Mycelium Biking

Eco-Design at its Best

Alexander Wagner
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Abstract

Mycelium Biking, a master thesis project about using mycology in eco-design made by design engineering student Alexander Wagner. The present global ecology drives researchers to find environmentally friendly alternatives to commonly used materials such as expanded plastics and concrete. The project examined the possibilities of implementing mycelium materials in systematic product development processes. The eligibility of the material was tested by developing products for electric cargo bikes and, by doing so, reduce their ecological footprint. Mycelium materials relevant to Industrial Design Engineering mainly because of their ecological qualities but also because of their performance and the wide range of applicable fields.

This study presents six different products developed for the cargo bike in which mycelium materials was considered eligible. The study also presents the material in general showcasing the applicability for other types of products. It was found most applicable for lightweight products used in friendly environments and with low demands on tolerances. These types of product don’t need additional coating, are self-compostable, are possible to create with no manufacturing costs and its production close-to carbon neutral.

Conclusively, any product developer in need of a material with an elastic modulus of 15MPa for densities 100kg/m$^3$ (These are the properties of untreated mycelium materials grown without pressure) should consider using mycelium materials. Designers have the option to design a product with a manufacturing process that need no supplementary energy and without any ecological footprint (should you assume availability of local feedstock). The ecological and economic benefits of such material are obvious and it is up to the designer to weigh them against the issues related to using the material (shrinkage, coating & quality).

**Keywords**: Mycology, Mycelium Materials, Eco-design, Cargo bike, Sustainability, Process Methodology, Material Testing.
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INTRODUCTION

“Mycelium Biking” is a master thesis project about using mycology in eco-design made by design engineering student Alexander Wagner. The present global ecology drives researchers to find environmentally friendly alternatives to commonly used materials such as plastic and cement. The project examined the possibilities of implementing mycelium materials in systematic product development processes. The eligibility of the material was tested by developing products for electric cargo bikes and, by doing so, reduce their ecological footprint. The thesis project was conducted at Semcon, Gothenburg Sweden, and equivalent to 30 Swedish university credits. The project was the final unit for Master of Science in Industrial Design Engineering at Luleå University of Technology.

1.1 Project incentives

The practice of design engineering is affected by a growing understanding of the ecological footprints caused by human. Awareness of the environmental pollution is pushing the search for new materials and solutions. Eco-design or “sustainable product development” is defined by Wimmer, Lee, Kun-Mo, Polak, & Springer (2010) as an approach to designing with special consideration for the environmental impacts of the products during its whole lifecycle. Examples of such areas are CO₂ emission, energy efficiency, recycling, and toxicity.

Most people have basic knowledge about edible mushrooms but know very little about the fungal workings underneath the ground. The mycelium is a fungal network of threadlike cells that spreads over large areas. The mycelium is essential for providing nutrition to the soil and a key element to the eco system (Stamets, 2005). One of the latest applications is to harvest the web-like growth of mycelium to bind organic material together (Holt et al. 2012). Growing fungus in proper conditions results in a material with properties similar to cement, engineered wood or plastic, depending on the manufacturing method. It is biological additive manufacturing, a combination of bio-engineering and additive manufacturing and the commercial use of Mycelium as a binding compound has been used since 2007 and have successfully replaced environmentally draining materials (Travaglini, Noble, Ross, Dharan, 2013). The extended use of mycelium would decrease global CO₂ emissions and the production of hazardous waste.

Semcon have conducted studies on electrically enhanced cargo bikes as a sustainable option to fossil fueled cars (S. Banér, personal communication, December 2015). They are forecasting cargo bikes to overtake extensive market shares in the forthcoming years and wants to investigate further improvements. One area of improvement is to reduce the ecological footprint by implementing sustainable materials in the design process.

1.2 Project stakeholders

The project is affecting Semcon and other product developers by researching and developing the mycelium materials. By implementing the material in products the knowledge is spread and can be used as a source of information for any designer who is interested in creating environmentally friendly products. Indirectly the study is affecting the cargo bike users offering a more sustainable product.

1.3 Project objectives and aims

The development of the material is stimulated by research and use in product design. By systematically researching the manufacturing process of mycelium materials and applicable founds on electrical cargo bikes, the project will contribute to the development of a sustainable option to fuel-based transportation. The environmental benefits of using the material are in accordance with the drive
behind the increased sales of electrical bicycles. The usage would further enhance the ecological message may be used as a sales pitch when marketing the product. By overcoming the difficulties of withstanding outdoor environment the implementation of mycelium will prove the applicability of the material in product design.

1.3.1 RESEARCH QUESTIONS
Research questions for the project are listed below. The project methodology and information gathering are designed to provide answers to the following questions:

**Primary focus (Mycelium Material):**
- How can Mycelium Materials be relevant for the field Industrial Design Engineering?
- How may product developers replace environmentally exhausting materials with mycelium materials without compromising on the material properties?
- How may mycelium material be implemented in industrial manufacturing process?
- What methods and compounds may be used to design and enhance the material properties?

**Secondary focus (cargo bike)**
- What parts could be replaced or added to cargo bikes using mycelium materials?
- How the product ecology is affected using mycelium materials?

1.4 Project scope
“Mycelium Biking” is the final thesis project for Master of Science in Industrial Design Engineering at Luleå University of Technology. The project is conducted at Semcon AB in Gothenburg over a 20-week period, is equal to 30 Swedish university credits and comparable to 800 working hours. The project should be considered an investigation on conceptual level. The final result is a “designer guide to mycelium materials” together with a product family for cargo bikes exploring the materials’ eligibility in product design. The concepts are presented digitally complemented with a physical prototype of one of the developed products.

1.5 Thesis outline
The study is divided in 7 chapters starting with this introduction. The following chapter presents the theoretical framework used in the study and how the scientific field is related to Industrial Design Engineering.

Process methodology and realization is presented in the next chapter under “Method and implementation”.

The succeeding chapter is the subsequent “Result & Final Result” containing for material data as well as visualizations and a “designers’ guide to mycelium materials”.

Last chapters are “discussion” & “conclusion” debating findings and further development. The research questions are answered and relevancy of the material evaluated.
2 THEORETICAL FRAMEWORK
The fundamental theory for this study is presented in the following section. The chapter describes how the scientific field is related to Industrial Design Engineering and then process different elements in the creation of mycelium material.

2.1 Industrial design
Simon (1996, p112) defines design as: “The process by which we devise courses of action aimed at changing existing situations into preferred ones.”
Friedman (2003) writes that industrial productivity is a requisite to meet the demands of a world inhabited by billions of people. Therefore, he claims, industrial design is affecting nearly everything we use or consume. In this perspective, the design process used by Industrial designers is the technical and social science on how to do things in order to accomplish goals. Friedman (2003) further adds that as designers take on increasingly important tasks, design now plays a role in the general evolution of the environment. Over the last decades there has been a shift in the view on environmental protection and sustainability in industrial design. Finkbeiner (2010) writes that the traditional approach on environmental technology is reactive and focuses on end-of-pipe solutions, meaning it is a separate process with post-manufacturing solutions. The modern approach on this matter is
proactive with sustainability integrated in the design process.

2.1.1 Eco design

Thoughts about environmentally friendly production emerged from the growing, understanding of the danger with pollution in the 1970s (Ben-Gal, Katz & Bukchin, 2008). It was not until the late 1990s that eco-design became a recognizable field with clear principles and guidelines on how to analyze the product lifecycle and how to achieve sustainable production and consumption (Thorpe, 2010).

Eco-design, or “sustainable product development” is defined by Wimmer, Lee, Kun-Mo, Polak & Springer (2010) as “an approach to designing products with special consideration for the environmental impacts of the products during its whole lifecycle. Examples of such areas are CO2 emission, energy efficiency, recycling and reuse, and toxicity (figure X).

Johansson (2002) states that while many of the success factors for integration of ecodesign are the same as for regular product development there are two areas which are specific to the integration of eco-design. These areas are competence and motivation and may be elevated through education and individual involvement/responsibility.

A poster summarizing EcoDesign and its relevancy for this project is visualized on a full page photo (figure 4).
2.2 E-biking in numbers

China dominates the global electrical bicycle market with an estimate of more than 40 million active units. (EBWR, 2013). Second largest is Europe with Denmark, Netherlands and Germany as the leading countries. The European market is still significantly smaller than the Chinese but is increasing rapidly each year. In 2014 over 1.3 million units were sold compared to 300 thousand units in 2008. (Bike-eu, 2016) (Figure 3). In Sweden roughly 50 000 units are sold each year but numbers are forecasted to increase greatly as Sweden being one of the highest ranked bike riding countries with almost 20% of the population using the bicycle every day (Cykelrapporten, 2014.)

Environmental impact
To motivate the use of Mycelium it is essential to have basic knowledge about the materials it is able to replace. The environmental impact of using cement and plastic is briefly presented below.

2.2.1 Cement
Cement production is responsible for approximately five percent of the global emission of CO² (Klee & Coles, 2004). The market is dominated by China who is responsible for more than half of the global consumption. There are alternative “green” solutions to regular cement and global actions have been made to lower the emissions. It has proved difficult to economically motivate the necessary changes, especially in developing countries, and the overall use of cement is increasing rapidly (Natesan, Smith, Humphreys & Kaya, 2003).

2.2.2 Plastic
Thompson, Swan, Moore & vom Saal (2009a) writes in an article named “Our plastic age” that in the year of 2009 the global use of plastic exceeded 260 million tones. The same article reports that the oil used to create this plastic accounted for four percent of the global oil and gas production and another four percent was spent to provide energy for their manufacture. In total the manufacturing of plastic is accounting for approximately eight percent of world oil production. Other environmental issues connected to the use of plastics are the waste management and leaching of chemicals from plastic products. The durability of the polymers is causing non-degradable debris in natural wildlife habitats and spreading toxic particles within their eco systems (Thompson, Swan, Moore & vom Saal, 2009b).
WHY ECO DESIGN

Ecodesign, or "sustainable product development" is an approach to designing products with special consideration for the environmental impacts of the products during its whole lifecycle. Examples of such areas is CO\textsuperscript{2} emission, energy efficiency, recycling and reuse, and toxicity. Modern product development is affected by a growing understanding of the ecological footprints caused by man. Awareness of the environmental pollution is pushing the search for new materials and solutions.

8 PERCENT OF THE GLOBAL OIL CONSUMPTION IS DERIVED FROM MANUFACTURING PLASTIC PRODUCTS

8 MILLION METRIC TONNES OF PLASTIC GOES INTO THE OCEAN EVERY YEAR

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Designers ability to integrate sustainability in the design process will have impact on the environmental evolution. The growing interest in alternative eco-friendly materials is reflected in product design. Industrial design is the communicating link between material science and the user and therefore essential for the expansion of the material.

Figure 4, EcoDesign Poster
Expanded plastic foams share many material similarities with mycelium materials. Their strength in relation to density makes the material ideal for lightweight and protective applications. The most commonly used plastic foam is polystyrene or “styrofoam” which produced using blowing agents to form bubbles in the material. The list of environmental issues related to the manufacturing and disposal of the material is long. The material is non-biodegradable and resistant to photolysis. Due to the low production cost, it is not economically defendable to recycle and collect Styrofoam and most material ends up taking up space in landfills or as plastic litter or debris in the ocean (figure 5). Worrel (2012) writes Styrofoam and EPP (expanded polypropylene) consumes as much as 25% of the total space in our landfills by volume. Other issues include the use of hazardous and environmentally exhausting components like CFC and HFC-143a.

2.3 Mycelium
This section presents basic knowledge about mycelium, how it grows and behaves. This is relevant information in order to understand the manufacturing process of mycelium materials. The mycelium is a network of threadlike cells that has the ability to spreads over large areas. It has the capacity grow several inches per day and contains enzymes that are essential for recycling dead materials and providing nutrition to the soil (Stamets, 2005). A mycelium network in eastern Oregon is said to be the largest organism in the world, spanning over an area as big as 1600 soccer fields and with an estimated age of 2200 years (Stamets, 2005). When the mycelium dominates a territory it bundles its nutritional resources together and begin the construction of the visible part of the fungus, the mushroom. Even though the mycelium does most of its working apart from the human knowledge it is vital to the ecosystem as we know it (Karimjee, 2014). When the mycelium binds biological matter they become natural composites. Two advantages of these natural composites include low cost production and lightweight abilities. These benefits makes it possible to claim the process of being carbon-neutral or even carbon negative if the biological matters has produced oxygen through photosynthesis during its life cycle (Travaglini, Noble, Ross & Dharan, 2013).

2.3.1 MYCELIUM MATERIALS
This section describes the current status of the research field, what leading companies there are and what kind of products they are offering. This is relevant in order to predict future application and increased use of mycelium materials.

2.3.1.1 History
The use of mycelium in creation of materials is a fairly modern invention. The first patent to be filed within this field was by Shigeru Yamanaka in 1989. His patent was about using mycelium to bond fibers into fabric or paper (Yamanaka, 1989). Since then there has been a number of studies within the area but is not until recent years that mycelium materials have received attention by media and designers. The reason behind the increased interest is mainly because of Eben Bayer and Gavin.
McIntyre, the two founders of Evocative Design. In 2006 they researched ways to use mycelium in order to create a biodegradable packaging material. The study resulted in the creation of Evocative, a company that has been receiving multiple design awards since their startup. They are now a major company offering a wide range of products made from mycelium. Another name that is often mentioned within this field is Phil Ross. He is an architect who researched the possibilities for mycelium materials. He is most famous for his mycelium bricks (figure 6) that he combines to create larger structures. In this process he lets the bricks grow into place bonding the blocks with mycelium to secure the structure (Duncheva, 2013).

Eric Klarenbeek is a Dutch designer who in the year of 2013 received attention for connecting a mycelium mixture to a 3D-printer. He managed to print living mycelium in combination with bio plastic to create a mycelium chair (Figure 7) that hardened over time (van den Haak, 2014).

2.3.1.2 Fungi species
The most commonly used fungal strains used for production of mycelium materials are Reishi and Oyster mushrooms. Jameson, Thomas & Williams (2014) claims that current research shows that Reishi mushrooms grow stiffer and stronger mycelium while Oyster mushroom grows faster.

