*** *Substrate mixer and air pipe transportation*

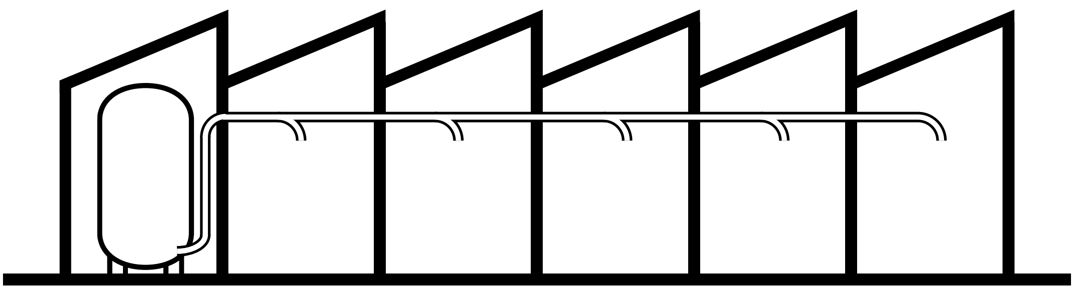


***Image 6.25:*** *Bioreactor and air blower transportation system*

colonised and crumbled substrate be transported from the bioreactor tank to the formation phase mould? Transportation the moist natural particles should be done sterile and ideally automatically. The solution to this challenge was found in a comparison made earlier in this report. MBCs resemble concrete much more than foams or FRPs and should be regarded as a dry of moist cement. Instead of poring blowing it through closed, sterile pipes would be an ideal and easy method to use. A sterile version of cellulose insulation blower would be required (images 6.21 & 6.22).

Such method would also be ideal for the immediate filling of the moulds. The blown particles would fill up very gently realising a loose and airy mixture perfect for a low weight insulating material. Even regardless from the potential successful development a bioreactor such method would be ideal for filling. Interestingly after this method was thought of it was found that it was already applied in the mushroom industry as well. Image 6.23 & 6.24 show the mixer, connected with pipes to a big filling station. Wet, mixed substrate is blown through in bag ready quantities.

### 6.3.2 The product phase

In the product phase the colonised material is turned into a product. It expands around both the formation (growth) and drying steps but also contains the additional steps required to add the Ecor, truly turning a material into a product. Learning from the analyses of 6.1 and faced with the challenges of 6.2 a number of solutions for this production phase will be presented.

**Working in batches**

The continuous production lines of foam and sandwich panel production reviewed in 6.1 not only are but also come across as highly efficient. It would therefore be easy to be inspired and suggest a similar production layout for MBC-based sandwich panels. When considering the characteristics of that product and its materials however, it becomes obvious that a continues process wouldn't be optimal for it. The following aspects were identified that make a production process working in a batch-like manner necessary. These will be discussed first where after will be elaborated on the features of the batch production.

The first argument against continuous production is the growth behaviour of the fungus. A continuous process would have as consequence that at the start of the production line freshly colonised substrate is being added while on the end fully grown chunks can be removed. As a result, the mould in which the fungus grows would effectively be endless. Although no specific research has been done on the topic the literature seems to suggest that fungal growth patterns change when in contained volumes. Travaglini (2014) mentions: "The current theory developed from observations on the geometry of sample growth is that the fixed volume of the mould encourages increased density of the mycelium hyphae, whereas growth unlimited by volume results in less homogeneous and less dense mycelium.". It is thus likely that continuous production would result in less densely grown MBC and therefore be undesirable.

As this aspect hasn't been thoroughly tested it would be to easy to dismiss this possibility based on one quote. However, there are more reason why continuous production doesn't fit the MBC production process. A second argument would be the speed of the process compared to that of foam production. Where foam expands in a matter of minutes MBC growth takes days. This would result in an extremely long production line, probably close a kilometre. This would be undesirable for a range of reasons. Of course, more and slower production line could be created but this would defy the point of continuous production. The last argument against a continuous process and for batch production regards the use of Ecor as the outer material. As mentioned, the material is currently made in limited sizes and isn't rollable. Even if production size would increase this would enable the use of larger moulds for batches but not result in the possibility to produce continuously.

Production in batches is thus a better match with the characteristics of the involved materials. Filling these batches with small volumes of in bags colonised material would be suboptimal. A process with base material production in a bioreactor and fillable moulds after would be more effective. In order to meet industry demands moulds would need to be adjustable in length, providing the needed flexibility to produce different sizes.

***Image 6.26 & 6.27:*** *Out- and inside of a button mushroom facility*

***Image 6.28:*** *Button mushroom beds being filled*

As specific moulds would likely need to be developed it may be more efficient to apply a similar strategy as with the bioreactor. As discussed in 6.2 control over the growth process is essential in realising both a qualitative product and run an effective fast process. With larger volumes this becomes more challenging than with the small bags used in mushroom production. Instead of placing the growth vessels inside a controlled environment it would be better to invest in high tech growing vessels (moulds) in which parameters can be controlled. Mildly controlling the surrounding environment of course, but primarily steering parameters specifically on batch level.

**Button Mushroom facilities**

Despite the use of specifically developed moulds that control the growth parameters the specifications the process demands from a production facility would still be high and specialistic. Temperature and sterility would need to be controlled inside the indoor environment the space would also have to allow large volumes to be handled. Large mushroom operations have the right facilities but not the right infrastructure to deal with larger volumes.

However, as discovered in the analysis of 6.1, this differs with button mushroom operations. Their production process is designed to deal with large volumes. It is likely that the complete infrastructure around it is also designed for larger volumes. On visiting such location, it was found that this is certainly is the case (image 6.28). This would have been of great inspiration if it were not for the fact the Dutch button mushroom industry is currently struggling (Van den Eerenbeemt, 2018). Low margins and high labour costs are driving operations abroad. Using the redundant facilities would be a great way to start producing MBC-sandwich panels. This also fits inside the circular mindset with which this process was conducted. Interesting would be to see what scale could be obtained using this production strategy, this will be explored in 6.4.

Besides dimensioned on dealing with large volumes the growing facilities in these farms are also perfect. It exists out of a large number of separate production cells, seen on the outside on image 6.26. The climate of each cell can be individually controlled. This allows for an almost continuous like production in batches. As one cell is being cleaned before production is initiated, another houses first day growth, its neighbour second day grow, and in the last panels are being dried and prepared for shipping. Also, the cells' interiors are optimal for the growth of the panels. The button mushroom beds are placed in racks with five stories, using space optimally (image 6.27). The beds of the visited facility were 1,26 wide and 26 meters long, perfect to produce the sandwich panels. Of course, adjustments are needed before this production can take place. At the end of this chapter such an adaptation will be discussed. However, both the facilities and the expertise in running them can prove vital in developing and starting a successful production process.

**Hollow Core Slaps**

One of the main identified challenges in 6.2 was the need for precise control over the growth parameters inside the panels. An additional difficulty was prevised in the form of the upper lower Ecor sheet sandwiching most of the MBC and thus block most of the needed gaseous exchange of the fungus. As discussed, aeration is crucial in both the growth and drying phase. As it is likely that the Ecor block the complete or partial exchange of gasses another method needs to be thought of. The only viable option to provide ventilation inside the panels seems to be creating ventilation shafts inside the panels.

In chapter 5 a method was explored to overcome the problems of shear force driven delamination in the panels. As this was the main identified cause of the underperformance of the panels. This method used tensioning cables through hollow cores in the material. It would be best if these hollow cores would already be present inside the panels and wouldn't need to be drilled through. The hollow tubular cores could also be used during the growth phase to promote optimal growth conditions and during the drying phase subtract moisture from the inside.

On the pictures to the right a prototyping process can be seen investigating the possibility to make these hollow cores (Image 6.29 – 6.33). Micro perforations in the wall of a glass, metal or plastic tube could provide the needed oxygen and be removed after production. Potentially more optimal would be the incorporation of Ecor or chemical free cardboard tubes with perforations. These could become

***Image 6.29 - 6.33:*** *The various steps of prototyping a hollow core slap*

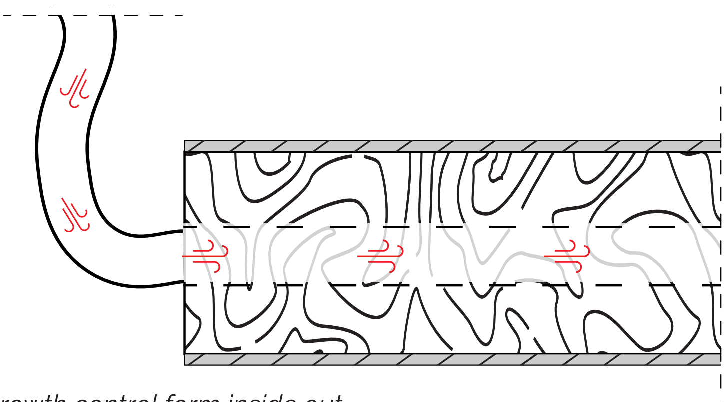


***Image 6.34:*** *Hollow core: growth control form inside out*

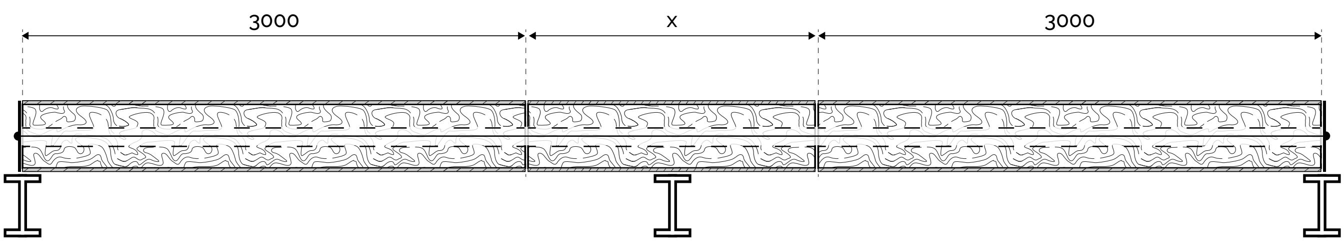



***Image 6.35:*** *The various steps of prototyping a hollow core slap*

grow together with the rest of the product and further strengthen the panels. The effect of this measure was shown in chapter 5.4.

The use of tensioning cables could also help solve an additional identified challenge. The currently limited size of the Ecor panels would restrict the size of the panels to 1250 by 3000 mm. Through the use of tensioning cables multiple panels could be linked to form one longer panel. Specially grown fitting pieces would allow for more size than multitudes of three metres to be made (Image 6.35). The tensioning rods also fulfil an extra safety function. If the cables would be secured to the main structure, they would be able to support the panels in the case one of them breaks. Preventing the immediate danger of a collapsing roof.

**Fungal connection**
The last solution presented in this subchapter focusses on the connection between the MBC core and the outer Ecor sheets of the panel. In chapter 5 this was shown to structurally be the weakest part of the product in a roof panel like load case. Further research is needed to develop methods to further strengthen this part of the product. An array of solution has been proposed in 5.4. For now, it was decided to incorporate the simplest of the presented solutions. Partially because the tensioning rods present a good solution around this problem and partially to prevent, potentially unnecessary, complication of the production process.

The selected method is the uniform application of pressure from outside the panel. Inspiration for this solution was found in the mechanisms used in the foam industry that prevent the foam from expanding unevenly (Image 6.36). Similar hinging arms could be mounted inside the growing racks and could be tensioned on the panels (Image 6.37). This also prevents bulging in the Ecor and achieves a flat product.

## 6.4 Production Scale

Impact is the main driver of this project. The scale on which the developed product and production can be applied has been one of the main pillars of the drive for impact. Both the technology as the industry context have been analysed in the first part of this project to allow for properly aligning supply and demand on a qualitative and quantitative level. In chapter 3 the needed scale for a successful solution has been explored. In the subsequent chapters qualitative aspects of the product and production have been the main focus, but always with this analysed scale in mind. In this subchapter that focus will be shifted back to the aspect of scale. Before a design of the production process is made, it will be explored if the presented solutions are indeed able to meet a production size comparable to volumes annually needed within the distribution centre construction industry. This won't be a full feasibility study but an exploration indicating if the proposed solutions are of the right order of magnitude.

Of all production solutions proposed in the previous chapter, there are two that affect scale most; the development of a bioreactor and the use of old button mushroom facilities. The overall success of the operation depends most on the first, but it doesn't affect its scale much. As more bioreactors would mean more output. The latter however, is much more of a potential bottleneck. Therefore, will first be investigated what output could be generated by one facility. And secondly how large the current and what a probable conversion rate of these operations would be.

With a simple calculation the optimal output of an operation can be determined. Considering a production process with a bioreactor generation fully colonised material in the vicinity the growth phase would solely exist out of the seven-day lasting formation phase, although this could potentially be speed up. A conservative estimate of a full week of drying would result in a total mould bound process of 14 days. With the growing racks being 1,26 wide and 26 metres long a total growth surface of 32,67 could be realised. But as it is unlike that the full surface would be useable it is best to be a little conservative again, so 25m2 per story. With 5 stories per rack and 4 racks per cell this results in total of 500 m2 growth surface per cell. The visited location had 14 halls and with 26 growth cycles per year this would total on an annual output of 182.000 m2.

The total demand for insulation from the distribution centre sector was found in chapter 3 to be 2.154.000 m2. One production location could thus produce 8,5 percent of the total demand. That means that with

***Image 6.36:*** *Foam expansion guiders*

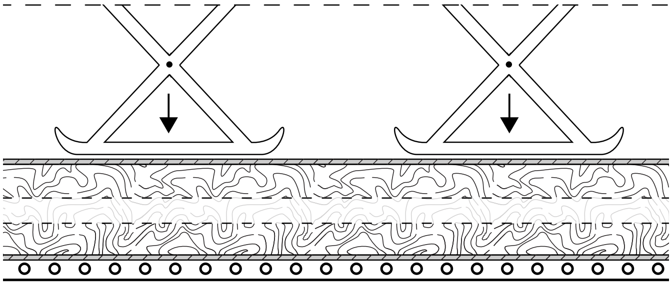


***Image 6.37:*** *Improving bond by pressure*

| | | |
|---|---|---|
| Locations | 1 | |
| Halls | 14 | |
| Racks | 4 | |
| Stories | 5 | |
| Width | 1 | m |
| Length | 26 | m |
| Growth | 1 | week |
| Drying | 1 | week |
| **Total annual production** | **189.280** | **m2** |

***Table 6.01:*** *Total annual production potential of one button mushroom farm*

***Image 6.38:*** *The 99 mushroom farms of the Netherlands*

twelve converted production locations the full demand could be produced. There are 99 mushroom producing companies in the Netherlands (Regiobedrijf), of which approximately 70% focuses on button mushrooms. A 17% conversion rate would be enough to supply the whole distribution sector with insulation material. In a more extreme case, the full Dutch button mushroom industry would be able to produce 40 percent of all rigid foam insulation used in the Netherlands annually.

Of course, such events are unlikely. Ultimately, converting old button mushroom production facilities isn't the only way to create an MBC sandwich panel factory. It probably just is the easiest and quickest. As more experience is gained with the production process it could very well be best to have a highly efficient optimised production facility newly build. But the matching order of magnitude of supply and demand show that the proposed production process could successfully scaled.

## 6.5 Process Design

See 6.39

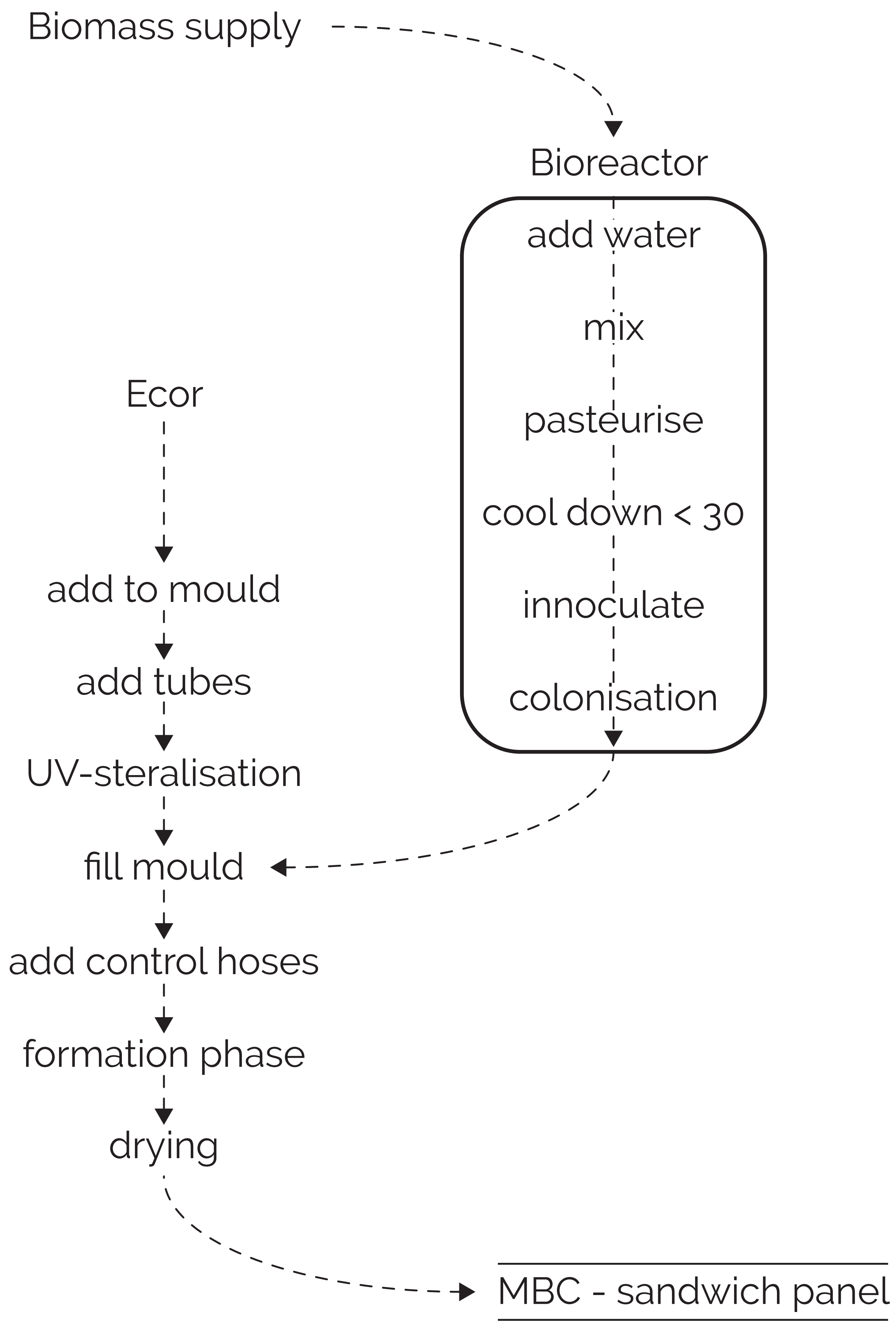



***Image 6.39:*** *MBC-sandwich panel production overvieuw*

# 7

# Conclusion

Congratulations, you have made it to the last chapter of this report. To wrap up the description of this project will be concluded with a collection of insights gathered throughout the course of this project. First of all, an overview of the findings will be given (7.1). The main research question will be answered with references to all covered sub-questions. Based on those findings and other insights gained in the course of this project future research directions and topics will be discussed (7.2). In addition to the proposed future research some recommendations will be made towards the scope of the scientific field and its ability to facilitate multidisciplinary exploratory project such as these in the future, their potential impact on students, innovation and societal progress (7.3). Finally, in 7.4, this report will be concluded with a positive glimpse into the future of the development of mycelium-based materials and their role in our society.