2.3.1.3 Inoculating Mycelium
This section describes in steps how the mycelium is treated to create the materials. Knowledge about the process is essential to gain understanding about the limitations and possibilities for the material. The end result differs with the use of different fungi species, the biomass blend and density of the inoculated biomass (Jameson et al 2014). Both Evocative (Bayer & McIntyre, 2009) and Phil Ross (2012) have patents for their specific way of inoculating the biomass but in general the inoculation process follows the standardized pattern described below (Karimjee, 2014):

- Biomass is cut into desired particle size,
- Pasteurize biomass to make it inert.
- Blend fungi spawn with biomass with ratio 1:5
- Place blend in sanitized molds of desired shape
- Let the fungi colonize the biomass in dark humid conditions for up to 2 week
Holt et al. conducted studies in 2012 comparing twelve different inoculation methods, using six different particle sizes and two methods for inoculation via a liquid or a solid substrate. He found the use liquid substrate was easier to implement and also resulted in more uniform growing. Regarding particle size, he did not manage to establish a clear relationship between size and resulting mechanical properties.

2.3.1.4 Current Mycelium Composite application

Depending on what properties and characteristics that is sought after the inoculated biomass may be treated in different ways. The following texts present different mycelium materials and how to create them.

Common for most application is to render the part inert once the required degree of mycelium growth on bio-matter is reached. This may be done at different temperatures and the goal is reduction of moisture content from 60-65% to 10-20% (Travaglini et al. 2013. & Evocative GIY, 2014). It has been proved possible to reach this moisture level using solar dryers which lowers energy needed for the drying process. This further enhances the ecological benefits of using mycelium by lowering the materials total life cycle energy input. A poster visually demonstrating the different applications is presented as Figure 10.

2.3.1.4.1 Mycelium foams

A foam is defined by Travaglini et al. (2013) as a three dimensional array of cells forming a cellular solid, such as cork, polyurethane foam, or bread. Mycelium foam is the most commercially incorporated application of mycelium with Evocative as the leading manufacturer (Lefteri, 2014). The mycelium foams are created by baking the inoculated biomass yo render the mycelium inert (Evocative GIY, 2014).

Travaglini’s et al. (2013) study on mycelium foams found that the strength of the material correlated to the moisture level in the foam. There is negative correlation between both tensile and compressive material strength and moisture level in the material and he suggests the use of coatings to decrease moisture diffusion. Bayer and McIntyre’s (2009) patent claims the same correlation and adds that the elasticity increases and elastic modulus decreases with the moisture level.

Publications by Pelletier et al. (2013), Travaglini et al. (2013) and Holt et al. (2012) all reach the conclusion that mycelium foams may serve as replacements for traditional plastic foams for applications including insulation, packaging (figure 8) and acoustical tiles.

Figure 7, Mycelium Foam - Wine Shipper. Photo: Mycomade

2.3.1.4.2 Mycelium Sandwich Panels

Sandwich material are created using a core material with low density and modulus in comparison to the material used for its skin. In theory the skins will carry the bending momentums while the core carries the transverse shear force (Harte, 2000). The material properties of uncompressed mycelium material correspond well to the requirements for core material. In Travaglini’s (2013) study the mycelium foam had a compressive strength almost three times the tensile strength. The low density and specific compressive strength makes it a sustainable option as the core of sandwich materials. Travaglini (2013) also suggests to use it in combination of fiber-reinforced skins made from eco resins in order to further enhance the ecological message.
2.3.1.4.3 Mycelium Bricks
Phil Ross created the first building entirely made out of mycelium using grown bricks. His installation was named “Mycotecture” and made from Reishi mushroom and bio mass (Fisher, 2010). The installation resulted in Philip filing a patent for the making of the mycelium bricks (Ross, 2012) (figure 9). The bricks are grown under compressive pressure and with small sized particles. This allows the density of the material to grow higher and enhances the material's ability to withstand dynamic forces. In his patent he claims the compressive strength to be 6 times higher over non-compressed, and flexural strength doubled (Ross, 2012). The manufacturing process is explained in full in his patent. Another successful project using mycelium bricks was done by architect David Benjamin in 2014. He built a 12-meter-high structure consisting of 10 000 bricks in collaboration with Ecovative (Arthur, 2014).

[Image 8, Mycelium Brick made by Mycotecture. Photo: Phil Ross]

2.3.1.4.4 Mycelium boards
Evocative is constructing mycelium boards with material properties similar to commonly used engineered wood. This is done by compressing inoculated biomass under heat and high compressive pressure. Customizing molds makes it possible create complex shapes and the benefits of using this material instead of regular engineered wood is that its adhesive-free, environmentally friendly, VOC Free and Class A Fire Rated. (Myco board, 2014)

2.3.1.4.5 Grow It Yourself (GIY)
Ecovative are selling bags of dehydrated mycelium inoculated cornstalks since 2014 (Ecovative GIY, 2015). The dry condition keeps the mycelium in hibernation and is reactivated by adding water and flour to the bags. The reactivated mycelium can be treated and placed in custom shaped molds made by the user. This allows designers from all over the world to experiment and research mycelium materials without having to perform the complex inoculation process themselves.

2.4 Sustainability of Mycelium material
Sustainability within product development is an evolving field. There are still some issues connected to the measuring of sustainability but one the more commonly used methods is Life Cycle Assessment (LCA) (Ullman, 2013). LCA is measuring the environmental impact related to various phases of product life, often called cradle to cradle. Evocative made an LCA in 2013 on their mushroom packaging material receiving following results: The production of 1m³ of material uses 652 MJ and releases 31 kg of CO₂ (Burzynski, 2014). Notable concerning these numbers is that drying of the products was shown to contribute over 50% of the entire life cycle carbon footprint. Another key feature in terms of sustainability connected to the usage of mycelium materials are local procurement, the bio-waste used as feedstock can be harvested locally regardless of where the product is manufactured. Resulting products are biodegradable and home compostable and meets ASTM standards (Ullman, 2013). This eliminates costs for the product end-life transports and landfill space and provides energy to the soil instead.
WHAT IS IT USED FOR

Figure 9, Current Mycelium Material Applications

FURNITURE
BRICKS
PACKAGING
TABLEWARE

ACOUSTIC INSULATION
LIGHTING
SURFBOARDS
TEMPORARY STRUCTURES
3 METHOD AND IMPLEMENTATION

Every topic describes the methods and techniques used in the specific phase and why they are relevant to the project. The relevancy and origin of the process theory is explained and the different phases are presented according to the order in which they were applied. The project implemented an IDEO process model along with consequential gates that needed to be fulfilled before initiating the next project phase. Figure 10 visualizes the project phases and methods used in the specific area.

![PROJECT PROCESS](image)

Figure 10, Design process overview

3.1.1 Process theory

A structured process is desirable in order to keep the project development generative, iterative and sharp (IDEO, 2016). The process used in the master thesis project is an alteration of the process defined in IDEO field guide for human centered design (2015). The project moves through three main phases: Inspiration, Ideation, and Implementation. Because of the high degree of scientific implementation in the project, methods and definitions was altering slightly from the toolkit instructions in the sense of being less human centered and more experimental in its nature. However, the general process methodology and purpose of the individual phases were similar and defined as follow.

**Inspiration**
- Understand the challenge
- Prepare research
- Gather inspiration
- Acquire current status
- Frame opportunities

**Ideation**
- Generate ideas
- Refine ideas

**Implementation**
- Realization
- Iteration
- Evaluation
Each phase had a well-defined “gate” that needed to be fulfilled before entering the next project phase. Stage Gate models are well established within product development and are being used in various ways (Wynn and Clarkson, 2005). The gate consists of criteria and is a useful tool to validate the project time schedule and progress. Cooper (2014) argues that the method often is used in overly strict manner limiting the creativity. The conceptual level of the project made it the possible to adapt a more flexible attitude towards the criteria and, by doing so, avoiding the negative effects defined by Cooper (2014).

### 3.2 Project planning

The initial phase of the project included planning and structuring. This was done in order to set up reasonable goals and to ensure they were reached within the time frame of the project. A Gantt chart was created to get visual overview of deliveries and the different phases. A Gantt chart is a tool for visualizing the planned time disposal. It is used to map activities and time against each other in order to describe the project timeline. The duration of different activities is visualized as horizontal lines that correspond to the timeline. (Johannesson, Persson and Pettersson, 2004) The chart provided structure and acted as a guideline throughout the project. The chart also visualized different stage-gates in the project (figure 11).

In order to set reasonable goal and share perspective the project objectives and research questions are developed in collaboration with both supervisors at Semcon and Luleå University of Technology.

![Figure 11, Gantt chart, Mycelium Biking](image-url)
3.3 Inspiration
The purpose of the phase was to collect knowledge upon which further work can be based. A comprehensive information gathering decreases the risk of design mistakes and overlooked issues. The information gathering was not secluded to initial project phases and data collection continued throughout the project to ensure decisions were scientifically grounded. The methods used in this phase are visualized in figure 13.

3.3.1 Literature review.
The goal of a literature review is to acquire the current state of knowledge (Bohgard, et al., 2008). The review conducted in this study covered relevant research fields such as mycology, mycelium materials, composites, bio-resins, electrical bikes and eco design. These areas were initially researched on a broad perspective but deepened as the project developed and the need for additional information was discovered.
To secure reliability in the collected data peer reviewed sources were used in the highest possible extent. Due to the novelty of the researched material there is limited availability of studies conducted within the area. This becomes obvious when searches “ecovative” and “mycelium material” on the extensive publication database Libris provides 7 respectively 2 peer reviewed matches. As a result, most information regarding the material was collected from commercial articles and the manufacturers’ websites.

3.3.2 Interview
In general, an interview is a communicative exchange between two people in which the interviewer gains information from the interviewee. The interviewer may ask predetermined questions in a specific order or ask questions more freely. The different
techniques are defined by Jordan (2000) as Structured interview, Semi-structured interview and unstructured interview, depending on how strict the questions are asked. The reason for conducting interviews is to provide the researcher with valuable qualitative information (G. Jarratt, 2015). According to Jordan (2000) there is less room for misinterpretation in interviews in comparison to questionnaires and by administering the interview directly to the participants the questions can be explained further for greater understanding among the participants. Since the material is continuously undergoing development, thesis student established contact with the leading researchers in the field to acquire the current status of knowledge. These interviews complemented the literature review and were essential to get hold of the unpublished expertise of the leading companies. This also proved important in order to prevent the research from being a replicate of the contacted companies own research.

The contacted companies were: Ecovative, Mycoworks & Fungi perfecti. The first two are manufacturers of mycelium material who are currently researching new applications for the material. The last one, Fungi perfecti, is a company started by Paul Stamets that specializes in selling mushroom cultivation tools. Paul Stamets have written several books about mycology and have been awarded innovation ambassador by AIIN (Stamets, 2006)

The companies were located in the United States which prevented the possibility of meeting in person. The interviews were conducted through emails and started with a set of predetermined questions (appendix 1) regarding the subjects:

- Mycelium Growth
- Support Materials
- Skins
- Mycelium Species

The questions were complemented with pictures from the first material testing session in order to get visual understanding. The interviews then continued with follow up questions depending on the individual answers.

3.3.3 Workshop - Bio composites in Cars

Another knowledge developing activity was participation in a workshop about bio composites in vehicles at textile fashion center in Borås. The workshop was organized by LIGHTer (figure 14), a cross-industry lightweight collaboration that works for the development of lightweight materials in Swedish industries (Lighter, 2013). The workshop consisted of talks and discussions about relevant topics. Participants presented their latest research and how they worked to reduce the ecological footprint by reducing weight and implementing biological materials in their products. The workshop provided insights in how the industry is working with ecodesign and what to expect in the future. The workshop highlighted issues with using organic materials and necessity for solving them in order to meet the global demands for ecological production. Samples of mycelium material were brought to the workshop and shown to participants in order to get recommendations on the project approach.

Figure 13, LIGHTer Logo. Photo: Lighter area webpage
3.3.4 Next step for cargo bikes
Semcon was conducting a study about the future use of electrically enhanced cargo bikes during the same time period as the thesis project. As the project aim for “Mycelium Biking” was to implement mycelium materials onto cargo bikes, I took use of the results from this study. Since the study investigated the user needs for electrical cargo bikes, the results proved valuable in the evaluation of what part to create in “Mycelium Biking”.

3.3.5 Benchmarking
Benchmarking is used to get comprehensive knowledge of possibilities and what solutions others are using. Stephen A.W Drew (1997) writes Benchmarking is applicable in multiple fields and the goal is to concentrate the attention towards the most interesting and notable solutions for the specific task. J. Main (1992, p. 104) defines the method with the following sentence: “The art of finding out, in a perfectly legal and aboveboard way, how others do something better than you do, so you can imitate-and perhaps improve upon-their techniques”.

In Mycelium Biking benchmarking was used in order to be inspired from other Eco-materials and study how they are implemented into product development. Benchmarking also proved valuable for identifying strengths and weaknesses by studying plastic competitors like Expanded Polypropylene and Styrofoam. Material samples were ordered from “3A Composites” that specialize in core materials and sustainable sandwich constructions. These samples were used to evaluate the mycelium material by comparing material properties and manufacturability. Ecological properties were collected for competitive materials in order to make fair evaluations. The retrieved parameters were: Feedstock, Energy consumption, CO₂ emission and disposal. All areas are well-defined within eco-design (Wimmer, Lee, Kun-Mo, Polak, & Springer, 2010) and the result was presented in tables.

An LCA-tool, Eco-indicator 99, was used in order to compare competitive materials with mycelium materials. The Eco-99 can deliver indicator values for a large number of frequently used materials and processes (Ullman, 2013). The result of the selected combinations is presented as an “indicator” calculated from data in mili-points (mPt). The tool can only be used for comparisons since the scoring is dimensionless.