## 7.1 Findings

This project had as objective to illustrate the value of nature-based circularity by illustrating its potential in creating composed and engineered circular products. Mycelium-based sandwich panels were hypothesised to be the perfect embodiment of such products. In order to effectively explore the feasibility of mycelium-based sandwich panels as a natural and circular alternative an industry-oriented product development approach was used. Therefore, this research focussed on what was thought to be the most important parameters determining the success of this novel product group that were feasible within the limitation of the research, being the structural behaviour and scaled production. The following main research question was composed and will now be answered:

*Are Mycelium-based Sandwich Panels a Product Category worth Developing further as a Nature-Based Alternative for Traditional Sandwich Products, considering a Suitable Industry context, their Structural Behaviour and intended Production?*

The short, but oversimplified, answer to that question is **Yes**. But a little more substantiation and nuance is needed to fully answer that question on level that honours the work of this project.

Both the general characteristics as the exact properties of MBCs have been explore. This project succeeded in getting a 'feel' for it and has applied that deeper understanding in tackling the further research questions. A possibly promising industry niche was found in the distribution centre construction sector and its dynamics have been studied. A number of quantitative and qualitative boundary conditions was collected that formed a foundation for the remaining research. Based on the analyses of the novel material and aimed industry niche it was identified that further, practical, research into the structural behaviour and scaled production of the product best suited its industry-oriented development approach and the knowledge gap identified in the research.

The experiments performed provided data on both the mechanical behaviour of MBCs and mycelium-based sandwich panels. Based on the processing and interpretation of that data can be concluded that both the properties of the material and the product are currently insufficient for the envisioned application. Weak adhesion of the individual components and premature delamination because of that were identified as the main cause for the underperformance of the sandwich panels. Further development is needed on a material, product and application level to achieve applicability, suggestions of potential fruitful development directions have been made. The order of magnitude of the results is however of such comparable quantity that, especially less demanding, employments of the product can on a short-term be accomplished. It is therefore interesting to see that this research has shown how the production process of mycelium-based sandwich panels could look like. By converting button mushroom facilities, a batch-based production system could be put into place with a scale adequate for the demands form the distribution centre construction industry.

In this explorative project it has been shown that this nature-based technology holds potential. Sandwich panels can be made with a certain quality and quantity. But although current product performance is not sufficient for the studied application other widespread uses can be foreseen. So, although further research is certainly needed in the development of composed mycelium-based circular products it can be concluded that based on qualitative and quantitative benchmarks these products can and likely will serve as a sustainable and circular alternative to traditional, oil-based, rigid insulation products.

## 7.2 Future Research

During this multifaceted project numerous knowledge gabs were identified that would be a great source of future research. The recommendations done in the section will however be limited to the main subject of this endeavour; mycelium-based sandwich panels. Three subdivisions were identified in which these topics will be discussed.

**Material development**

The main focus of this project's development approach laid with the material's mechanical properties and its production. Due to constrains in time and focus certain crucial aspects of the product have been left out of the scope. This policy was in line with the discussed and used industry-oriented development approach. However now is established that mycelium-based product holds significant potential for application the following material properties should be considered:

1. Exploring methods to lower the materials thermal conductivity

2. Exploring methods to influence and improve the materials behaviour to fire

3. Mapping the materials environmental impact and exploring potential after life scenarios

The exploration of MBC's mechanical behaviour has been explored in this project, but that endeavour has illuminated new areas in which the material can be developed. Diving deeper into the theory of foam materials and the functioning of the mechanical performance could provide insights that can help strengthen it. Ashby's and Gibson's book 'Cellular solids: structure and properties' seems like a good starting point (Ashby & Gibson, 1997). As mentioned in chapter 5.5 an additional field of interest could turn out to be the computational simulation of the materials performance. If successful it would surely mean a great acceleration of the materials development.

**Product development**

The industry-oriented product development approach resulted, similar as with the material development, in the prioritisation of certain aspects while others were ignored for now. A mostly ignored aspect on the level of product development was the application of roofing material and water tightness of the product. When the product development reaches a finalising pre-production phase, such aspects should be explored as it is otherwise likely a good 'circular' product will be irreversibly combined with non-recyclable products effectively diminishing its impact.

Structural performance related aspects of the sandwich panels were of course researched. Continuation of that research should primarily focus on improving the binding between the Ecor and MBC-core. In 5.4 a number of suggestions has been made how this could be achieved. Further product related mechanical improvements could be sought for in the design of the product. Especially corrugated Ecor sheets but also other intervention on the level of product design could be explored and turn out to level the current performance gap between MBC and traditional sandwich panels.

**Production Development**

Finally, future research could be done in the direction of further production development. Most aspects of production will be trivial and are likely to come on the plate of a party that wants to commercially exploit such an operation. However, during the course of this project to research topics were identified that earn scientific attention. The first is the development of methods influence the growth parameters of the fungus on an industrial scale. As these parameters are fairly known, the focus should lay with exploring different controlling mechanisms and their effect on the material. This would likely be a multidisciplinary project involving mycology, material science and biotechnology.

The most prominent and most crucial production development topic identified in this project is that of a solid-state fermentation bioreactor. Research into controlling fungal growth in large volumes should be prioritised as it would allow for the large-scale availability of colonised substrate and would thus result in cheaper and better MBC products.

## 7.3 Recommendations

**The Bio-Based Building Movement**

A growing niche in the building industry is the bio-based building movement. With a variety of motives ranging from health benefits, ecologic ideals and the pursuit of circular economy they strive to realise buildings that meet modern standards using mere natural materials. Although the main available option in most of history, the past century has seen a lack of research and development into more advanced ways of using these materials. This has caused a gap to form between performance and requirements. Closing this gap is essential in the strive for bio-based buildings and building methods. Although in the recent years a renewed interested in natural materials has led to an increase in options for a lower grade segment of interior applications such as flooring, acoustic and furniture options. The challenge now is to tackle a number of more demanding technical problems. When starting this project in 2016 very little was being said about bio-based and natural construction methods in university. That has changed in the recent years, but I would like to urge further dedication into that subject as its multifaceted benefits have well been established and great opportunity awaits.

**Biodesign & Bioneering**

It is hoped that this project can contribute to the general acceptance of nature-based circularity as a solution for the sustainability challenges of the building industry and the built environment at large. As mentioned throughout this project, convincing the industry is thought to be critical for the implementation of such solutions. However, the role of the scientific engineering community in exploring and maturing new innovations is not the be underestimated. A different mindset is needed for this community to fully accept nature as a source of inspiration. Biomimicry has shown the potential strength in (technical) design of adapting such mindset but there is much more to be explored, as partly shown in this report. Ultimately the objective should be the effectuation of a paradigm shift with as main result the implementation of a field called ‘Bioneering’ (Pioneering through biological engineering). It would be tremendous if this project contributes to a change of course in that direction.

**BT Explore Lab**

On a more personal note I would like to applaud a recent development which I would otherwise recommend now. In 2016 my graduation project started as a quest. Since, I have encountered this need to understand and solve societies problems numerous times with other students. My advice has always been to see your graduation project as just another study project, just longer. After, you still have your entire life to investigate and tackle important problems. Being aware of this would have altered my course of the last years. However, that would have been a shame. It should not be necessary to discourage students to go on a quest just so they don’t get lost. Graduate students are in their creative heydays, not bound to any obligations, and have nine months to dive deep into a subject. The force of innovation those students have together is immense and when properly tamed could solve global challenges. Their quest should be encouraged but guided. Because the skills needed for such quest are hardly ever of the kind taught in universities. The Explore Lab graduation studio used to be the place were this did happen. But as a Building Technology student you were thought to not be in need of such guidance. Since last year this flaw has been redressed, a development I would have wished to take place earlier. But am happy it has been done now and I look forward to all the beautiful innovation it will spark in the future.

## 7.4 The Future of Mycelium

The future of fungal materials and other biomaterials is likely to be bright. The call for circular solutions has inspired a generation to explore new realms and look for solutions. A growing number of more critical consumers will likely force manufactures to leave unsustainable and semi sustainable practices. A drive away from linear production and down cycling will automatically lead in the direction of natural materials. Together with breakthroughs in biotechnology as CRISPR will likely mean that micro-organisms are the factories of the future. From that perspective mycelium-based composites are just a clumsy mixture of fungus and natural materials. It is likely that more advanced technologies and materials will be developed in the coming years. Solid state fermentation could very well play an important part in these developments as it is ideally suited to convert biomass of all sorts into valuable compounds. Breakthroughs in the creation of SSF bioreactor are needed to ease the process and allow for scaled production. This could spark the widespread use of MBC products but also of whole range of other, currently unthinkable, applications. That moment might just be closer than expected. In the fall of last year MBC world leader Ecovative announced the founding a dedicated research facility in industrial fungal SSF, called Mycelium Foundry One (Bayer, 2019). Where that will take us only the future knows.

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# Apendix 1 - Study of precedents

Name: **Mycotecture**

Creator: **Philip Ross - MycoWorks**

Year: **2009**

Type of work: **Mainly Art, building orientated**

Production method: **Mould, bricks**

Material: **Fibre based mycelium composite**

Quality: **Low**

Name: **Mycelium Project 1.0**

Creator: **Eric Klaarenbeek**

Year: **2013**

Type of work: **Art**

Production method: **3D-printed mould**

Material: **Fibre based mycelium composite + PLA**

Quality: **High**

Name: **HiFi**

Creator: **Marc Benjamin – The Living (In cooperation with Ecovative & Arup)**

Year: **2014**

Type of work: **Architectural**

Production method: **Mould, bricks**

Material: **Fibre based mycelium composite + Gipsum**

Quality: **High**


Name: **Mycelium Experience Packaging**

Creator: **Davine Blauwhoff - TU Delft IDE**

Year: **2016**

Type of work: **Product design**

Production method: **Mould**

Material: **Fibre and granulate based mycelium composite**

Quality: **High**

Name: **Mycelium packaging**

Creator: **Ecovative**

Year: **2007**

Type of work: **Product development**

Production method: **Mould**

Material: **Fibre based mycelium composite**

Quality: **Medium**


Name: **Greensulate**

Creator: **Ecovative**

Year: **2010**

Type of work: **Archtectural object**

Production method: **Mould multiplex applied after**

Material: **Fibre based mycelium composite + Multiplex**

Quality: **High**

Name: **Mushroom Tiny House**

Creator: **Ecovative**

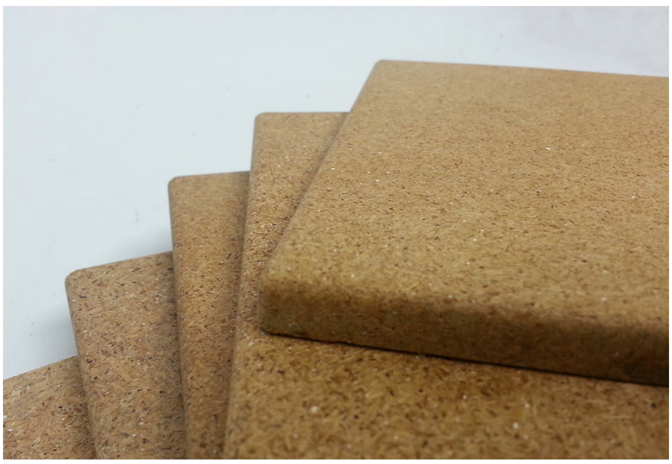
Year: **2013**

Type of work: **Architectural**

Production method: **Wood acts as mould**

Material: **Fibre based mycelium composite + Woden slats**

Quality: **High**



Name: **MycoBoard**

Creator: **Ecovative**

Year: **2014**

Type of work: **Wood like panels**

Production method: **Heat pressed**

Material: **Flax - Canola - Hemp - Soft Wood - Hard Wood + Mycelium based resin**

Quality: **High**

Name: **Ecovative Interior Wall Panels**

Creator: **Ecovative**

Year: **2016**

Type of work: **Interior (acoustic) panels**

Production method: **Compressed**

Material: **Fibre based mycelium**

Quality: **High**

Name: **MycoTEX**

Creator: **Aniela Hoitink - Neffa**

Year: **2016**

Type of work: **Art**

Production method: **Combining thin layers of pure mycelium grown on a petri dish to form a textile**

Material: **Raw pure mycelium**

Quality: **Medium**

Name: **Mycelium Growing Architecture**

Creator: **Sebastian Alvarado Grugiel - IAAC**

Year: **2014**

Type of work: **Archtectural object**

Production method: **Cartboard waffle grid functions as mould**

Material: **Fibre based mycelium composite + cartboard**

Quality: **Low**

Name: **Mycelium Tectonics**

Creator: **Gianluca Tabellini - University of Bologna**

Year: **2015**

Type of work: **Architectural**

Production method: **Tensioned Fibre Colonisation**

Material: **Continious Fibre based mycelium composite**

Quality: **Medium**

Name: **Grown Structures**

Creator: **Aleksi Vesaluoma - Brunel University**

Year: **2017**

Type of work: **Structural prototype**

Production method: **Free from tube**

Material: **Fibre based mycelium composite + tube shaped cotton bandage**

Quality: **Medium**


Name: **Shell Mycelium**

Creator: **Degradation Movement Manifesto**

Year: **2016**

Type of work: **Archtectural object**

Production method: **Wooden Shell acts as mould**

Material: **Fibre based mycelium composite + Wood**

Quality: **Low**

Name: **MycoTree**

Creator: **Dirk Hebel (Karlsruhe Institute of Technology), Philippe Block (ETH)**

Year: **2017**

Type of work: **Structural**

Production method: **Mould**

Material: **Fibre based mycelium composite**

Quality: **Prestine**

## Appendix 2.1 - Literature Review: Bending

Appels (2019). Fabrication factors influencing mechanical, moisture- and water-related properties of mycelium-based composites.

**General Info**

| | |
|---|---|
| Subject (keywords): | Exploration |
| Company: | Mogu |
| Fungi: | Trametes multicolor, Pleurotes ostreatus |
| Substrates: | Rapeseed straw, Beech sawdust, Cotton |
| Type of material: | **Foam**, Heat pressed, cold pressed |
| Types of tests: | Tensile, **bending** (and non-mechanical) |
| Test Methods: | three-point bending, 2mm/min, |
| Growth time: | 34 days (14+14+10) |

| **Properties** | **Ingredients** | **Density** | **Flex strength:** | **Flex Ela Mod** |
|---|---|---|---|---|
| (TRN) | Trametes, Straw | 100 Kg/m3 | 0,22 MPa | 3 MPa |
| (PCN) | Pleurotes, Straw | 130 Kg/m3 | 0,05 MPa | 1 Mpa |
| (PRN) | Pleurotes, Cotton | 130 Kg/m3 | 0,06 MPa | 1 Mpa |
| (TBN) | Trametes, Sawdust | 170 Kg/m3 | 0,29 MPa | 9 MPa |

**Main insight**

-

Holt, G., (2012). *Fungal Mycelium and Cotton Plant Materials in the Manufacture of Biodegradable Molded Packaging Material: Evaluation Study of Select Blends of Cotton Byproducts*

**General Info**

| | |
|---|---|
| Subject (keywords): | Multi, production |
| Company: | Ecovative |
| Fungi: | Ganoderma sp. |
| Substrates: | cotton |
| Type of material: | Foam, Brick |
| Types of tests: | density, compressive**, bending**, thermal (and others) |
| Density: | 66,5 – 224 kg/m3 |

**Mechanical Insights**

No clear influence of particle size on material performance. This could have to do with the normalisation towards a density of 32,04kg/m3 of Polystyrene packaging.
Flexure Strength = between 7,0 – 26,1 kPa
Elastic Modulus = between 122,8 – 674,5 kPa

**Other insights**

Fig 2 shows figure of production plant Ecovative.
shrinkage of 0,5 to 2,5 percent (more with liquid than grain
Density can be lower with liquid
No density overview, so hard to interpreter poor Thermal conductivity and bending

## Appendix 2.2 - Literature Review: Sandwich Panels

Travaglini, S. (2014) Mycology Matrix Sandwich Composites Flexural Characterization

**General Info**

| | |
|---|---|
| Subject (keywords): | |
| Company: | MycoWorks |
| Fungi: | Ganoderma lucidum |
| Substrates: | red oak (without and with carbon and bamboo fibre skins) |
| Type of material: | Sandwich Composite |
| Types of tests: | bending, 4 point |
| Density: | 318 kg/m3 |
| Growth time: | 14 days |

| Results | Maximum force (N) | Core shear strength (kPa) | Flexural Modulus (MPa) | Yield strength (MPa) | Peak Flexural Strength (MPa) |
|---|---|---|---|---|---|
| Core only | 43.6 | 36.2 | 168 | 0.7 | 1.4 |
| Carbon fiber skin | 95.6 | 76.6 | 296 | 2.6 | 2.9 |
| Bamboo fiber skin | 209.7 | 63.3 | 645 | 0.4 | 0.9 |

**Main insights**
Beams were made through adhesion with non-natural glues.
comparable stress strain plots to this research

Jiang, (2014). "A New Process for Manufacturing Biocomposite Laminate and Sandwich Parts using Mycelium as a Binder."

**General Info**

| | |
|---|---|
| Subject (keywords): | Production, resin infusion, |
| Company: | Ecovative |
| Fungi: | not disclosed |
| Substrates: | Ecovative material + jute burlap, linen cloth |
| Type of material: | Sandwich |
| Types of tests: | None/production |
| Growth time: | - |

**Main insights**
Purely focused on the production aspect of mycelium sandwich laminates. Not for the purpose of building material but undefined freeform applications, but with the intend of infusing bioresin.
Corn starth is used to solidify fabric sandwich layers. Colonised particles are then added in order and allowed to grow and solidify. This method allows for growth outside mold because the fabric is turned into the mold. The starch is also consumed by the mycelium stilmulating surface growth and adhesion. Because of fabric, freeform applications are possible.

Jiang, (2016), A New Approach to Manufacturing Biocomposite Sandwich Structures: Mycelium-Based Cores

**General Info**

| | |
|---|---|
| Subject (keywords): | Sandwich structures |
| Company: | Ecovative |

| | |
|---|---|
| Fungi: | non disclosed |
| Substrates: | 50-50 kenaf hemp (Jute, Flax, Cellulose laminates layers) |
| Type of material: | Sandwich |
| Types of tests: | Bending, 3-point |
| Density: | Non disclosed |
| Growth time: | pre-grown, 5 days of 2$^{nd}$ growth fase. (24'C) |

| **Results** (3x10 samples) | **Elastic Modulus** | **Standard Deviation** |
|---|---|---|
| Jute | 4654 kPa | 1754 |
| Flax | 4650 kPa | 756 |
| Cellulose | 6567 kPa | 1264 |

**Main insights:**

Only one force-deflection cruve was shown, so not much insight on the fail behaviour can be gained.