3.3.6 Material testing
In order to acquire practical knowledge about the material, the material was tested in two stages. Both tests were done using Ecovative’s GIY as a base material and grown according to the Instructions & safety document (Ecovative GIY, 2015). The GIY material specifics are presented in figure X. By using GIY, the inoculation of substrate is outsourced and the result more unison due to the experience and tools owned by Ecovative. The quality of the tests was standardized which makes it easier to evaluate the results. The reactivation process of the GIY is visualized in figure 14. The reactivated mycelium-substrate mixture was broken up and put into molds where they were left to grow in a dark and humid environment until completely colonized.
3.3.7 Material Test Session 1

The initial testing was done using box shaped molds of different dimensions (figure 16, molds). These parts were made in order to get hands-on feedback on the material properties and to examine the behavior in different densities and in combination with other materials. Design engineer Stefan Banér at Semcon, experienced in composite and lightweight materials, assisted with knowledge about ways to enhance the material properties by adding other compounds. Both organic and inorganic support materials were tested to examine adhesiveness of mycelium. The support materials tested were: flax fiber, carbon fiber, vectran, composite breather and glass fiber.

The parameters tested in the first test were:
- Density
- Support material
- Air supply
- Adhesion
- Fiber direction
- Nutrition
The parts were evaluated by measuring the structural abilities in correlation to material combinations and dimensions. The parts were cut in order to analyze the cross sections and mycelium growth with a microscope. The microscope had a magnification capacity of 200 and pictures of parts were sent to Ecovative in order to get experienced researchers to comment on the results and pose recommendations for the next test.

### 3.3.7.1 Material Test session 2

The result from the first tests served as a foundation for the next tests that further investigates the structural ability of the material in dimensions suitable for measuring material properties (Figure 17). 3D-printed molds with dimensions defined in ASTM D638 were created using CAD. The molds were made in regards to the shrinkage measured in the first material testing. The parts were weighed before baked and weighted again every half hour in order to systematically observe the moisture level in the part. According to GIY instructions parts are finished when 30% of the original weight is measured.

![Figure 16. 3D printed molds. photo: Alexander Wagner](image)

The parameters tested in the second test were:

- Growth time
- Skins/laminates
- Substrate size
- Oxygen supply
- Coffee grounds
- Epoxy adhesion

In order to examine these parameters, the following parts were created:

1. Reference part. Dim: 20x 8 cm, Thickness 12mm
2. Grinded substrate. Dim: 16x 8 cm, Thickness 12mm
3. Flax skin (one side only). Dim: 20x 8 cm, Thickness 20mm
4. Organic veneers (Balsa wood). Dim: 20x 8 cm, Thickness 20mm
5. Coffee grounds 1:10. Dim: 14 x 8 cm, Thickness 20mm
6. Tensile test ASTM D638 Type III
7. Tensile test ASTM D638 Type III supported with flax
8. Compressive test ASTM D1621. 8x8cm thickness 30mm
9. Detailed part (see figure 18 for dimensions)

![Figure 17- Detailed part for material testing session 2. Photo Alexander Wagner](image)

The parts were evaluated by comparing parts with competitive materials (see benchmarking) and again analyzing mycelium growth using microscope. Material tests were conducted at the material lab facility at Luleå University of Technology in order to get factual numbers on the properties. The tests were made according to apparatus and dimensions defined in ASTM D638 (Standard Test Method for Tensile Properties of Plastics) and ASTM D1621 (Standard Test Method for Compressive Properties of Rigid Cullular Plastics).

### 3.3.8 GATE

The information gathering was summarized by visually presenting the compiled data on posters. This way of communicating information made it easy to forward the results in an interesting manner. The posters were also used as tools in the following project phase as a source of inspiration for innovative work.
3.4 Ideation
In this phase results from the information gathering was applied in a conceptual design process. A range of methods (figure 19) were used in order to identify a suitable part where the material may be implemented. The collected material data is evaluated against the identified needs in the project “next step for cargo bikes” to examine possible solutions. Creative methods such as workshop, different brainstorming techniques and scamper were used to get a divergent range of possible solutions. The phase resulted in selecting what part to create and different concepts on how it may be constructed. The selection was made using differing evaluation methods in collaboration with users and supervisors. The work is complemented a list of requisites for the part that is to be created. The list is essential in order to evaluate whether the final product.

3.4.1 Moodboard
A moodboard was created in order to communicate intangible values and underlying demands behind sustainability in product design. Baxter (2005) says moodboards are used to describe different situations and may act as a tool to steer the work in the right direction. The moodboard was later shown to participants in the concept development phase and used as a basis of discussion and innovation.

3.4.2 Design Workshop
The method is defined by Wikberg Nilsson, Å., Ericson, Å. & Törlind, P. (2015) as a creative meeting where people gather to explore a certain topic. The participant does not have to belong to the
target group or have any prior knowledge within the field. The participants examine a particular subject using altering methods. The goal is to use collaboratively discover opportunities and gain deeper understanding of the issues using the creative potential within the group.

Early in the ideation phase, a workshop was organized at Semcon to kick start the concept generation and to gain perspective on the task (figure 20). Employees at Semcon were invited to partake in the discussion. Thesis student Alex acted as facilitator throughout the whole session and made sure the discussions were relevant. The workshop was introduced with presentation of the previous phase using posters and parts from the material testing and benchmarking. Discussion about the hierarchy of needs and possible solutions followed. Methods Brainsketching, Scamper and Dark horse were used in order generate concepts.

The term brainsketching was first mentioned by VanGundy (1988), describing it as a visual technique developed by his students. The participants start by sketching solutions to a specific problem individually on papers. After a few minutes, they briefly share their solutions and switch papers within the group. The participants then continue sketching with the existing sketch as a source of inspiration. According to R. van der Lugt (2002), brainsketching provides qualitative results with good links between the ideas.

The brainsketching session conducted in the project somewhat altered from classic brainsketching in the sense that switching of paper was replaced with discussions. The method was done by thesis student and employees at Semcon (6 participants) during the workshop. They used the workshop discussions about needs as a basis for the sketching. The participants sketched on templates with semi-transparent pictures of the Livelo cargobike to simplify dimensioning and perspective (figure 20). Every participant made one concept for each of the following topics:

- How many/which needs is possible to combine in one concept?
- A concept using the high tech solutions to meet needs (projected gps, voice control etc)
- A concept with innovative placement of lights and/or speakers (blinkers, head lights, cargo
- Lights, theft alarm, horn, music)
- A concept with innovative storage/loading solution
- A concept using the soft properties of mycelium material.
- A concept using the structural properties of mycelium material.

3.4.3 Brainsketching
Brainsketching is a technique that uses collective sketching to generate solutions.
Each round was approximately five minutes long, followed by two minutes of presentation of the results. The group then discussed the produced concepts for every topic and sketched alterations and combinations collaboratively. The procedure was replicated for every topic and resulted in 30 papers filled with ideas. The method ended by further discussing the sketches and each participant got to choose a favorite concept.

### 3.4.4 Dark horse

The name “Dark Horse” origins from horse racing where the term “dark horse” implies an uncertain horse with high odds, meaning it is likely to lose but with great reward if winning. In product development a dark horse is a concept with daring, radical and often impossible suggestions on how to solve the problem (Wikberg, Ericson, & Törlind, 2015). This was done in order to widen the range of solutions (concept pool) and to help participant to “think outside the box”. The generated dark horse-concept rarely provides the final solution but may spark ideas.

During idea generation the dark horse method was used to trigger new creative energy into participant. The participants were asked to pause the current method and instead sketch a concept according to specific prerequisites. Example of such prerequisites used were:

- “How would a concept look according to premise:
  - … 50 years into the future?”
  - … Crazy expensive?”
  - … For kids?”
  - … Using living material?”

### 3.4.5 Scamper

This method was used in order to further develop the concept generated from brainsketching and workshop discussions. The method is founded by Bob Ebelre and combinations collaboratively. The procedure was replicated for every topic and resulted in 30 papers filled with ideas. The method ended by further discussing the sketches and each participant got to choose a favorite concept. The questions are designed to alter the perspective upon which the concepts are perceived in order to make sure the concepts meet the needs in a satisfying manner. (Wikberg Nilsson, Ericson & Törlind. 2015). All concepts were clustered and laid down on the workshop table. Participants of the workshop developed concepts individually and collectively by combining concepts from different cluster groups and asking following questions:

- Substitute?
- Combine?
- Adapt?
- Modify?
- Reverse?
- Put to other use?

During the following discussions the total amount of concepts was narrowed down to six concepts chosen for their qualities and degree of innovation.

### 3.4.6 Dot Voting

Dot Voting is an evaluation method that is useful in order to get a perspicuous view of concepts and to sort out unsatisfactory ideas (Wycoff, 2004). All participants get a predetermined amount of votes. The voting is conducted using post-its of different colors to mark which concepts are preferred. The colors represent different values or characteristics found in the
concepts. For example, dot voting may be used in combination with the previously mentioned dark-horse method where crazy or impossible concepts are noted for their qualities as leverage to viable solutions (Wikberg-Nilsson, 2015).

Dot voting was used to evaluate the concepts on a general level. A selection of 6 concepts was used for this method. Thesis student positioned himself alongside the Livelo Cargo bike outside the semcon dining area and stopped lunch guests on their way to the cafeteria and asked them to partake in the dot voting. Participant received one blue colored post-it worth 2 points and one yellow colored post-it worth 1 point.

3.4.7 Design format analysis
The method may be used as a tool for analyzing different design elements of various concepts. By using a structured matrix, the concepts are scored in accordance with how well they correspond to the defined values. The results provide understanding of weaknesses and strengths from a perceptual viewpoint and enables numeric comparison (Warell, 2005). The format analysis was conducted together with product developers at Semcon in order to ensure reliable results.

The areas of value used in this project was
- Usage of material abilities
- Novelty/innovation factor of product
- Visibility of product
- Excitement

These areas were chosen because of how they correlate to qualities sought after in final product and their relevancy to the project scope.

3.4.8 List of requisite
Johannesson, Persson & Pettersson (2013) writes that it is beneficial to construct a list of requisite in order to clarify goals and assure satisfying deliveries. They further add that the list should be constructed so that the included content may be used as a foundation in the search for designs and constructions as well as a tool for evaluation the final solution.

The list created in this study was twofold with one list defining the material requisite with focus the mycelium material. The other list defined product functions and requisite on implemented technology.

3.4.9 GATE
The phase was finalized by defining what concept was to undergo further development. The selection of concept was done in collaboration with supervisors at both Semcon and Luleå Technical University with the result from evaluation methods as a foundation. The chosen concept was complemented with the list of requisite.
3.5 Implementation
The implementation phase was focused on visualizing and finalizing all product concepts (figure 21). Most effort were put into the the creation the final prototype for chosen the concept. The detail design work started in a diverging manner using prototyping and CAD to experiment with alterations of the selected concept. Prototyping allowed experimental testing of function and shape and was used in both digital and physical forms. Additional material testing and converging evaluations was conducted before deciding on a final appearance.

3.5.1 Rapid prototyping
In order to experience sketched/discussed shapes it is useful to create simple physical models. These models are used to aid communication and creative work. It may be used to generate ideas and to establish shared perspective on the problem. (Wikberg-Nilsson et al., 2015 Michael Schrage says the following about prototypes in his book Serious Play (2000, p.20):

“The value of prototypes resides less in the models themselves than in the interactions - the conversations, arguments, consultations, collaborations - they invite”.

Rapid prototyping was used to test and compare different techniques of manufacturing molds and to evaluate tolerances and geometries for mycelium
parts. Test parts was designed in order to reach conclusions regarding how to deal with shrinkage and coatings. The different mold manufacturing techniques tested was 3D-printed molds and was vacuum pressed molds.

**Vacuum press**
The vacuum pressed molds (figure 23) were created in the Luleå University of Technology prototype lab by working foam into desired shapes and used as a plug. Based on one of the sketches from “scamper” during ideation (figure 41, top left corner), parts were created in order to evaluate vacuum pressing as a manufacturing method for mycelium material. The vacuum press at Luleå technical university malfunctioned during the time of manufacture so a hot air gun was used form the plastic sheets instead. The quality of the mold was affected but considered to be good enough” for the experimental testing. The parts were mirrored reflections of each other which allowed comparative evaluation.

![Figure 23, Molds for prototyping](image)

**3D-printing**
The 3D printed molds were created in CAD and printed using PLA-plastic- PLA is made from renewable recourses and naturally biodegradable. (Drumright, Gruber, & Henton, (2000). Experimental prototyping with 3D-printed molds had already been done in early material tests (see “detailed part”, material test session 2) but was further investigated using CAD geometries from the final stages of ideation (figure 43).

3.5.2 Function & technology
The list of requisite catalogs functions and technology that is housed by the selected concept. The created prototype is created on conceptual level with focus on demonstrating the mycelium material and therefore, most functions and electrical components are just demonstrated theoretically. The implementation of these function was validated by presenting existing solutions using the same technology proving the feasibility.

3.5.3 CAD & Evaluation
With gained knowledge from material experimentation and rapid prototyping, detailed design work on the selected concept was initiated. Different concept was first sketched and then constructed in 3D to get a better sense of volume and dimensions. The concepts were constructed in regard to the limitations of mycelium materials, manufacturability and aesthetics. The visual expression of the Livelo cargo bike was analyzed in order to create concepts with high sense of belonging. The concepts were validated against the list of requisite and evaluated with expert consulting using the in-house competence at Semcon. Experienced Industrial designers posed their opinions from an aesthetic viewpoint whereas mechanical engineers help solving structural issues.

**Material testing**
Additional material testing was conducted in order to test different manufacturing techniques and specific properties used in the product concepts. Tests also included coloring and coat finishing. Coloring was tested using natural dyers, charcoal and coffee. These test were conducted as the parts needed to darken in order share the same visual expression as the Livelo cargo bike.
A simplified version of the European standard test for helmets for pedal cyclist (EN1078) was done to prove the concept claims. The test was done using 2 x 2kg weight, fastened on a mycelium part with dimensions: 10x10x3cm, that was dropped onto concrete flooring through guided free fall reaching an impact velocity of 5,5m/s (figure 24). The impact was analyzed using a high speed camera and deceleration was measured by calculation of distance traveled after impact. To meet standard criteria, peak deceleration must be less than 250g.

**Manufacturing**

The physical prototype was made solely using 3D-printed molds and parts. This was due to lack of a vacuum press in the manufacturing facilities. The molds were created in PLA plastic using a Makerbot 3D-printer. The five mycelium parts were left to grow for 12 days before rendered inert through baking at 90°C until weighing 35% of original weight. The parts were colored using coffee to get a dark surface finish. In order to prevent moisture diffusion, epoxy coating was applied in thin in layers and sanded in order to get a smooth surface.

**Visualization**

All product concepts were constructed using the software SolidWorks on top of a digital representation of the Livelo bike. This was done in order to ensure proper dimensions and to demonstrate functions. The products were rendered using Keyshot 3.5.4 GATE

The phase ended with presenting the final results. Found and knowledge about mycelium materials was demonstrated in the form of a guidebook but also through presenting the product concepts for the Livelo cargo bike, both visualizations and the physical prototype.
4 RESULTS
This chapter is a collection of the research results gained from using the methods described in the previous chapter. The findings are presented in the order they were received and clustered in regard to the different project phases.

4.1 Inspiration
The following chapter reports the results following the methods used in the data collection and analysis-phase. The gate was reached by visual summarization of compiled data in the form of posters.

4.1.1 Literature review
The factual part of the literature review is presented in the theoretical framework. The review was summarized in an explaining poster describing the research field. The poster proved useful as an academic tool when communicating the project and is presented below (figure 23).

4.1.2 Interviews
This section is a summary of the answers to the semi-structured interviews provided by Emily (Director of First Impressions at Ecovative) and Sophia (Mycoworks). Answers are categorized in different areas listed below.

Mycelium growth:
- Growing at higher density will increase the strength of the composite.
- Adding small amounts of substrate like coffee (nitrogen) grounds to GIY bags have had good results.
- Evocative thought my samples looked “dry” and that I should experiment with growing in more humid environments

Support Material:
- Ecovative have had good results letting mycelium grow around plywood base
- Mycoworks have used bamboo and hemp as support material

- Both companies claim it is essential with adhesiveness between support material and mycelium and therefore organic materials are preferred for this purpose
- Any material would need to adhere to or be fully encapsulated by the mycelium to lend any support to the GIY.

Skins
- Using organic skins like bamboo veneers eliminates the need of glue
- Both companies have had good results using sandwich structures with interior and exterior skins

Mycelium Species
Different fungal species will feature different mycelium properties. MycoWorks are public about using Reshi in many of their formulations. Ecovative sometimes use different strains for different purposes. However, the name of the strains they use is a trade secret protected by their patent

4.1.3 Material testing
The following section presents the results and conclusions from material testing sessions 1 & 2.
**MYCELIUM MATERIALS**

- Eco design at its best

Product design is affected by a growing understanding of the ecological footprints caused by man. Awareness of the environmental pollution is pushing the search for new materials and solutions.

Most people have basic knowledge about edible mushrooms but know very little about the fungal workings under the ground. Mushrooms are only the fruit of a larger organism that is called mycelium. The mycelium is a fungal network of threadlike cells that spreads over large areas. The mycelium is essential for providing nutrition to the soil and is a key element to the ecosystem.

Engineers have now discovered a way to harvest the web-like growth of mycelium to bind organic material together. Growing the fungi in proper conditions will result in a material with properties similar to both cement, engineered wood and plastics.

The use of mycelium as a replacement for environmentally damaging materials will reduce the consumption of energy and fossil fuels. The long-term goal for this field is to decrease global CO₂ emissions and the use of hazardous materials.

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**HOW**

By letting mycelium colonize agricultural waste is a natural line we are binding the organic matter together. This process is called inoculation and takes 2-3 days.

The inoculated substrate is chopped into small pieces. Additional nutrient air is added and the substrate is placed in molds. The material is left to grow for another 6-8 days.

The material is removed from the mold and dried. Heating the material to 90 degrees will render the fungus inert and stiffen the material. The result is a strong, biodegradable product with great ecological qualities.

---

**WHY**

Eco design or "sustainable product development" is an approach to designing products with special consideration for the environmental impacts of the products during their lifecycle. Examples of such areas are CO₂ emissions, energy efficiency, recycling and reuse, and toxicity.

Mycelium materials aim to replace traditional use of plastic and possibly even cement. Cement production causes 5 percent of the global CO₂ emissions and plastic manufacturing is responsible for 10 percent of the global oil and gas production.

Other environmental issues connected to the use of plastics are the waste management and leaching of chemicals from plastic products. The suitability of the polymers is causing non-biodegradable debris in natural wildlife habitats and spreading toxic particles within their ecosystems.

Mycelium materials are biodegradable, their process carbon-neutral and will fertilize soil in the end of their life cycle. Sustainable design at its best.

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**WHEN**

The leading company within this field, Ecovative Design, already have a large scale manufacturing of their Mycelium Foam with customers all over the world.

The material is undergoing an extensive development process and new applications are being researched consistently. The potential for this material is undeniable, the question is how easy it is to penetrate the existing market.

Additional research and successful projects is probably needed before mycelium material may overtake substantial market shares from the materials it aims to replace. With this said, it’s still thrilling to think that in the near future we will have the possibility to grow our own houses and furniture.

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Figure 25, Poster literature review. Made by: Alexander Wagner
**Test session 1**

Session fundamentals:
- Base material: Ecovative GIY
- Support materials: Flax, Carbon fibre, Diolen, filt & glass fibre.
- Added nutrition: Wheat and instant coffee
- Amount of tests: 12 bricks of different size and thickness

**Tested parameters:**
- Growth time
- Density (pressure)
- Moisture
- Adhesion
- Baking time
- Added nutrition
- Geometry size
- Air supply
- Mold materials
- Epoxy molding
Figure 26 is a collage of selected pictures taken during test session 1. Due to inexperience with working the material nine out of 12 test bricks were baked (meaning the mycelium growth halted) too early resulting in inhomogeneous growth with most mycelium growth secluded to edges of the material. The phenomena is illustrated in figure 26. This had a negative effect on the material properties and made it difficult to certain evaluate parameters tested with these parts. The three parts that were left to grow longer showed great potential and better material properties. Notable is that the parts in question were left to grow 3 times longer than recommended by the reseller of the material. Figure x is a comparative picture taken with magnitude 20 in the center of two cross section. The left is grown for 17 days and the right one for 7. The mycelium growth in the left one is apparent and is almost crystal-like in its nature. The sizes of the chips are remarkably smaller than in the left one suggesting a substantial break down by the mycelium.

Conclusions from Material Session 1

- Non-organic support materials are discarded due to low adhesiveness
- Added nutrition is not improving mycelium growth
- Added moisture doesn’t seem to improve mycelium growth, quite the opposite.
- Hard to evaluate small geometries
- Small geometries more vulnerable to defects due to the organic growth.
- Stiffness increases with baking time and decreased moisture level
- Possible to use 3D-printed molds
- Epoxy coating is possible to do in the same mold as the part due to shrinkage of 5% (figure 29)
Test session 2
Session fundamentals:
Base material: Ecovative GIY
Support materials: Flax fiber, epoxy, balsa wood & gelcoat
Added nutrition: Wheat and coffee grounds
Amount of tests: 9

Tested parameters:
- Growth time
- Skins/laminates
- Substrate size
- Oxygen supply
- Coffee grounds
- Epoxy adhesion

detailed part was created to evaluate the ability to mold small features, sharp edges and surface detail level. Figure 29 visualizes the rupture of the part as an effect of molding thin holes in the part.

Test session 2 turned out unsatisfactory. Five out of the created parts were contaminated early in the growth phase which inferred with the mycelium growth (figure 28). The cause of contamination was either due to the organic support materials used or due to contaminations introduced by the instruments used in the manufacturing. The parts never developed homogenous mycelium growth in the core and received bad material properties as a result. The parameters tested in these parts still needed more investigation since the bad growth made it impossible to evaluate the parts fairly. Luckily the parts that were created for testing the material properties were not contaminated (figure 31) and were tested at the Luleå Material testing facility.

The detailed part (figure 32) experienced contamination on the upper surface but analysis of cross section revealed no inference with mycelium growth. Property-wise the part seemed unaffected by the contaminations as a contrary to other parts. It is likely due to the fact contaminations appeared late in the growing phase. The

Figure 30 Contaminated part, organic sandwich test. Photo Alexander Wagner

Figure 31, Cross section of contaminated part. Photo: Alexander Wagner

Figure 32, Surface contaminations on detailed part. Photo Alexander Wagner
Conclusions from session 2

• Organic support material may be bearers of contaminations and it is advised to soak them in anti-bacterial solution before used.
• Grinding substrate makes the part more vulnerable to contamination
• Small geometries in molds make it difficult to release part from mold.
• Coffee grounds seem did not improve mycelium growth (Part contaminated, may be the cause of bad mycelium growth)

• Adhesion between organic veneers and biomass is good and does not need additional glue to stick.
• Thin geometries are more vulnerable to shrinkage deformation.
• Oxygen supply does not seem to have any particular effect on mycelium growth.
• Broken parts can be healed/grown back together if kept in humid conditions

Testing of Material properties
The following section presents the material data received from the tests conducted composite testing facilities at Luleå technical university
The chart (figure 34) visualizes the Stress/strain relation during the conducted tests. The flax-fiber supported specimen (represented by the red curve) performed slightly better than the regular. By analyzing the curve it is possible to assume that the flax fiber did not lend support to the part until very end of the elongation phase. The peak value (tensile strength) for both specimens was measured to approximately 1MPa and the elastic modulus was extracted by calculating the mean incline in the linear phase (Strain: 0.01 to 0.05). The mean modules resulted 15,6MPa respectively 19,2Mpa. The measured properties are presented in relation to comparative materials under benchmarking. The specimens used in the tensile test were bone shaped in order to control were the rupture would occur (S. Banér, personal communication, January 2015). During both tensile the break occurred close to the bottom clamp (figure 35). This made it difficult to calculate the cross section area and affected the reliability of the tests. Since the rupture occurred in the same spot for both tests it is reasonable to suspect that the bottom clamp pressed the specimens to hard and caused deformation that interfered with the test. Observed benefits and challenges is presented in figure 36.
Figure 36, benefits and challenges

- Shock absorbant
- Acoustic absorbant
- Biodegradable
- Low cost production
- Made from waste
- Naturally fire resistant
- VOC & formaldehyde free
- Lightweight
- Possible to mold complex shapes
- Material properties
- Non waterproof
- Long growth time
- Inhomogenous quality
- Needs coating
- Adhesion to non-organic materials
4.1.4 Workshop - Bio composites in Cars

This section summarizes the information gathered during the LIGHTer workshop in Borås, both information regarding the driving force behind the implementation of lightweight materials and information about bio composites. LIGHTer was founded in order to meet the present and forthcoming global environmental challenges. Designing lighter products is an obvious and easy way to reduce the use of resources and increase energy efficiency. This is especially viable within the transport industry since the weight directly correlates to the amount of energy needed to drive the vehicle. As an example studies have shown that the use of sandwich materials in a 50-seater bus reduces the CO$_2$-emissions by 36 tones during its life cycle by removing heavy raw materials (Airtex, 2014). To replace traditional material with composites is one of the easier ways to reduce weight without compromising on the material properties. The traditional issue with doing this has been the energy needed to produce fibers and ecological aspect of the adhering resins. Therefore, the interest in bio composites emerged due to the environmental benefits of harvesting natural products.

A general problem with implementing natural composites in product design is the ability to ensure homogenous quality due to the organic nature of the material (LIGHTer, 2016). In large scale product manufacturing a materials property is based on the weakest outcome which makes it difficult for materials with deviating properties. This is especially notable in fields with high perquisites on material properties.

Conclusions from workshop relevant to thesis project Mycelium Biking:

- The problem with implementing bio composites is the inability to ensure unison quality due to the organic growth of the material
- The overall viewpoint was that bio composites are will experience an increased use in the upcoming years
- Profiling with environmentally friendly manufacturing and products is trendy and valuable as a marketing tool.

4.1.5 Next step for cargo bikes

The project objective for next step for cargo bikes is defined; the scope is to develop improvements and/or new solutions for the cargo bike with the purpose of changing people’s transportation behavior, by e.g. replacing the car with a cargo bike (Bertilson. et al., 2016). A pre-study focused on need-finding was conducted in the end of 2015. The existing market was analyzed using methods PEST and SWOT and user needs extracted using interviews, survey and personas. Relevant inputs for project “Mycelium Biking” was illustrated in an informative poster (figure 37) and used during ideation.
LIVELO CARGO BIKE
NEEDS & APPLICATIONS

WHY USE MYCELIUM MATERIAL ON ELECTRICAL CARGO BIKES?
The environmental benefits of using the material is in accordance with the underlying drive behind the increased sales of electrical bicycles. The usage would further enhance the ecological message and act as a sales pitch when marketing the product. By overcoming the difficulties of withstanding outdoor environment the implementation of mycelium will prove the applicability of the material in product design.