No density or weight data was given, so no quantitave comparison can be made with the

Ziegler (2016), Evaluation of Physico-Mechanical Properties of Mycelium Reinforced Green Biocomposites Made from Cellulosic Fibers

**General Info**

| | |
|---|---|
| Subject (keywords): | |
| Company: | Ecovative |
| Fungi: | non-disclosed |
| Substrates: | Ginning waste & hemp + Cotton/hemp fabric woven/unwoven |
| Type of material: | Sandwich |
| Types of tests: | compressive, tensile (and others) |
| Density: | non-disclosed |
| Growth time: | pre-grown, 5 days of 2$^{nd}$ growth fase. (24'C) |

**Main insights:**

adjusted mounts for testing has to be made.

# Appendix 2.3 - Literature Review: Mechanical (Non-Bending)

Elsacker E, (2019) Mechanical, physical and chemical characterisation of mycelium-based composites with different types of lignocellulosic substrates.

**General Info**

| | |
|---|---|
| Subject (keywords): | Exploration |
| Company: | - |
| Fungi: | Trametes versicolor |
| Substrates: | hemp, flax, softwood, straw (loose, chopped, dust, pre-compressed, tow) |
| Type of material: | Foam (different pre-processing) |
| Types of tests: | density, compressive, **thermal** (and non-mechanical) |
| Density: | 88,8 – 159,3 kg/m3 |

Heisel, F.A. (2018). Design, Cultivation and Application of Load-Bearing Mycelium Components: The MycoTree at the 2017 Seoul Biennale of Architecture and Urbanism.

**General Info**

| | |
|---|---|
| Subject (keywords): | MycoTree, compression only |
| Company: | MycoTech |
| Fungi: | Ganoderma Lucidum |
| Substrates: | woodchip+sawdust, sugarcane+casave roots |
| Type of material: | Brick |
| Types of tests: | density, compressive |
| Density: | 420 – 440 kg/m3 |

**Main insights**

particle size determines composite typology: sawdust becomes brick. Loose particles become foam. The match between fungi and substrate determines growth. Clearly visible on figure 3.

Heisel, F. a. S., (2017). Design of a load-bearing mycelium structure through informed structural engineering.

**General Info**

| | |
|---|---|
| Subject (keywords): | Structural Design |
| Company: | MycoTech |
| Fungi: | Ganoderma Lucidum |
| Substrates: | sugarcane + cassava roots |
| Type of material: | Brick |
| Types of tests: | none |

Islam, M.R. (2018, Mechanical behavior of mycelium-based particulate composites

**General Info**

| | |
|---|---|
| Subject (keywords): | compressive behaviour, computanional approach |
| Company: | Ecovative |
| Fungi: | non disclosed |
| Substrates: | non disclosed |
| Type of material: | Foam, Pure |
| Types of tests: | compression, simulation |
| Density: | 121 -133 kg/m3 |

**Main insights**

Computanional aproxination of mechanical behaviour of MBC's possible.

Islam, M.R. , (2017) Morphology and mechanics of fungal mycelium

**General Info**

| | |
|---|---|
| Subject (keywords): | Tension, compressive behaviour, computanional approach |
| Company: | Ecovative |
| Fungi: | non disclosed |
| Substrates: | non disclosed |
| Type of material: | Foam |

Types of tests: tension, compression, simulation
Density: Non disclosed

Lelivelt, R. J. J., (2015). The production process and compressive strength of Mycelium-based materials

**General Info**
Subject (keywords): Production Process, Compressive strength
Company: independent – contact with Mogu
Fungi: Pleurotus Ostreatus, Trametes Versicolor
Substrates: hemp (particles, mat, fibres), wood chips
Type of material: Foam
Types of tests: compression
Density: 170-260 kg/m3

**Main insights**
*Basidiomycota* is the preffered group of fungi because of their ability to fuse their mycelium into a dense mass. (Carlile & Watkinson 1995)

Sun, W., (2019). Fully Bio-Based Hybrid Composites Made of Wood, Fungal Mycelium and Cellulose Nanofibrils.

**General Info**
Subject (keywords):
Company: Ecovative
Fungi: undefined - basidiomycete
Substrates: Spruce, pine, fur
Type of material: Pressed
Types of tests: mechanical and non-mechanical
Density: 300 – 600 kg/m3

**Main insights**
Scanning Electron Microscopy (SEM) can show fungal growth (quality).

Teixeira, (2018). Production and mechanical evaluation of biodegradable composites by white rot fungi.

**General Info**
Subject (keywords):
Company: independent
Fungi: Pleurotes ostreatus, pleurotes eryngii, pycnoporus sanguineus
Substrates: coconut powder, wheat bran
Type of material: Foam/brick
Types of tests: compressive, tenancity
Density: not stated

**Main insights**
small weightloss. 60 -70 percent water, 68-76 percent weightloss.
Haneef 2017 – pleurote ostreatus showed growth of hyphae in length whereas Ganoderma lucidum presented branching, increasing the density of the mycelium
pycnoporus sanguineus - far superior in compression.

Travaglini, S. (2013). Mycology matrix composites.

**General Info**
Subject (keywords):
Company: MycoWorks
Fungi: Ganoderma lucidum
Substrates: Red Oak wood chips
Type of material: Foam
Types of tests: compressive, tensile
Density: 318 KG/m3

**Main insights**
different mechanical behaviour with different material types. Elastomeric, elastic-plastic, elastic-brittle. Figure 2 explains the difference between open and closed cell foam. figure 3 shows behaviour in compression and tensile

load.
Formula by Ashby to evaluate Elastic modulus in comparison to density of substrate and mycelium. Potential way to express growth quality after mechanical testing.

Z. (Joey) Yang, F. Zhang, B. Still, M. White, P. Amstislavski, Physical and Mechanical Properties of Fungal Mycelium-Based Biofoam, J. Mater. Civ. Eng. 29 (2017) 04017030. doi:10/gc4kq9.

**General Info**

| | |
|---|---|
| Subject (keywords): | Bioengineering process |
| Company: | Independent? |
| Fungi: | non disclosed – (a basidiomycete fungus) |
| Substrates: | Sawdust of alaska Birch, millet grain, wheat bran |
| Type of material: | Foam |
| Types of tests: | wave velocity, compressive, Thermal |
| Density: | 160 – 280 kg/m3 |

# Appendix 2.4 - Literature Review: Thermal Insulation & Fire Behaviour

Elsacker E, (2019) Mechanical, physical and chemical characterisation of mycelium-based composites with different types of lignocellulosic substrates.

**General Info**

| | |
|---|---|
| Subject (keywords): | Exploration |
| Company: | - |
| Fungi: | Trametes versicolor |
| Substrates: | hemp, flax, softwood, straw (loose, chopped, dust, pre-compressed, tow) |
| Type of material: | Foam (different pre-processing) |
| Types of tests: | density, compressive, **thermal** (and non-mechanical) |
| Density: | 88,8 – 159,3 kg/m3 |

| Type | Density (Kg/m3) | Thermal conductivity |
|---|---|---|
| Flax (chopped) | 159,3 | 0,0578 (0,0550 - 0,0603) |
| Hemp (chopped) | 94 | 0,0404 (0,0386 - 0,0417) |
| Straw (chopped) | - | 0,0419 (0,0417-0,0421) |

Travaglini (2015) Thermal Properties of Mycology Materials

**General Info**

| | |
|---|---|
| Subject (keywords): | Exploration |
| Company: | Mycoworks |
| Fungi: | Ganoderma lucidum, Laetiporus sulphureus |
| Substrates: | hemp, husk, wood |
| Type of material: | Foam (different pre-processing) |
| Types of tests: | density, compressive, **thermal** (and non-mechanical) |
| Density: | 315 – 773 kg/m3 |

**Main insights Insulation**

- sandwich tested for insulation
- extreme high densities found. Still thermal conductivity equal to Balsa wood. More like bricklike material.

thermal conductivity 0,053 – 0,077

**Main insights fire safety**

maximum use temperature, American alternative to fire bahviour test. No risk till 300’C. Average max temp 390’C.

Jones, M, (2018) Waste-derived low-cost mycelium composite construction materials with improved fire safety

**General Info**

| | |
|---|---|
| Subject (keywords): | Exploration |
| Company: | Mycoworks |
| Fungi: | Ganoderma lucidum, Laetiporus sulphureus |
| Substrates: | hemp, husk, wood |
| Type of material: | Foam (different pre-processing) |
| Types of tests: | density, compressive, **thermal** (and non-mechanical) |
| Density: | 315 – 773 kg/m3 |

Jones, M,(2017) Thermal degradation and fire reaction properties of mycelium composites.

**General Info**

| | |
|---|---|
| Subject (keywords): | |
| Company: | Independent |
| Fungi: | Trametes Versicolor |
| Substrates: | Rice hulls |
| Type of material: | Foam |
| Types of tests: | Fire Behaviour |
| Density: | 315 – 773 kg/m3 |
| Growth time: | 12 days |

# Apendix 3.1 - Internet analysis DC construction

**Jumbo**
https://www.youtube.com/watch?v=pqKP_w9DfaM

Main insights

- Robots, hight from 13 to 22 meters
- 11500 foundation piles
- Solar panel covered roof.
- OSR – order, storage and retrieval system

No Humans, different climate? Very cold??

**Zalando**
https://www.youtube.com/watch?v=vpGwhGPaLwU

Main insights:

- 100.000 m2, total floor surface 350.000m2

- double layered?