Applications for Mycelium Material
• Replacement
• Encapsulation
• Dynamic Force absorbent
• Structural (sandwich)
• Esthetic surfaces

Factual inputs
(Next step for cargobikes)
• Families with young children dominate the existing market
• In 2018 electrical bicycles will represent 50% of the total market
• Patents within the field have increasing with 15% per year since 2000

Most important features
(User interviews)
• Maneuverability
• Comfort/ergonomics
• Visibility
• Quality
• Stability

Figure 37, Needs & Applications-Poster, “Next step for cargo bike.” Made by Alexander Wagner
4.1.6 Benchmarking
The benchmarking results are presented in tables and pictures below. A poster of visualizing a selection of futuristic and smart bicycle gadgets (figure 38) was made to chart trends and to use as source of inspiration during ideation.
Material properties
Table 1 lists the most commonly used competitor materials and their properties in comparison to the mycelium material. Figure 39 is a picture of different core materials samples comparable to mycelium material in their material properties. The post-its reveal the material properties were D stands for density in kg/m³, C stands for compressive strength at 10% compression and T for tensile strength in the plane. These materials were used to compare material properties between mycelium material and some of the material it poses to substitute.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>Appearance</th>
<th>Applications</th>
<th>Density (kg/m³)</th>
<th>E-modulus (MPa)</th>
<th>Compressive Strength at 10%</th>
<th>Flexural strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mycelium Foam</td>
<td></td>
<td>Packaging, insulation, acoustic absorbers, bricks,</td>
<td>60-160</td>
<td>15 (?)</td>
<td>55-120 kPa (?)</td>
<td>0.5-1 MPa</td>
</tr>
<tr>
<td>Source: Ecocative</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mycelium Board</td>
<td></td>
<td>Furniture, structural, architectural panels, doors</td>
<td>800</td>
<td>2500</td>
<td></td>
<td>15 MPa</td>
</tr>
<tr>
<td>Source: Ecocative</td>
<td></td>
<td>cares</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded Polypropylene</td>
<td></td>
<td>Lightweight replacement for wood &amp; metals,</td>
<td>20 – 60</td>
<td>75-300 kPa</td>
<td></td>
<td>270 to 600 kPa</td>
</tr>
<tr>
<td>Source: ARPRO</td>
<td></td>
<td>cushioning and structural applications</td>
<td></td>
<td></td>
<td></td>
<td>(Tensile)</td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td></td>
<td>Disposable products, coolers, cushioning</td>
<td>40</td>
<td>5</td>
<td>170 kPa</td>
<td></td>
</tr>
<tr>
<td>Source: EPA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td></td>
<td>Outdoor, aviation, boats, sandwich material,</td>
<td>500-1000</td>
<td>4000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source: AlrexBatec</td>
<td></td>
<td>furniture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td>Building, structural, furniture</td>
<td>2200</td>
<td>30000</td>
<td>20-40 MPa</td>
<td>3-5 MPa</td>
</tr>
<tr>
<td>Source: The Physics Factbook</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This proved useful as a physical evaluation tool to complement the numeric comparative table 1.

Figure 39, benchmarking comparable material samples
Ecological properties

Table 2 presents ecological properties of mycelium material in comparison to materials it aims to replace. The numbers are collected from Brian Hitlons study “Using LCA to Prioritize Process Changes: A Mushroom Packaging LCA Case Study” from 2013. The LCA tool, Eco-indicator 99. Does not work very well on Mushroom materials since it does not account for the benefits of composting and the use of waste materials. The resulting analysis for Mushroom materials becomes 0mPt per kilogram. The same calculation for 1 kg of Styrofoam is presented in figure 40 with the resulting value of 388mPt. The values have no meaning except in comparison with each other.

Table 2, Ecological Properties, Benchmarking

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Mj/m3</th>
<th>Kg/m3 (co2)</th>
<th>Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mycelium Material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural waste</td>
<td>652</td>
<td>31</td>
<td>Self-compostable</td>
</tr>
<tr>
<td>Plywood</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood fibre</td>
<td>4984</td>
<td>114</td>
<td>landfills</td>
</tr>
<tr>
<td>Styrofoam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petrochemical extraction</td>
<td>4667</td>
<td>462</td>
<td>Landfill</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement aggregates</td>
<td>5760</td>
<td>550</td>
<td>landfills</td>
</tr>
</tbody>
</table>

Eco-Indicator 99 modified for The Mechanical Design Process, 5th Edition

Product or component
Expanded polystyrene

Project
Mycelium Biking

Production
Materials, treatments, transport and extra energy

<table>
<thead>
<tr>
<th>Material or process class</th>
<th>Material or process detail</th>
<th>Units</th>
<th>Amount</th>
<th>Indicator</th>
<th>Result (mPts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics</td>
<td>PS (EPS)</td>
<td>kg</td>
<td>1,00</td>
<td>360,000</td>
<td>360,00</td>
</tr>
<tr>
<td>Plastics_processing</td>
<td>Injection moulding - 1</td>
<td>mPts</td>
<td></td>
<td>21,00</td>
<td>21,00</td>
</tr>
<tr>
<td>Total [mPt]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>381,00</td>
</tr>
</tbody>
</table>

Disposal
Disposal processes for each material type

<table>
<thead>
<tr>
<th>Disposal class</th>
<th>Disposal detail</th>
<th>Amount</th>
<th>Measure unit</th>
<th>Indicator</th>
<th>Result (mPts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill</td>
<td>Landfill</td>
<td>1</td>
<td>7,400</td>
<td></td>
<td>7,40</td>
</tr>
<tr>
<td>Total [mPt]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7,40</td>
</tr>
<tr>
<td>Total [mPt] (all phases)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>388,40</td>
</tr>
</tbody>
</table>

Figure 40, Eco99- tool for evaluating sustainability
4.1.7 Moodboard
The moodboard (figure 41) consists of a selection of pictures visualizing four guiding words of value.

4.1.8 GATE
Following posters (Figure 39) were created to summarize the phase. Together with the posters created for methods “next step for cargo bikes”, “benchmarking” and “moodboard” they make a fair, visual representation of the work conducted during the data collection and analysis.
Mycorena: Eco-friendly alternative to plastic, cement, and engineered wood.

Product design is affected by a growing understanding of the ecological footprints caused by man. Awareness of the environmental pollution is pushing the search for new materials and solutions. Most people have basic knowledge about edible mushrooms but know very little about the fungal workings underneath the ground. Mushroom is only the fruit of a larger organism that is called mycelium. The mycelium is a fungal network of threadlike cells that spreads over large areas. The mycelium is essential for providing nutrition to the soil and is a key element to the ecosystem.

Engineers have now discovered a way to harvest the web-like growth of mycelium to bind organic material together. Growing the fungi in proper conditions will result in a material with properties similar to both cement, engineered wood and plastic. The use of mycelium as a replacement for environmentally draining materials will reduce the consumption of energy and fossil fuels. The long-term goal for this field is to decrease global CO\textsubscript{2} emissions and the use of hazardous materials.

By letting mycelium colonize on agricultural waste is a natural and fine web is binding the organic matter together. This process is called inoculation and takes 2-3 days. The leading company within this field, Ecovative Design, already have a large-scale manufacturing of their Mycelium Foam with customers all over the world. The material is undergoing an extensive development process and new applications are being researched consistently. The potential for this material is undeniable, the question is how easy it is to penetrate the existing market. Additional research and successful projects is probably needed before mycelium material may overtake substantial market shares from the materials it aims to replace. With this said, it’s still thrilling to think that in the near future we will have the possibility to grow our own houses and furniture. So keep an eye out for this groundbreaking material.

Or if you want to get involved, buy the Ecovative Grow It Yourself-kit. With the kit you receive inoculated biomass and instructions on how to create your own design. Maybe you’ll be the one who invents the next application for mycelium materials!

**Ecodesign, or “sustainable product development” is an approach to designing products with special consideration for the environmental impacts of the products during its whole lifecycle. Examples of such areas is CO\textsubscript{2} emission, energy efficiency, recycling and reuse, and toxicity.**

Mycelium materials aims to replace traditional use of plastic and possibly even cement. Cement production causes 5 percent of the global CO\textsubscript{2} emission and plastic manufacturing is responsible for 10 percent of the global oil and gas production.

Other environmental issues connected to the use of plastics are the waste management and leaching of chemicals from plastic products. The durability of the materials is causing non-degradable debris in natural wildlife habitats and spreading toxic particles within their ecosystems.

Mycelium materials are biodegradable, their process carbon-neutral and will fertilize soil in the end of their life cycle. Sustainable design at its best!
4.2 Ideation
The following chapter reports the results following the methods used in the generative ideation phase. The gate for Ideation was reached by develop six potential product concept and by selecting one of them for demonstrating the material by manufacturing a physical prototype.

4.2.1 Workshop
The workshop discussion revolved around needs for cargo bikes and areas of application for the mycelium material. Possible applications for the mycelium were discussed and listed as followed:

- Replacement
- Encapsulation
- Dynamic Force absorbent
- Structural (sandwich)
- Aesthetic surfaces

The needs are listed below and extracted from data collection (“next step for cargo bikes” & “benchmarking”):
- Extra luggage Carrier
- Rain protection
- Lights (headlights, surrounding, cargo light)
- Integrated lock
- Speakers (Music, horn, alarm)
- Blinkers
- Smartphone mount/charger
- Bumper
- Reflexes
- Helmet storage
- Rearview mirrors/camera
- GPS
- Safety lane projection

Workshop discussions about these needs were used as a foundation for the following generative methods.

4.2.2 Brainsketching
The session resulted in more than 50 concepts with focus on meeting the extracted need user need from “next step for cargo bikes”. The limitations of mycelium materials were discarded in the session order to not restrain the pool of possible solutions. Figure 43 is a selection of a number of concepts generated in the session.
4.2.3 Scamper
The generated concepts were clustered and laid out to for good visual overview. The method resulted in 6 product concept presented below (figure 41).

1. A handlebar cover with wind protection, IR-heating, rearview mirror, headlights, blinkers, speakers, back camera, smartphone mount & laser projection.
3. A luggage carrier with mycelium growing around poeltry net for safety qualities
4. Lighting concept, Headlight, Blinker, rearview mirror
5. Mycelium helmet
6. sandwich flooring

Figure 44. Mycelium implementation, resulting concepts from ideation
4.2.4 Dot voting
Product developers and other personal at Semcon distributed points with values 1 & 2 on the selected concepts. The handlebar cover scored the most points followed by the mycelium helmet. All concepts except for the sandwich flooring, that received one point, scored similar points which made it difficult to draw conclusions from the result.

4.2.5 Design Format Analysis
The evaluation matrix was used as a guideline for deciding what part to create in final project phase. As the words of value were not weighted, the result was only seen as a pointer in discussions about what part to make a physical prototype of. Figure 45 envisages the filled matrix were the bumper and handlebar concepts scored the highest.

Figure 45, Evaluation matrix
4.2.6 GATE
The gate following ideation is presented in figure 47. The reasoning behind the selection of the part is presented along with a list of requisite that process both material and functional demands.

List of requisite

Multi Gadget Handlebar Cover

Why create this part?
The concept scored highest in the evaluation methods and is considered the most attractive product. The concept was also selected due to the novelty of using mycelium materials for encapsulation. A good prototype would demonstrate the applicability of using mycelium for a whole new range of products. Its many functions and electrical components makes the handlebar cover ideal to validate the capability of combining mycelium with other materials as well as solving the issues connected to coating and shrinkage.
Product Properties

- The product must be able to withstand outdoor environment
  - Waterproof
  - Functional in temperatures between -5 and 30 degrees Celsius
  - UV-light
  - Withstand bumps and scratches
- Biodegradable (electrical components excluded)
- Lower CO₂ emissions than competitive materials (plastics)
- Manufactured with methods suitable for industrial scale production
- Visual expression fitting for the Livelo cargo bike

The mycelium handlebar cover should administrate following functions:

Headlight
- Provides good surrounding light.
- Being controlled from the center panel.
- Adjustable in intensity
- Recyclable
- Changeable/repairable

Blinkers
- Visible from behind and in front of the cargo bike.
- Controlled without taking hands of handlebar.
- Recyclable

GPS
- Smartphone stand connecting the phone to the product
- Laser projecting arrows onto ground
- Speaker assisted navigation

Alarm
- Speakers may be used as signal horns
- GPS-tracker to be used for anti-theft functions

Cameras
- Connected to smartphone via Bluetooth
- Sensors warning biker for approaching vehicles (front & back)

Safety projections
- Led/laser projected lines/symbols to create space awareness

Smart Handlebars
- Electrically heated handlebar
- Haptic Warnings
- Tracking pad for displays

Figure 46, List of requisite, Gate Ideation
4.3 Implementation
The following chapter reports the results following the methods used implementation. The gate for Implementation is presented under section “Final results”.

4.3.1 Rapid prototyping
The prototyping was focused on mold making and manufacturing methods. Selected geometries also made it possible to observe how the material shrinkage affected tolerances and thinner geometries. Comparative evaluations on 3D-printed- vs Vacuum pressed molds are listed below with regards to parameters: shrinkage, coating, surface finish, coloring and growth (figure 45).

Conclusions, Vacuum vs 3D-print:
Common conclusion for both methods of mold making include: Holes and thinner geometries are vulnerable to shrinkage are preferably manufactured after the part is dried in order to control dimensions and stability. Plastic wrapping is useful for removing the grown mycelium material from the mold, especially in thin sections, but may infer with the growth. Wrinkled plastic can cause ridges in the surface affecting the final result. Differences between the two methods are presented in table 3.

Figure 47, Vacuum press mold prototyping, Photos: Alexander Wagner
Table 3, D-print vs Vacuum press

Conclusively, the recommended mold manufacturing method would be a combination of the two eliminating the downsides of individual methods. The plug would be 3D-printed in order to ensure geometry dimension. The plug would then be sanded to receive good surface finish and used to create molds in the vacuum press. The molds would be transparent allowing surveillance of the mycelium growth. Same molds could later be used when applying coats and be reused for a new part. This combination of method would be the most suitable for large scale mold making.

4.3.2 CAD & Evaluation

Experimental digital prototyping was used to set the final design for the multi gadget cover selected for detailed design. Sketched concepts were narrowed down to two concepts (figure 49) through consultation with product developers and designers at Semcon. The final concept of the Multi Gadget Cover is a combination of the two concepts (figure 50) and presented fully in the following chapter “final result”.

4.3.3 Material testing

The deaccelerating capacity of the material was tested according to European standard EN1078 for bicycle helmets. The test was conducted in a primitive way using free weights instead of drop apparatus and the specimen was dropped onto concrete flooring instead of an anvil (figure 49). Due to lack of proper testing gear, the presented result should be view as guiding numbers pointing towards the right direction. The calculations are presented fully in appendix. The impact force for predefined drop parameters and impact contraction (Δd) measured to 0,6 cm was 8100 Newton. The resulting deceleration is then calculated to 225g.

Figure 48, Test specimen and weights
Figure 49, Process visualization

CAD PROTOTYPING
MONO LIGHT CONCEPT

CAD PROTOTYPING
HEADLIGHT CONCEPT

Figure 50, CAD prototyping concepts
5 FINAL RESULT

The final result for this study result will be presented in two parts. The first part summarizes findings on using mycelium material in product development. The second part demonstrates the implementation of the material in a specific design project by using findings presented in the first part. The material part is presented as a beginners guide to using mycelium materials and the second part is using computer generated visualizations to present the different product concepts. The results finishes with a detailed explanation of the “Multi Gadget Handlebar Cover”, chosen through evaluation methods accounted for in earlier sections, using visualizations and the physical prototype (figure 51) created during implementation.
5.1 A designers’ guide to mycelium materials
The following section is a brief introduction to mycelium material iterating the knowledge gained from research and experimental testing conducted in this study.