**Wijnen Bouwgroep**
https://www.youtube.com/watch?v=tuWKno8uKsw

- Corrugated steel plate roof. In situ covered with insulation plates and roofing material.

**LIDL**
Waddinxveen - https://www.youtube.com/watch?v=YZNeYDbdWE0

- Prefab concrete walls (large LEGO) and concrete columns
- Steel roof beams
- Steel profiled roof with a dubble layer of insulation. Cross pattern. Plate size 1 x 2 meter?

LIDL Oosterhout - https://www.youtube.com/watch?v=pqKP_w9DfaM

- Prefab concrete walls covered with long foam plates (10m?)
- Corrugated steel roof

**Hoogvliet**
- https://www.hoogvliet.com/officiele-bouwstart-hoogvliet-distributiecentrum
- https://www.logistiek.nl/warehousing/nieuws/2017/08/hoogvliet-bouwt-nieuw-distributiecentrum-bleiswijk-101157897?vakmedianet-approve-cookies=1
- https://www.arcadis.com/nl/nederland/wat-we-doen/projecten/europa/nederland/attractief-duurzaam-distributiecentrum-voor-hoogvliet/

DC Costs

https://www.logistiek.nl/warehousing/artikel/2017/12/een-nieuw-dc-bouwen-dit-zijn-de-belangrijkste-kosten-101161132?vakmedianet-approve-cookies=1

- Sprinklers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# Apendix 3.2 - Interviews

**LIDL**

**Koen Harleman**
**Sustainability and Innovation Manager**

**Habeon Architecten**

**Diederik de Jonge**
**Architect**

**Nexteria**

**Cor van Dijken**
**Sustainability Managers**

**Kingspan**

**Vincent Grieten**
**Technical Service Engineer**

**Vragen aan Kingspan**

- Welke producten van jullie zijn geschikt voor grote industriehallen?
- *X-deck / Coldstore, koel en vries. Andere typen voor schuine en bolle daken.*
- Geen product voor 2e leven. Kijk op de website.
- Welksandwichproducten van Kingspan zijn geschikt voor de daken van grote industriehallen
- Klopt het dat sandwichpanelen eigenlijk altijd in de geven worden gebruik en niet het dak?
- Een van de bouwers die ik intervieuwe had het over de problemen van vervormingen in het
- dak met sandwichpanel. Waardoor een stalendak met een tweelaags in kruisverband liggend schuimen isolatielaag losliggend op het dak superieur is. Herkent u dit probleem en wat zijn de oplossingen?
- Verder is het transport van de sandwichpanelen een probleem. 2 bij 20 meter uit me hoofd is daar maatgevend in transport.
- Hoe kijkt Kingspan naar de producten die ik net genoemd heb in het kader van circulaire economie. Is een prefab systeem beter of zijn de schuimen losse blokken beter? Of wordt er hard gewerkt aan andere circulaire producten.
- U herkent de problemen niet. Nou is dat natuurlijk niet heel erg omdat het schuimt ook van Kingspan is.

**Vragen voor Heembouw/Habeon**

- Circulariteit is (nog) geen uitgekristalliseerd begrip. Welke visie op Circulariteit past volgens Habeon bij de typologie distributiecentrum? Wat is jullie visie op de circulariteit van distributiecentra?
- Wat is de rol voor de bouwmethode in die visie?
- Wordt er gebruikt gemaakt van Sandwich Panelen?
- Welke bouwmethode is voor het dak gebruikelijk?
- Wat is de rol van materiaalgebruik in die visie?
- Wat voor isolatiemateriaal wordt er gebruikt? PIR?
- Wat is de voornaamste uitdaging bij de ontwikkeling van circulaire DC's?
- Transport van bouwelementen?
- Is het gebruik van sprinklers standaard in DC's?
- Zijn wet en regelgeving of eisen van klanten aan de prestaties van een gebouw momenteel een beperkende factor? En zo ja, welke van de twee is beperkender en waarom?
- Welke ontwikkelingen gaan de circulariteit in de bouw/ van distributiecentra versnellen, afremmen?
- Is er veel vraag naar circulaire DC's? En wat voor partijen zijn daar in geinterreseerd?

**Links to interviews**

- Cor van Dijken: https://drive.google.com/open?id=1rDp6hjD4VleEs7pBzceuQRv1yr2rMQl3
- Vincent van Grieten: https://drive.google.com/open?id=15o8ChGbzbZacHqWU1jSiNOQKGeZ9lfjH
- Koen Harleman: https://drive.google.com/open?id=1sRrNV9j1vZKTi9fzYvd3A4kR-Bkbxxv2

# Apendix 4 - Sample Assesment

| Sample nr | Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|---|
| Foam | | | | | | |
| 1 | 595,5 | 74,0 | 49,9 | 2,2 | 182,0 | 82,8 |
| 2 | 594,5 | 73,5 | 51,2 | 2,2 | 184,0 | 82,2 |
| 3 | 596,0 | 73,0 | 49,6 | 2,2 | 176,0 | 81,6 |
| 4 | 596,5 | 71,5 | 49,0 | 2,1 | 174,0 | 83,3 |
| 5 | 595,0 | 73,5 | 50,0 | 2,2 | 178,0 | 81,4 |
| Average | 595,5 | 73,1 | 49,9 | 2,2 | 178,8 | 82,2 |
| Average deviation | 0,6 | 0,7 | 0,6 | 0,0 | 3,4 | 0,6 |
| Standard deviation | 0,7 | 0,9 | 0,7 | 0,1 | 3,7 | 0,7 |
| | | | | | | |
| Sandwich | | | | | | |
| F1 | 596,0 | 74,0 | 50,3 | 2,2 | 374,0 | 168,6 |
| F2 | 596,0 | 75,0 | 50,2 | 2,2 | 390,0 | 173,8 |
| F3 | 596,0 | 74,0 | 49,9 | 2,2 | 372,0 | 169,1 |
| F4 | 596,0 | 74,0 | 49,2 | 2,2 | 372,0 | 171,4 |
| F5 | 596,0 | 74,0 | 49,4 | 2,2 | 366,0 | 168,0 |
| Average | 596,0 | 74,2 | 49,8 | 2,2 | 374,8 | 170,2 |
| Average deviation | 0,0 | 0,3 | 0,4 | 0,0 | 6,1 | 1,9 |
| Standard deviation | 0,0 | 0,4 | 0,4 | 0,0 | 8,1 | 2,1 |

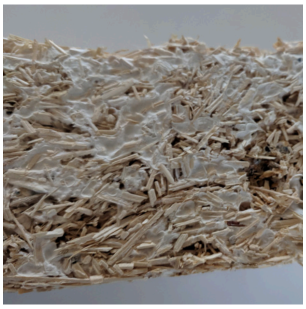
| Sample | Delamination | | Centre to crack centre |
|---|---|---|---|
| | type | location | mm |
| F1 | 2-sided | mirrored | 60 |
| F2 | 2-sided | mirrored | 30 |
| F3 | 1-sided | bottom | 0 |
| F4 | 2-sided | mirrored | 40 |
| F5 | 1-sided | bottom | 10 |

| Sample | Centre to crack centre | Length of crack | Times own weight |
|---|---|---|---|
| | mm | mm | |
| 1 | 23 | 45 | 8,97 |
| 2 | 3 | 45 | 8,23 |
| 3 | 3 | 15 | 8,55 |
| 4 | 73 | 35 | 8,25 |
| 5 | 3 | 25 | 9,38 |

# FOAM PANELS - MBCs
## Sample 1

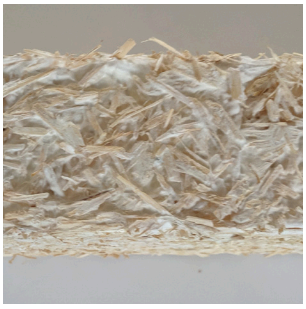
| Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|
| 595,5 | 74,0 | 49,9 | 2,2 | 182,0 | 82,8 |





# Sample 2

| Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|
| 594,5 | 73,5 | 51,2 | 2,2 | 184,0 | 82,2 |



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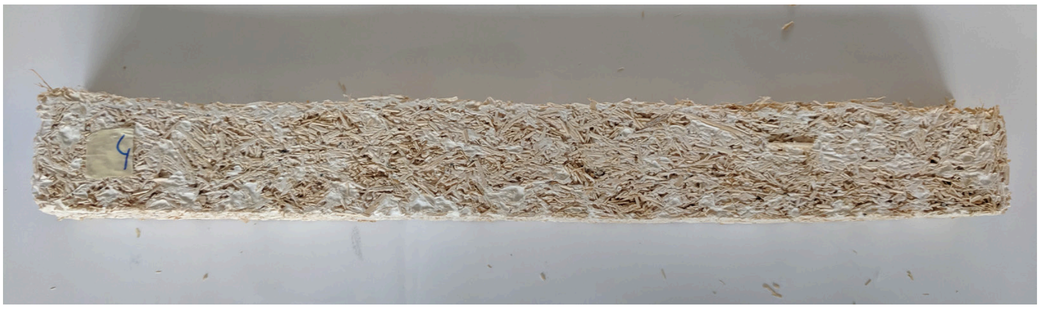
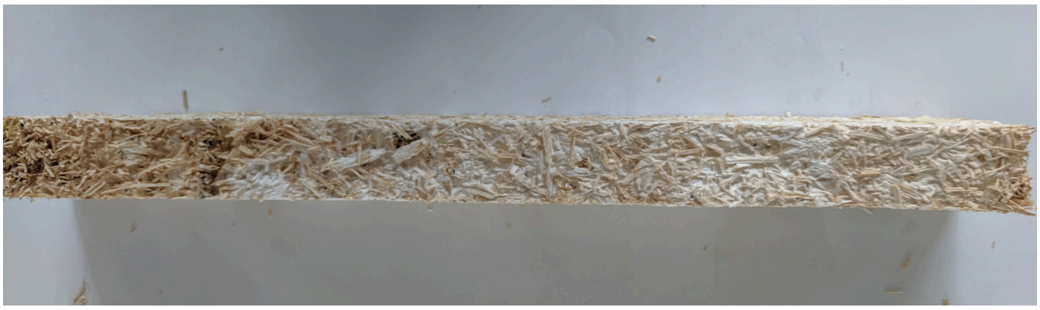
# Sample 3

| Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|
| 596,0 | 73,0 | 49,6 | 2,2 | 176,0 | 81,6 |


# Sample 4

| Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|
| 596,5 | 71,5 | 49,0 | 2,1 | 174,0 | 83,3 |




# Sample 5

| Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|
| 595,0 | 73,5 | 50,0 | 2,2 | 178,0 | 81,4 |

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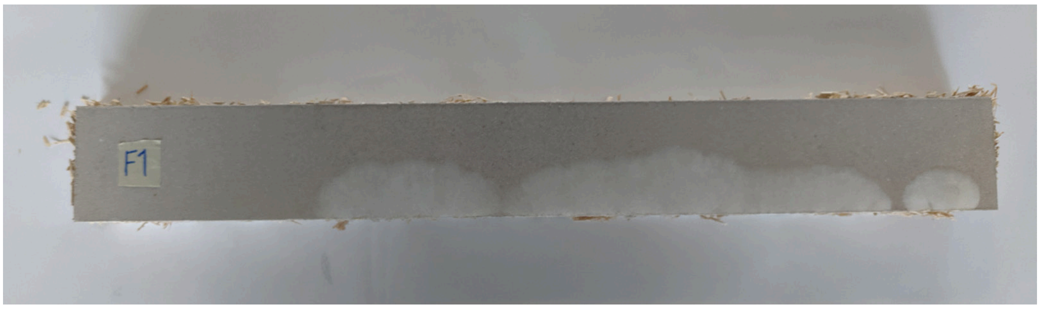
# SANDWICH PANELS - MBCs
# Sample F1

| Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|
| 596,0 | 74,0 | 50,3 | 2,2 | 374,0 | 168,6 |







# Sample F2

| Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|
| 596,0 | 75,0 | 50,2 | 2,2 | 390,0 | 173,8 |


# Sample F3

| Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|
| 596,0 | 74,0 | 49,9 | 2,2 | 372,0 | 169,1 |



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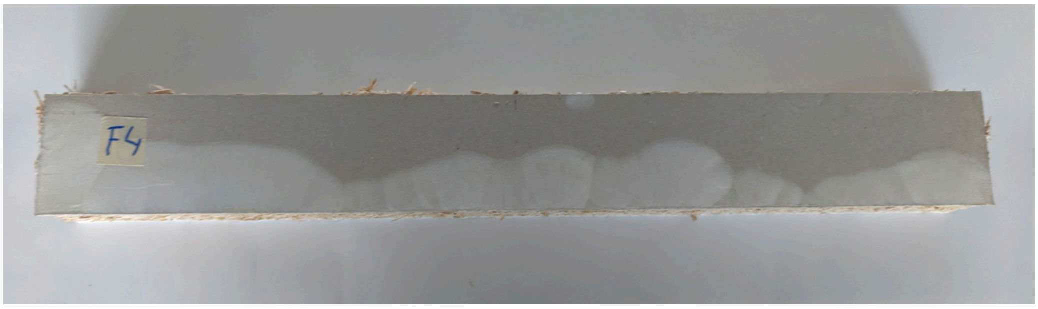
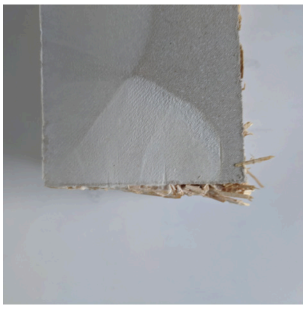
# Sample F4

| Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|
| 596,0 | 74,0 | 49,2 | 2,2 | 372,0 | 171,4 |







# Sample F5

| Length | Width | Thickness | Volume | Weight | Density |
|---|---|---|---|---|---|
| 596,0 | 74,0 | 49,4 | 2,2 | 366,0 | 168,0 |



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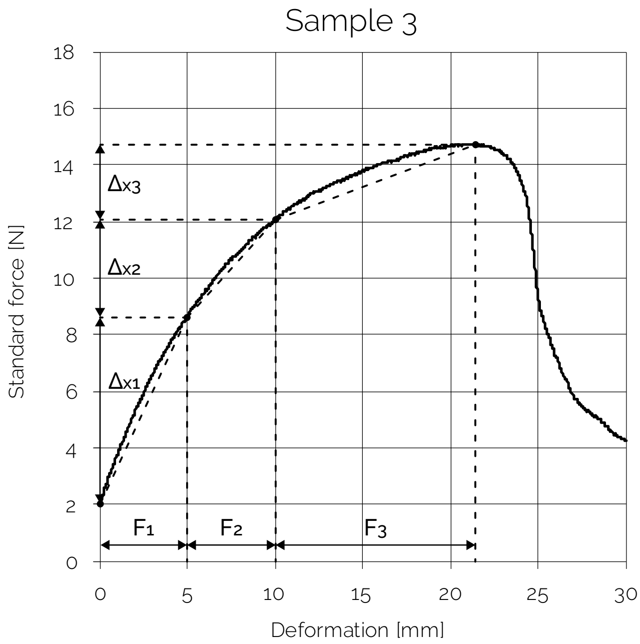
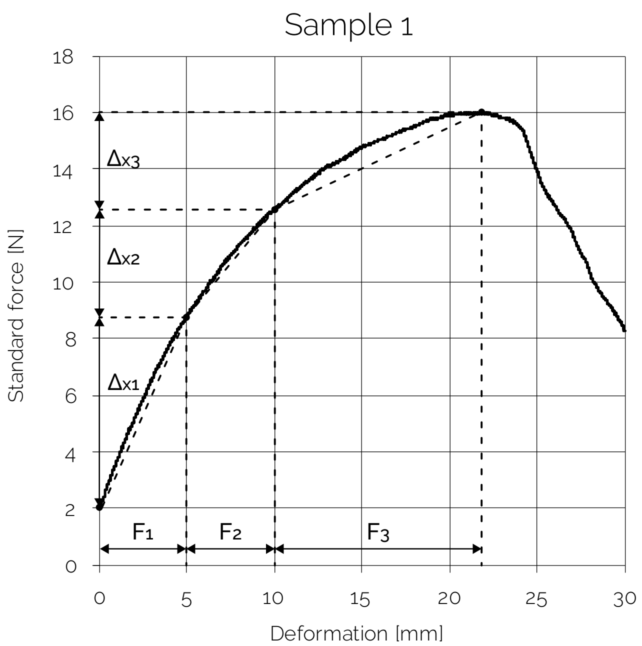
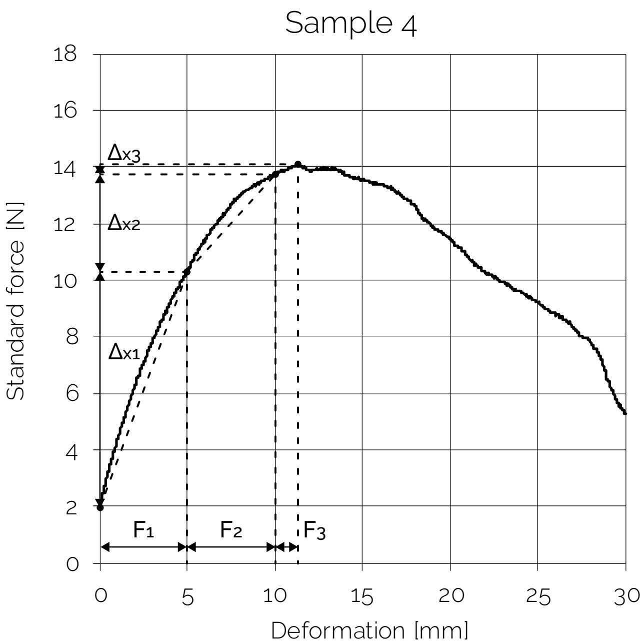
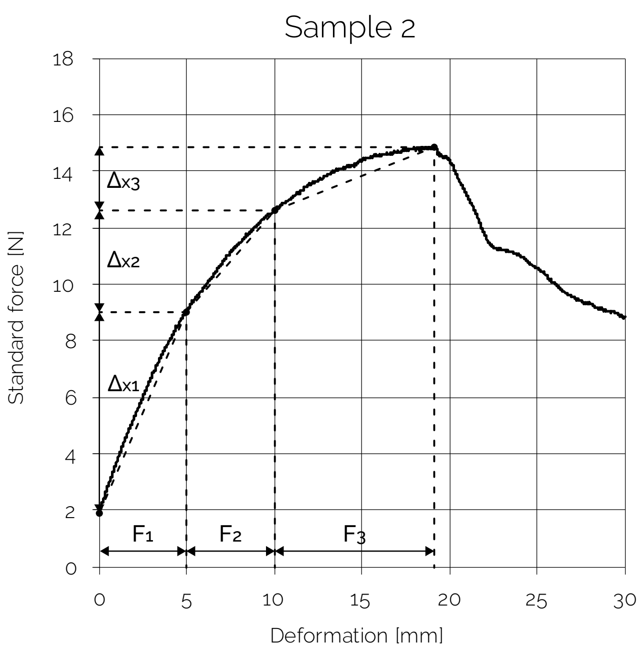
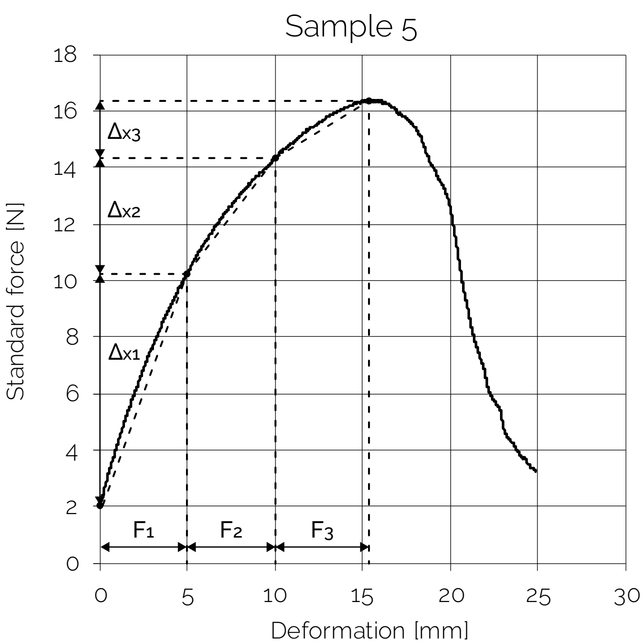
# Apendix 5.1 - MBC's E-modulus