5.1.1 Why eco-design?
Eco-design, or “sustainable product development” is an approach to designing products with special consideration for the environmental impacts of the products during its whole lifecycle. Examples of such areas are CO₂ emission, energy efficiency, recycling and reuse, and toxicity.
Modern product development is affected by a growing understanding of the ecological footprints caused by man. Awareness of the environmental pollution is pushing the search for new materials and solutions. Designers’ ability to integrate sustainability in the design process will have impact on the environmental evolution. Product design is the communicating link between material science and the user and therefore essential to meet the global ecological demands.

5.1.2 Mycelium materials
Are manufactured through biological additive manufacturing, a combination of bio-engineering and additive manufacturing. The natural composites are using the breakdown capacity of the mycelium to bind organic fibers together with a web-like structure (figure 52). The threadlike cells of mycelium penetrate the cellular walls of organic compounds and break it down do its basic components. The mycelium extends into the host cells through which they “feed” and extends through the tips. The growth is causing a mechanical adhesion between the hyphae and the particle as the mycelium grows around and through each fibre. Or as Ecovative founder Eben bayer says; “like a tree root stock holding onto soil”. (Bayer, May 20, 2016). No additional energy is required to stimulate the growth and the process is stopped by drying the part and render the mycelium inert. The process may be halted at different mycelium/feedstock-ratios depending on what properties that is sought after in the final product.

Figure 52, Mycelium in 200x Enlargement

5.1.3 Growth
The material growth is induced by introducing mushroom spores to biomass. This process is called inoculation and can be done at home with simple tools. It is also possible to buy pre-inoculated biomass from Evocative, decreasing the risk of contamination. The use of different fungi species, biomass blend and fiber-size affects the material outcome and can be customized for specific tasks. Evocative are using a special (trademark secret) fungi strain together with corn stalk husks and hemp. The resulting material is suitable for most common application and the author recommends the use of evocative’ products and to build upon their research instead of inoculate the biomass yourself and start the optimization process from scratch.
HOW TO GROW THE MATERIAL

When the mycelium binds biological matter they become natural composites. Two advantages of these natural composites includes low cost production and carbon storage. These benefits makes it possible to claim the process of being carbon-neutral or even carbon negative if the biological matters has produced oxygen during its life cycle.

1. By letting mycelium colonize on agricultural waste a natural a fine web-like structure is binding the organic matter together. This process is called inoculation and takes 3-6 days.

16 DAYS

Depending on what properties that is sought after, the manufacturing process may alter between 8-16 days.

2. The inoculated substrate is chopped into small pieces. Additional nutrition as added and the substrate is placed in molds, the material is let to grow for another 8-10 days.

3. The material is removed from the mold and dried. Heating the material to 90 degrees will render the fungus inert and stiffen the material. The result is a strong, biodegradable product with great ecological qualities.

Figure 53, Manufacturing process, Final Result
The inoculated mass is packed in sterile molds of desired shape. The Mycelium digests the biomass over a 3-week period in humid conditions and room temperature. The growing environment should be isolated to prevent other fungi to interfere with the growth and compete with the original strain. The growth is halted by drying the part. By reducing the moisture content of the part (from 60-70% to 10-20%) the mycelium is rendered inert a ready to use. The process is visualized as a poster (figure 49).

5.1.4 Properties
When presenting the properties of mycelium material, it is important to account for both ecological and material properties to do the material justice. As the benefits of mycelium material are mainly ecological designers and manufacturers will have to calculate whether the environmental benefits triumphs over eventual mechanical or/and economical losses.

Re-use
The commercial use of mycelium materials (evocative, 2014) is produced using agricultural waste, meaning procurement costs of the feedstock is negligible and does not require any excessive area for producing.

Disposal
The product is naturally biodegradable and will break down in 30-90 days in the users’ own backyard, providing nutrients to the soil instead of occupying space in landfills. Styrofoam and EPP, two of the closest material relatives in term of mechanical properties, is currently occupying 25% of global landfills (Huffingtonpost, 2016).

Energy
The energy cost of the manufacturing process is close to zero: This is possible since the growth of mycelium is stimulated by breaking down and harvesting the energy of the feedstock. The process occurs without supplementary energy inputs and the drying/finalizing of the product can be used using solar dryers (travegli, 2013). The only energy needed for manufacturing will then consist of transporting costs and factory sterilization and maintenance. Research in this study presents numbers comparing energy needed and CO$_2$ emissions for manufacturing mycelium and Styrofoam (similar material properties). Styrofoam emits nearly 15 times more CO$_2$/m$^3$ and need 10 times more energy MJ/m$^3$ than mycelium materials.

Local feedstock
The biomaterial-waste used as feedstock could be harvested locally regardless of where the product is manufactured reducing transporting costs.
Other favorable characteristics of mycelium materials are listed and described below:

**Class A fire rated**
Mycelium materials are natural fire retardant and flame proof up to 240° Celsius (Ecovative, personal communication, March 2016)

**VOC & formaldehyde- free**
The natural adhesiveness between eliminates the need of environmentally damaging binding agents used in competitive materials like plywood or Styrofoam

**Self-Healing**
Rupture in products can be cured through introducing inoculated biomass to the break and letting mycelium bind the part together again.

**Shock absorbent**
The material has good impact absorbing abilities which makes it ideal for protective applications.

**Acoustic absorbent**
The materials ability the absorb sound is being harvested in commercial products all over the world providing better ergonomics and soundscapes.

**Mechanical**
The mechanical properties of mycelium materials, presented visually in figure 58, are highly customizable. The resulting properties are depending on a number of various parameters such as; feedstock material, fungi species, mycelium/feedstock-ratio, density & moisture content.
The mean elastic modulus of test specimens created in this study was calculated to 15 MPa at density 140kg/m3. That is about 5 times stronger than Styrofoam at density 60kg/m3. By growing the material under pressure or/and drying the material using warm presses (Myco board, 2015) it is possible to increase density and stiffness greatly. Evocative claims their Myco board have an elastic modulus of 2000Mpa which is comparable to the modulus of plywood or MDF boards.
WHAT PROPERTIES DO I GET

Depending on what properties and characteristics that is sought after the inoculated biomass may be treated in different ways. The material properties are affected by altering with density and growthtime of the designed part. The properties may also be enhanced by adding support materials.

**PROPERTIES OF MYCELIUM MATERIAL**

Tested at Luleå composite testing facilities

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DENSITY:</td>
<td>140 kg/m³</td>
</tr>
<tr>
<td>E-MODULUS:</td>
<td>15 MPa</td>
</tr>
<tr>
<td>TENSILE STRENGTH:</td>
<td>1,15 MPa</td>
</tr>
<tr>
<td>COMPRESSIVE STRENGTH:</td>
<td>To be measured</td>
</tr>
</tbody>
</table>

**MYCO BOARD**

Ecoative are using form presses to compress the mycelium material to receive higher density. The material properties of this material is. Modulus 2500 Mpa at density 800 kg/m³.

**SUPPORT MATERIALS**

The organic adhesion between mycelium and natural materials makes it easy and energy efficient to enhance the material properties.

- **FLAX**
  - For improved tensile strength
- **VENEERS**
  - Skins for improved flexural strength
- **COFFEE**
  - Higher density and stiffness

5 x

The modulus of styrofoam foam at density 40 kg/m³.

/2

The modulus of plywood at same density (MYCO BOARD).

3 x

The tensile strength of Expanded polypropylene at density 60 kg/m³.

**HOW TO MEASURE THE ECOLOGICAL PROPERTIES?**

Figure 54, Properties of mycelium material
5.1.5 Challenges, and how to work with them

This section addresses issues connected to the manufacturing of mycelium materials.

**Geometries**

The reducing of moisture content in order to render the mycelium inert is causing problems with dimensioning and tolerances. Mycelium materials are subject to shrinkage of about 4-9% when dried (Ullman, 2013). The shrinkage is causing deformations of the part that is difficult to control. The shrinkage percentage depends on unique geometric features. The deformation is visualized in figure 59 comparing a rendered image with the manufactured part.

![Rendered image vs Physical part](image)

Figure 59, Comparative pictures, Render & Physical

As the figure implicates, the final shape is of the grown part looks crooked and organic in comparison to the digital version. Thin geometries and holes are especially vulnerable to the shrinkage and it is advised to avoid geometries smaller than 1cm. Parts should have a draft angle of 3° degrees to get them out of the molds. Molds could be over-dimensioned to compensate for the shrinkage.

The baked material is easy to work and one way to ensure tolerances is to manufacture important geometries or hole afterwards. This would add another operation to the manufacturing process but could solve shrinkage issues.

**Surface**

Closed molds are preferred in terms of receiving good surfaces. Exposed areas are more likely to experience airborne contamination and the mycelium expansion will produce choppy surfaces in not contained. In manufacturing, the most important surfaces should be facing the mold walls.

**Coating**

The mycelium material growth is rendered inert through drying. The mycelium will be reactivated through exposure to humid environments and continue to break down the product and lose its stiffness. The product is said to last approximately one month in saltwater but would need coating to prevent moisture diffusion in order to create lasting product. The issue is magnified as most conventional coatings are derived from petroleum based oils and non-biodegradable. The use of such coatings would diminish many of the ecological benefits of using mycelium materials as the composting of the product would be difficult.

There are biodegradable epoxy resins that would be applicable for this purpose. One example is the bio-based epoxy derived out of Castor oil researched by Park, Jin & Lee (2004). The issue with biodegradable coatings is that exposure to outdoor environment might initiate the breakdown of the coating which eventually would lead to moisture diffusion and failure of the mycelium material. This problematic with coatings have not been addressed in this study and additional research is needed before making conclusions regarding the durability of the product.

The process of applying coatings to mycelium material may take use of the material shrinkage. By using the same mold as for growing and let the coating fill the gaps caused by shrinkage, the final product would receive good finish with exact dimensioning.
5.1.6 Support materials
The Mycelium may be used in combination with other materials in order to enhance the material properties. As the mycelium breaks down and adheres to organic materials, the need for gluing is removed if combined with organic support materials. This makes the material suitable to use in organic sandwich structures with mycelium material as the core. The creation and durability of this type of sandwich was tested in this study with positive outcome using veneers out of balsa wood.
Other support materials include fabrics made of organic fibers such as flax or hemp. The fabrics may be used as skins or be implemented within the part. The fabric enhances the tensile strengths of the part with the mycelium stiffening the fabric by binding individual fibers together.
Adding coffee grounds to the feedstock also seems to affect the material properties. The nitrogen in coffee grounds fuels the mycelium growth (studio murmur) while the relative density is increasing.

5.1.7 Applications
The strength-to-weight ratio and the force absorbing abilities makes the materials ideal for protective packaging. Packaging is the most commonly used commercial application but other applications include: insulation, absorbents, furniture, bricks, lamps, boards & encapsulation.
The material similarities with expanded plastic foams implicates that the material is implementable in product made of those materials. Examples of such product would be: temporary tableware, helmets or picnic coolers.

Sandwich structures with mycelium material cores would be applicable in types of structural flooring or furniture. Office desks or chair seatbacks would be natural product for this type of application.
The applicable fields are many as the material properties are customizable. Figure 60 list some applicable fields as a result of conclusions made in this study.
The aesthetic properties of the material are accounted for as the marketing value increases. The material is suitable in products that wants to be associated with sustainability.
The novelty of the research area also implies further development of the material in upcoming years. As mentioned in previous section, the limiting factors and challenges as of today are shrinkage, surface finish, regulating moisture level and homogenous growth. These material characteristics make it difficult to argument for the use of mycelium materials in product with high demands on tolerances and quality.

5.1.8 Sustainability
The sustainability of the material is apparent in the comparative table (table 4) illustrating the ecological benefits of mycelium material in comparison to plastic from energy consumption viewpoint. Other sustainable properties owned by mycelium materials presented in the study include low CO$_2$-emissions and natural adhesion.
The material is clearly best suited for temporary structures and for use in indoors environment. This would diminish the need for coatings and the problems (ecological and economical) and operations connected to it.
MYCELIUM APPLICATIONS

Aesthetic
Marketing
Profiling
Unique

Temporary Structures
Packaging
Pop-up structure
Tableware

Mechanical
Economic
Ecologic
Local

Absorbent
Acoustic
Impact protection
Insulation

Adhesive
Myco-Boards
Sandwich structures
VOC & Formaldehyde free

Figure 56, Mycelium Application

<table>
<thead>
<tr>
<th>Plastics</th>
<th>Mycelium Material</th>
</tr>
</thead>
<tbody>
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<td><strong>Energy content to produce:</strong></td>
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<tr>
<td>• The energy required to make final shape</td>
<td>• Energy required to grow parts (almost none)</td>
</tr>
<tr>
<td><strong>Disposal</strong></td>
<td><strong>Disposal</strong></td>
</tr>
<tr>
<td>• Landfill &amp; debris</td>
<td>• Composted</td>
</tr>
<tr>
<td><strong>Transportation</strong></td>
<td><strong>Transportation</strong></td>
</tr>
<tr>
<td>• Procurement transportation</td>
<td>• Collection of local agricultural waste</td>
</tr>
<tr>
<td>• Transport to costumer</td>
<td>• Transport to costumer</td>
</tr>
</tbody>
</table>

Table 4, Plastic vs Mycelium
5.2 MYCELIUM IMPLEMENTATION RESULTS
The following section presents developed product concepts for the Livelo cargo bike using mycelium materials. Figure 61 iterates the relevancy of using mycelium materials for this purpose.

WHY USE MYCELIUM MATERIAL ON ELECTRICAL CARGO BIKES?

The environmental benefits of using the material is in accordance with the underlying drive for increased sales of electrical bicycles. The usage would further enhance the ecological message and act as a sales pitch when marketing the product. By overcoming the difficulties of withstanding outdoor environment the implementation of mycelium will prove the applicability of the material in product design.

Conclusively 6 product concepts (figure 57) were selected as implementable with positive outcome, meaning the usage of mycelium enhances the resulting product. The eligibility for the material used in the specific products have been demonstrated by conducting experiments and research presented in the study. 5 concepts are presented on a theoretical level with computer generated visualizations displaying the looks and functions together with a complementary explanatory text. One of the concepts (the multi-gadget handlebar cover) was chosen for further development and was manufactured using project-defined manufacturing methods. The physical prototype shows the applicability for integrating electrical components and functions but is primarily demonstrating the material and how to deal with material issues like coating and sectioning.
MYCELİUM BIKING

Product concepts

1. Functional Bumper
2. Sandwich Flooring
3. Rearview Lighting
4. Sustainable Helmet
5. Battery Protection
6. Multi Gadget Cover
The **Functional Bumper** is a concept utilizing the shock-absorbing abilities of mycelium materials. The lesser maneuverability of the cargo bike in comparison to regular bicycles makes it a liability in traffic. The front bar of the cargo bay is located at knee height and the purpose of the bumper is to dampen eventual collisions and protect co-road-users.

The density and elastic modulus of mycelium materials are highly customizable and further development of this concept would include calculating the optimal ratio for the specific purpose.

As seen in the renderings above (figure 63) the bumper also houses other functions. A headlight and speaker is integrated in the center part and two lasers/LED projectors are located on the sides. The lasers may project safety lanes as visualized in figure 64 to improve awareness of the cargo bike in darker environments.
The **Rearview Lighting** Concept (figure 65) is using mycelium materials for encapsulation of LED lights. The product is fastened on the roll-over-protection bar with cords running along the cargo bay. The product administrates both headlights and blinkers. The blinkers are controlled from the handlebar using a thumb switch and the signals are visible to other road-users from both behind and front. A rear view mirror is implemented on the backside facing the rider. The rearview mirror allows the rider to keep track of traffic behind without diverting attention, turning the head or body.
The **sustainable helmet** (figure 66) offers an environmentally friendly way of protecting the bike riders head. The helmet would be constructed in three layers, the innermost layer would consist of cloth padding, the core would be porous mycelium material and the outer shell would consist of flax fibre fabric and bio-harts. The mycelium core absorbs the dynamic force of the impacts while the outer composite shell shelters the core from water and decreases friction against the ground and the risk of neck cranks. The physical similarities between mycelium materials and Styrofoam implied mycelium would be suitable in the construction of helmets. A drop test was conducted according to EU-standards proving the applicability of the material. The helmet could be manufactured using a single mold for both growing and coating and the same mold could be used multiple times (figure 67).
The **sandwich flooring** (figure 68) is a concept where the existing, solid wooden bottom of the cargo bay is replaced with a sandwich structure. The sandwich structure consists of a mycelium material core compressed between wooden veneers. The organic adhesion between the skins and the mycelium removes the need for additional glue between the materials. This is a unique ability of mycelium materials and makes it possible to create fiberboards or sandwich cores without using formaldehyde or VOC. The resulting material would be lighter but share the same material properties as the existing solution. Other benefits include manufacturing costs and the reuse of agricultural waste by implementing mycelium.
The **battery isolation** concept (figure 69) is a product using mycelium material to safe-keep and isolate the battery. The box would be lockable and prevent eventual theft and eliminating the need to carry the battery with you. The box would be dimensioned to fit other personal objects as well allowing the rider to store valuables on the bike. In order to improve safety even more,

the material could be grown around poultry netting (figure 70). The combination of wire net and mycelium have been proved possible by earlier studies (studio murmur) and would protect the box from being cut open. The isolating properties of the material will reduce energy diffusion in cold temperatures and extend the battery life.
The **Multi Gadget Cover** (figure 65) is a handlebar windshield. The product is mounted on the existing handlebar and made of mycelium material resting on a metal frame that supports the structure. The mycelium encapsulates electrical components and the prominent location of the product displays the usage of organic material. The visibility of mycelium enhances the ecological message of the product and the combination of natural materials and technical solutions draws attention to the bicycle. The shield addresses the user need of freezing when biking in windy/rainy/cold conditions. Chilled muscles are subject to lower reaction speed, force and precision (AFS, 2009:2) and may affect the bike riders’ ability to maneuver in traffic. The shielding is an evident physical function but the product offers many other features explained next.
Lights
The product encapsulates 3 types of lighting (figure 66).

Headlight
The headlight is located in the center part of the product framed with an oval-shaped geometry to mimic the visual language of the cargo bike. The light is controlled from the center panel and adjustable in intensity.

Area Light
The area lights are located within the mycelium mart of the wings. The light provides visual good overview of the bike surroundings and cargo bay.

Blinkers
Blinkers are located in the end of the wings and controlled from a switch on the handlebar brakes. The signals are visible from both front and behind.

GPS-laser
A laser projector is located underneath the headlight with the ability to project navigation instructions onto the ground, and by doing so, removing the need to avert attention from traffic. Figure 73 visualizes the technique.
Displays
The product is equipped with a touch display administrating all features and functions (figure 68). The product also offers a smartphone stand that enables the use of one additional display. A concept app using the smartphone display is illustrated in figure 76.

Speakers
Two speakers are located beside the product display. The speaker may be used for different features. These include; auditive navigation, theft alarm, warnings, Music or Horn

Smart Grip
The concept includes handlebar grip features. Electrically heated grips have been used on motorbike for years and will be implemented in the product. The grips will also house vibrators for haptic feedback to warn the rider of fast approaching objects.

Sensors & Cameras
A camera with motion sensor is mounted underneath the saddle (figure 75) and connects to the product display through Bluetooth. The backward-facing camera provides the rider with overview of traffic without turning or diverting attention from the direction of movement. The sensors are connected to the speakers and grip vibrators with the ability to alarm the rider

Navigation
A built in GPS allows the rider to navigate though the city. The navigation is aided by speakers, projectors and may be used on either display.
A smartphone mount on the center panel makes it easy to administrate functions using the smartphone display.

FUNCTIONS
Rearview camera
Navigation
Speakers
GPS-tracking
Horn

Navigation tools may be used in combination with the GPS-laser projector and speakers of the handlebar cover.

The phone is connecting a rearview camera through Bluetooth enabling overview of traffic without turning. Sensors notifies the rider of fast approaching objects.

Figure 72, Concept smartphone application, Made by Alexander Wagner
Following pages presents the physical prototype for the Multi Gadget Cover Concept. The presented result is focused on the creation of mycelium material. Electrical functions and complementary materials are to be viewed upon as assistances to showcase the mycelium material rather than a part of the result. The mycelium parts are manufactured based on manufacturing methodology defined in the study. The prototype consists of following components (figure 71):

5.3 List of components

**Mycelium parts:**
- Wing x2
- Top
- Bottom
- Headlight frame

**3D-printed parts**
- Wind cover x2
- Support Frame
- Blinker encapsulation

**Plastic:**
- Display
- Button
- Light glass

**Electronics**
- LED strips (Arealight x2, headlight)
- LED blinkers

5.4 Manufacturing Mycelium material
The production of the mycelium parts is visualized in figure 78, from reactivation of mycelium to coloring and coating. Notable is that growing molds were 3D-printed instead of vacuum pressed. Vacuum pressed molds would have been preferred as the mycelium material parts were coated but tooling equipment limited the selection of manufacturing method. The mycelium parts were painted with concentrated coffee in order to match the visual expression of the Livelo cargo bike in terms of color. Coffee as dying medium has ecological advantages as the color is extracted from used coffee grounds, using bio-waste as pigment. As 3D printed molds are not suitable for applying coating (as described in the “designers guide to mycelium
materials”), the epoxy resin was instead painted on in layers and sanded to receive uniform, shiny surfaces.

5.4.1 Assembly and Finishing

The shrinkage proved difficult to control and the parts experienced deformations resulting in inaccurate meetings and bad fitting (figure 79). The tolerances would have been better using vacuum pressed molds with epoxy resin filling the cavities created during shrinkage. The issue regarding that method of manufacturing is ecological instead, questioning the sustainability of the product when using substantial amounts of epoxy. Parts were sanded and machined in order to improve geometry dimensioning but as the parts interacted with a 3D-printed frame of exact dimensions, the liberty of resizing the product was strictly limited. The prototype had glitches between shell components that needed more work in order to prevent moisture to reach inner part material and electrical components (figure 79). All mycelium material components were manually worked after drying but the product is still deemed ineligible for encapsulation purposes for this specific way of manufacture. The amount of effort needed, in terms of time and machinery, to get the parts acceptable is not in relation to the cost and quality of the product.
MULTI-GADGET MYCELIIUM COVER

Figure 75, Final prototype, Presentation & Issues

Coating & Protection issues

Tolerances & fitting

Interaction with other components
6 DISCUSSION

The following section discusses the presented study. The text positions the results and the authors states his own recommendations regarding future research and appliances of the material. The text also contains reflections about the reliability of the research and the relevance to industrial design engineering.

6.1 Positioning the results

The discussions regarding the results are divided in methodology, mechanical properties, ecological properties and material applications.

Methodology

The project process was based on the IDEO field guide for human centered design. It proved applicable though most of the information gathering methods were focused on developing the material in a scientific way rather than focusing on the users. This was planned as the needs extracted from “next step for cargo bikes”, the project in which the materials eligibility was tested, was collected through various user centered methods and the validity of using these needs as a base in ideation was deemed reliable.

As the major manufactures all operate in America, the interviews were conducted over email due to time difference. The digital delay and issues following having a written conversation made understanding and conversational flow more complicated.

I also had issues with receiving detailed answers regarding inoculation, adhesion, fibre/mycelium ratio & material data due to company proprietary.

Material properties

The numeric properties are primarily based on the material testing conducted in the material testing facilities at Luleå Technical University. The testing intended to follow instructions described in the specific standards but was not able to meet all listed demands. The standards recommend testing of 8 specimens for each material type whereas I only had access to one sample for each type. The bone-shaped geometry of the specimen is designed to control were the rupture occurs. In both tests the specimens broke close to the bottom clamp suggesting exaggeratedly tight fastening of the specimens. The location of the ruptures aggravated calculations of elastic modulus. These factors undoubtedly affected the outcome and the results are therefore deemed unreliable. The numeric values should be viewed upon as guidelines rather than absolute truth.

The growth time required in order to get uniform growth throughout the whole part was close to double the amount of days recommended in the instructions (GIY, 2015). In communication with Ecovative regarding the matter they believed it could be a subject to humidity and temperature levels in growth environment or that mycelium had been damaged due to cold climate during shipping. As I experimented with different temperatures and humidity levels without establishing clear relation it is valid to suspect the second option affected the bags in some way. Whether the prolonged growth time affected the final result is hard to know without conducting additional comparative studies. This should be considered when reviewing the results and may have colored conclusions in an overly negative way.

The collected research for study was generally positive towards to use of mycelium in product design. Travaglini’s et al (2013) article states positives conclusions regarding the material but is also discussing the deviating results in both his own and others studies. Holt et al. (2012) and Jameson’s et al. (2014) studies both show differing results without clear explanations. The material testing
conducted in this master thesis have demonstrated the same problematic. This is possibly due to the organic nature of the compounds making it difficult to receive uniform results and isolate deciding parameters. A general problem with implementing natural composites in product design is the ability to ensure homogenous quality due to the organic nature of the material (LIGHTer, 2016). In large scale product manufacturing a material’s property is based on the weakest outcome which makes it difficult for materials with deviating properties. This is especially notable in fields with high perquisites on material properties. On the other hand, Evocative have established a large scale manufacturing ensuring the customers of specific material properties (Ecovative GIY, 2014) on their products. This indicates that it is possible to overcome the unreliable nature of organic growth by using proper inoculation methods and tools.

Ecological properties
Duncheva (2013) is raising a question regarding the actual ecological properties of mycelium materials. She questions how much energy is needed for the manufacturing, referring to the maintaining of humid and warm conditions during the growth. This is a valid enquiry when referring to the comparative table of CO₂ emissions per m³ (Holts, 2013) presented in this study in relation to Travaglini’s (2013) claim of the manufacturing process being carbon-neutral or even carbon-negative. The LCA (Ullman, 2013) is also highlighting the issue presenting facts showing that more than 50% of the total energy consumed in manufacturing comes from drying. Even though it is possible to reach energy-neutral values in theory using solar dryers it might be hard to implement in reality, as it makes the manufacturing dependent on good weather.

One of the bigger issues with implementing the material is moisture diffusion, making coatings a must in creation of long lasting products. In order to keep biodegradability of the product, the coating should to be degradable, as the coating and mycelium materials will be difficult to separate. There exist a number of bio-based and degradable coatings (park, 2004) and the research field is evolving with the increased demands for sustainability. As of today, many of the promising products are still being researched and are manufactured to costumers on request. As this study was focused on mycelium materials and not biodegradable coatings, the subject is viewed upon as a topic for future research.

Material applications
The Myco-board is created using a hot press to densify the material (mycoboard, 2015). The material then experiences a secondary bonding complementing the mechanical bonding between the hyphae and feedstock (E, Bayer, personal communication, June 2016). This way of manufacturing mycelium material results in very different mechanical properties. Density is similar to plywood and the elastic modulus is increased by factor 200. As this way of processing mycelium is relatively new (difficult to retrieve data) and I did not have access to proper tools, conclusions and discussions about applications and implementation are based on the traditional use of mycelium materials. This is relevant since the new way of manufacturing mycelium affects the ecological properties through adding the pressing operation and the secondary type of binding.

Based on the outcome of the physical prototype it seems difficult to argument for the eligibility of mycelium material in encapsulation applications. The material has astonishing ecological properties as the manufacturing process cost neither energy nor resources (made from waste) but is performing poorly in terms of dimensioning and tolerances. In
commercial plastic manufacturing, tolerances over 1% are considered large (Nielsen, 2016) and mycelium materials are subject to shrinkage between 4-9% (Ullman, 2013). The numbers highlights the issue and makes it easy to understand that standardized methods to address this problem is needed should the material replace non-expanded plastic as well.

6.2 Relevance
As mentioned by Friedman (2010), designers’ ability to integrate sustainability in the design process will have impact on the environmental evolution. The growing interest in alternative, eco-friendly materials is reflected in product design. Mycelium materials are validating the statement considering the amount of attention the material is receiving in comparison to the actual use and material properties. The knowledge about mycelium materials is spread through products using the material and the development stimulated by research and attention in media. Industrial design is the communicating link between material science and the user and therefore essential for the expansion of the material.