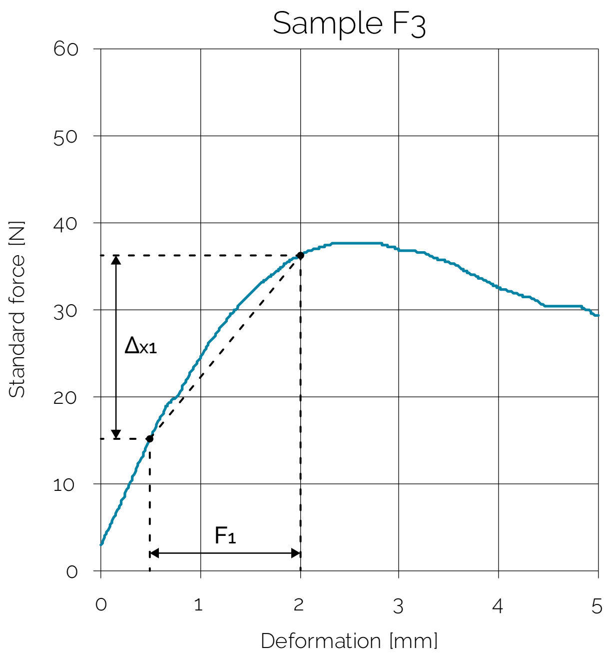



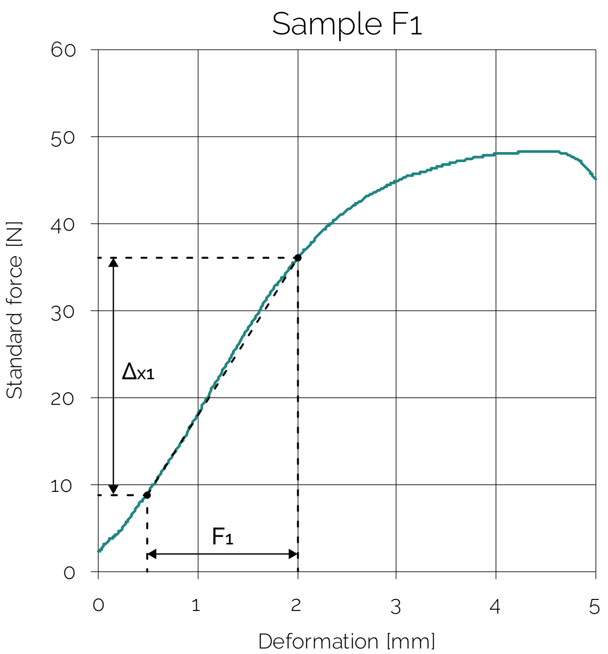



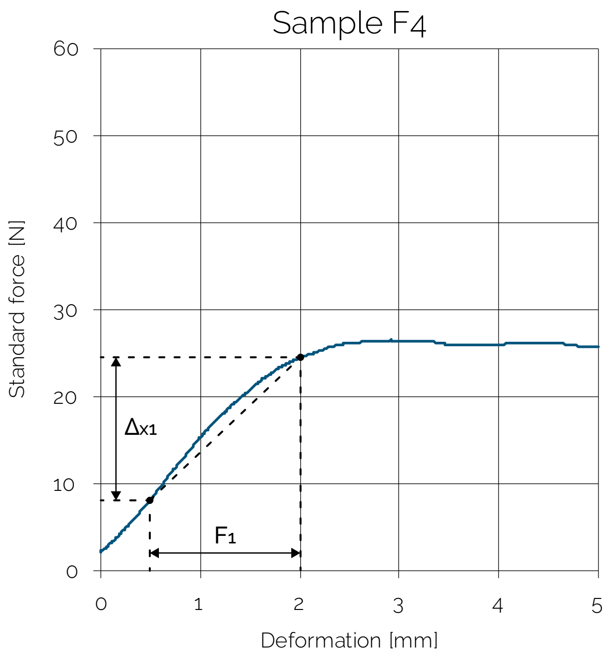



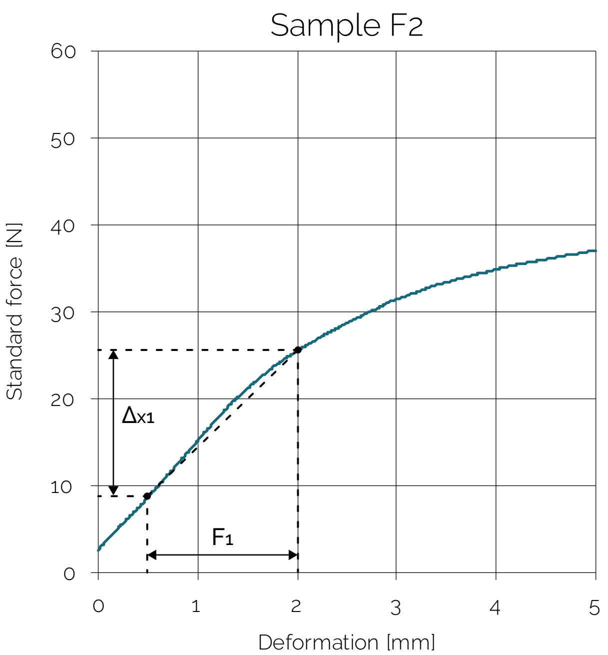



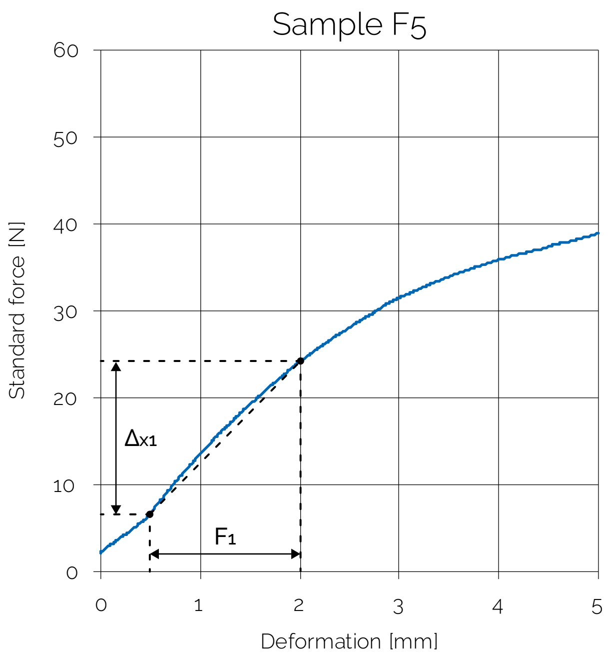
# Apendix 5.2 - Sandwich Panels E-modulus



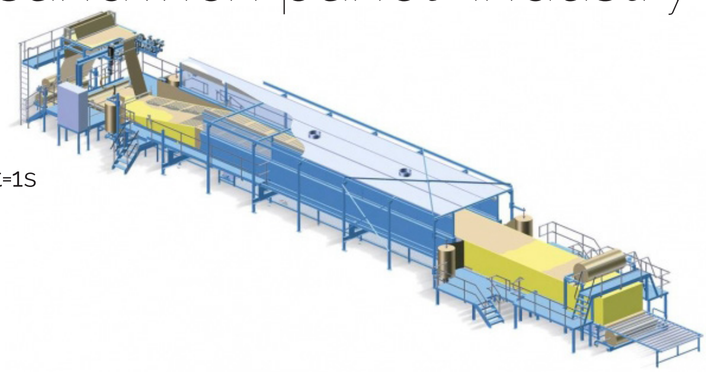
# Apendix 6.1 - mushroom industry analysis

**Sources used:**

- Promo video Pilzgarte: : https://www.youtube.com/watch?v=LjtIbDQq4cg
- Promo video Bank Mushrooms: https://www.youtube.com/watch?time_continue=1&v=cKLFqduGuls&feature=emb_logo
- Peter Oei - Mushroom cultivation IV
- Paul Stamets - Growing gourmet and medicinal mushrooms


Mrs. Kim

# Apendix 6.2 - foam and sandwich panel industry analysis



**Sources used:**

- https://www.youtube.com/watch?v=KRpwypk9pjg&t=1s
- https://www.youtube.com/watch?v=OyKq3PYXTBU
- https://www.youtube.com/watch?v=76CXgSHweFU
- https://www.youtube.com/watch?v=8XXY_lE2-zA