6.3 Reflection
The limited range of scientific articles about the subject led to use of less reliable references such as website magazines and unpublished university reports. This may have affected the scientific reliability of some of the claims made in the study. Since the material is continuously undergoing development the reported status of the research field may not be up to date due to the use of old sources. Another perceived issue regarding the subject is that leading researches within the field are not sharing their research due to trademark secrecy. Another remark is that some of the referenced authors have personal interests in mycelium materials, meaning they are connected to companies profiting from selling the product. This may have colored their conclusions about the material in an overly positive way. Because of the novelty of the field there is much additional research needed before mycelium material may overtake substantial market shares from the materials it aims to replace. Evocative, the leading company within this field, are both contributing and withholding the development of the material. They released a Grow It Yourself-kit in that was nominated for the London Design Museum’s Design of the year award in 2015. (Manton, 2015). With the kit one receive inoculated biomass and instructions on how to create your own design. This is a great way of outsourcing the research and involve more people into the development of the material. The negative regarding Evocative in this matter is that they are protective of their manufacturing on a detailed level. The author found it hard to get information about their inoculation process and implicates it is hard for others to replicate and build upon their research. The behavior is understandable for any innovative business enterprise but it is slowing down the development process.

6.4 Future work
Based on the information gathered during this project the author has recommendations for future research that would be beneficial for the field.

6.4.1 Fungi species and biomass.
As Jameson et al. (2014) writes in his material study about mycelium, additional studies about the use of different fungi species in creating mycelium material is needed. Research comparing the most commonly used fungi in regards to growth time, performance and manufacturability. Since different fungi prefers to grow on different organic compounds (Stamets, 2005) different biomass should have been tested in this study as well. Categorization of different species and their properties
would make it easier to design the mycelium material for the specific product.

### 6.4.2 Integrated functionality

An interesting research area would be to investigate the possibility of integrating other fungal functions in the manufacturing of products. An example of such studies is done by Edward (2013) who designed a lamp that grew edible mushrooms to be harvested by the buyer. Fungi have the ability to break down hazardous chemicals (Stamets, 2005), a function that could be integrated in the manufacturing as waste management. Future research could also investigate the use of waste material like non-biodegradable plastic could be used to enhance the material properties of the mycelium material.

### 6.4.3 Coatings

Mycelium materials are naturally biodegradable and the fungus will be re-activated if environmental humidity is higher than ten percent (Travaglini et al. 2013). Research on how to implement environmentally friendly coatings to make the products more durable and still keep its biodegradability is needed.

### 6.4.4 Shrinkage

As the high shrinking percentage is a major factor for implementation of mycelium materials, additional research is needed on how to control the shrinkage in order to meet higher demands on tolerances. High shrinkage is apparent in other materials fields too (Nielsen, 2016), and a recommended approach would be to implement and experiment with methods on how to solve the issue from their fields.
8 CONCLUSIONS
The chapter presents project conclusions through answering the research questions. Conclusions are reached regarding mycelium material from a general standpoint and in regards to the implementation onto the Livelo cargobike.

8.1.1 How are Mycelium Materials relevant for Industrial Design Engineering?
Designers play an important role in the environmental evolution (Friedman, 2010) and are the communicating link between material science and user. Increasing demands on sustainability in product development makes Mycelium materials relevant to Industrial Design Engineering mainly because of their ecological qualities but also because of their performance and the wide range of applicable fields. Mycelium materials are not breaking any new grounds in material performance and are barely matching the mechanical properties of the materials they hope to replace. The relevancy of using the material lies within the ecological aspect of product design engineering. This study found Mycelium materials to be eligible in a number of different product types. The most applicable field though, is lightweight products used in friendly environments with low demands on tolerances. These types of product don’t need additional coating and if the mycelium materials have sufficient material strength for specific task, it is possible to create a product that requires no energy to manufacture, is close-to carbon neutral, renewable and made from waste. The manufacturing cost for this product, excluding transportation, would then only consist of mold making and growing facilities. The relevancy of using the material becomes even greater considering that the closest material relative in terms of mechanical properties is expanded plastic foam. These foams are derived from fossil fuel and consume as much as 25% of global landfill by volume. Table below is a comparative table illustrating (in a general way) the differences in sustainability between Mycelium materials and Plastic Foams.

<table>
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</tr>
</tbody>
</table>
8.1.2 How may product developers replace environmentally exhausting materials with mycelium materials without compromising on the material properties?

The research presented in this study suggests that it is possible within lightweight products with low requisites on tolerances and homogenous quality. The material has successfully replaced plastic foams and adhesives (Travaglini et al. 2013) in packaging and as a replacement for engineered wood (mycobord, 2015). As for replacing structural elements like cement, additional research needed before it may be used commercially. Architect David Benjamin’s 12-meter-high structure proved it achievable (Arthur, 2014) and Phil Ross’s claim about his Mycelium Bricks being stronger than concrete suggests future development within the field.

Compression of the material during manufacture is affecting the properties of the end product. High density strengthens the material, especially the ability to withstand compressive loads (Ross, 2012). Maintaining low density gives the material lightweight properties and makes it suitable to use in insulation, packaging and as a core material in sandwich structures. Moisture level in the material is connected to the elasticity and strength of the material and may be altered with in to get the desired properties (Bayer & McIntyre, 2009). Moreover, the material is Class 1 fire retardant rated but needs coating in order to withstand water (Lefteri, 2014).

The material is naturally biodegradable meaning it will decompose if exposed to humid conditions (Travaglini et al. 2013). This may be seen as something good from an ecological point of view but makes it difficult to create lasting products without the use of coatings. The manufacturing time may be seen as a hindrance. The growth time for current commercial products is 5-7 days (Lefteri, 2014) though this study found that time to be insufficient to receive mycelium growth throughout the whole part.

Conclusively, any product developer in need of a material with an elastic modulus around 15MPa for densities 100kg/m³ (These are the properties of untreated mycelium materials grown without pressure) should consider using mycelium materials. The designer then have the option to design a product with a manufacturing process that need no supplementary energy without any ecological footprint, should you assume availability of local feedstock. The ecological and economic benefits of such material are obvious. It is up to the designer, for the specific task in hand, to weigh these benefits against the issues that comes with using the material (shrinkage, coating & quality). There are methods to lower the impact of these issues, but these methods add operations, materials and cost to the manufacturing process, affecting both ecological and economical benefits.

8.1.3 How may mycelium material be implemented in industrial manufacturing process?

Based the findings in this study and through analysis of the current research status it is considered somewhat difficult to manufacture the material yourself. By working together with experienced manufacturers like Ecovative, industrial designers may construct the material properties to match the specific problem. Evocative’s commercialization of their product also proves the material can be used for large scale manufacturing.

The manufacturing process is simple and does not require advanced gear (Ecovative GIY, 2014). Tools and equipment need to be sterile but the product may be produced anywhere on the globe.
8.1.4 What methods and compounds may be used to design and enhance the material properties?

The Mycelium may be used in combination with other materials in order to enhance the material properties. As the mycelium breaks down and mechanically adheres to organic materials, the need for gluing is removed if combined with organic support materials. This makes the material suitable to use in organic sandwich structures with mycelium material as the core. The creation and durability of this type of sandwich was tested in this study with positive outcome using veneers out of balsa wood. Other support materials include fabrics made of organic fibers such as flax or hemp. The fabrics may be used as skins or be implemented within the part. The fabric enhances the tensile strengths of the part with the mycelium stiffening the fabric by binding individual fibers together. Adding coffee grounds to the feedstock also seems to affect the material properties. The nitrogen in coffee grounds fuels the mycelium growth (studio murmur) while the relative density is increasing. Compressive pressure during growth makes the density of the material to grow higher and enhances the material's ability to withstand dynamic forces. Studies show the compressive strength of the parts becomes 6 times higher over non-compressed parts, and flexural strength doubled (Ross, 2012).

8.1.5 What parts could be replaced or added to cargo bikes using mycelium materials?

The material is not assumed strong enough to replace any structural elements without strengthening of other materials. By growing the material between veneers, the material can be used as a loadbearing sandwich structure in, for example, the cargo bay. Its protective properties make it suitable for use as impact protection purposes like, bumper or helmet. Its insulating properties can be harvested to safe-keep and isolate the battery to prevent energy diffusion and theft. The material can also be used in encapsulation purposes on products with low loreances.

8.1.6 How is the Cargo bike ecology affected using mycelium materials?

The environmental benefits of using the material is in accordance with the underlying drive for increased sales of electrical bicycles. The usage would further enhance the ecological message and act as a sales pitch when marketing the product. The product is powered by electricity during its life time which may raise concern about the ecology. If the battery is charged using oil-derived energy the winnings of using mycelium materials are annihilated. Though it is important to remember that it is the implemented technology causing these concern, not the material itself.
References


AFS 2009:2. 5 § Arbetskyddsstyrelsens föreskrifter om arbetsplatsens utomning. Collected 14 september, 2015, at Arbetsmiljöverket url: www.av.se


Nielsen,M 2016, Designing plastic parts, educational material for plastic course at Semcon Gothenburg.


Appendix 1 – interview questions

Initial interview questions used during information gathering. Presented in form of screenshot of email conversation.

Hi,

I’m Alexander Wagner, Design Engineering student currently conducting my master thesis project about mycelium materials. I believe designers have a responsibility as the intermediating link between users and material science to spread the knowledge about sustainable materials. The project objective is to research the possibility of implementing mycelium materials in the development of a cargo bike. The project plan is attached to this email if you are interested in a more detailed description.

I’m at the initial project phase collecting data and reviewing relevant publications. The material needs to have good material properties to match the requisite for project task and have to be able to withstand outdoor environment. I have started to experiment with ways to strengthen the material by adding support material and pressurise the evaporative GIY and have some questions I’m hoping you could help me with.

Support materials

I’m referring to materials that may be implemented to the core structure of the mycelium matrix and thereby enhance the material properties. I have looked for research about support materials for the mycelium but have trouble finding reliable results. My questions regarding this are:

What is your status in this field?

Have you found any materials that is that is suitable for this purpose?

Is adhesiveness between support materials and mycelium a necessity to improve properties?

Follow up question, is it important that the support material is organic or is it possible to get the hyphae to bind to plastic materials as well?

Substrate

How is the size of the compost affecting the material properties? For example what would happen if I would mix the mixed GIY before placing it into molds?

Is it possible to alter the mycelium growth by adding nutrients to the GIY?

Is it possible to enhance the properties by adding other agricultural waste materials to the GIY?

Mycelium

Does the mycelium material properties depend on what fungal species that’s used and what species is used in the GIY?

Skins

What’s your experience in creating sandwich panels?

What material are you using for your skins?

Does mycelium provide enough strength to bind the skins or is additional “glue” needed to get the skins to stay?

I would be very thankful if you could help me answer some of these questions. I will happily keep you updated in my research and share my findings.

Kind Regards

Alexander Wagner
Appendix 2 – GIY data
The table presents material data of the GIY from Evocative Design. Collected from Ecovative product gallery website.

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Ecovative</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density</strong></td>
<td>–</td>
<td>80-130 g/L</td>
</tr>
<tr>
<td><strong>Thermal Resistance</strong></td>
<td>ASTM D2844</td>
<td>R 3.6 Per Inch</td>
</tr>
<tr>
<td><strong>Compressive Strength (10%)</strong></td>
<td>ASTM D695</td>
<td>55-100 kPa</td>
</tr>
<tr>
<td><strong>Compressive Elastic Modulus (10%)</strong></td>
<td>ASTM D695</td>
<td>690-1034 kPa</td>
</tr>
<tr>
<td><strong>Flexure Strength</strong></td>
<td>ASTM D1037</td>
<td>413-1000 kPa</td>
</tr>
<tr>
<td><strong>Flammability</strong></td>
<td>TGA Test</td>
<td>Stable to 340°C</td>
</tr>
<tr>
<td><strong>Fire Resistance</strong></td>
<td>ASTM E84</td>
<td>Class A Firewall</td>
</tr>
<tr>
<td><strong>Flame Spread</strong></td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td><strong>Smoke Developed</strong></td>
<td>–</td>
<td>50</td>
</tr>
<tr>
<td><strong>Aldehyde &amp; VOC Emissions</strong></td>
<td>ASTM E1333</td>
<td>&lt; 0.01 – 0.03 ppm</td>
</tr>
<tr>
<td><strong>Water Vapor Transmission</strong></td>
<td>ASTM E96</td>
<td>30 US Perm, Class 1 Vapor Retarder</td>
</tr>
<tr>
<td><strong>Mold Resistance</strong></td>
<td>ASTM C1338</td>
<td>Pass</td>
</tr>
<tr>
<td><strong>Water Sorption</strong></td>
<td>ASTM C1134</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Airborne Sound Transmission</strong></td>
<td>ASTM E1050</td>
<td>0 – 6300 Hz</td>
</tr>
</tbody>
</table>
Appendix 3 - Velocity calculations

This tool was used in order to calculate drop height in material testing. Average impact force was later used to calculate, the sought-after, deceleration.

**Impact Force from Falling Object**

Even though the application of conservation of energy to a falling object allows us to predict its impact velocity and kinetic energy, we cannot predict its impact force without knowing how far it travels after impact.

If an object of mass $m = 4 \text{ kg}$ is dropped from height $h = 1.4 \text{ m}$, then the velocity just before impact is $v = 5.2383 \text{ m/s}$. The kinetic energy just before impact is equal to its gravitational potential energy at the height from which it was dropped:

$$K.E. = 54.879 \text{ J}.$$  

But this alone does not permit us to calculate the force of impact!

If in addition, we know that the distance traveled after impact is $d = 0.01 \text{ m}$, then the impact force may be calculated using the work-energy principle to be

$$\text{Average impact force} = F = 5487.95 \text{ N}.$$  

Greater penetration implies smaller impact force. Harder ground, less penetration, higher impact force. If it bounces back, the impact force is even greater because of the greater change in momentum.

Note that the above calculation of impact force is accurate only if the height $h$ includes the stopping distance, since the process of penetration is further decreasing its gravitational potential energy.