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Designing Circular Applications of Mycelium-Based Materials for Aircraft Cabins

MSc Graduation Project 2023

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hyfen

Designing Circular Applications of Mycelium Based Materials within Aircraft Cabins

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Preface

As someone having grown up in largely the 21st century, I was exposed to the grim reality of climate change and ecological deterioration from a very raw age. In 2021, I was a freshly minted graduate student at the Faculty of Industrial Design Engineering at TU Delft, focused yet on trying to grasp the nuances of sustainable design.A client case of designing a sustainable aircraft seating concept by a large aircraft manufacturing company during the advanced embodiment design Msc course exposed me to the aerospace sector's critical crisis. I tried to graze the surface of ecological composites through this project. My continued Internship in the aviation sector solidified my conviction that it is an industry with a very high need for sustainable & circular interventions.

Parallely, explorations in Biodesign and bio-based materials in my elective course Living Artefacts were helping me revisit my passion for biology and nature. A discourse on the unharnessed potential of DIY & bio-based materials during a summer school on Circular Economy by TU Delft & Aalto University sparked my curiosity. It sounded a bit far-fetched when I pitched to myself the idea of a thesis about using bio-based materials in the aviation sector - one with such stringent requirements. At the same time, I chanced upon this proposed thesis case by Airbus wishing to research fungal biotechnology, specifically mycelium-based materials for aircraft cabins. It was perfectly complementary to my own idea and immensely validating.

In February 2023, this incredibly eye-opening thesis assignment began. Over 20 weeks, I experimented, analysed and most importantly, envisioned and designed circular applications of mycelium-based materials for use within an aircraft cabin. The key idea was to be able to inspire researchers and designers in the aviation sector, by putting a drop in the ocean of possibilities. This thesis details my positively convoluted journey. It is that of an utterly unknowing student trying to understand a complex living organism of nature, and the nuances of a complex industry struggling to be sustainable. It ends with a graduate design engineer, having made an earnest effort to demonstrate how the aerospace industry could also strike a balance with nature.

Somewhere along this process, I have pushed my boundaries of understanding myself as a designer and as a person. Working with a living organism like Mycelia is truly humbling, and it has redefined my vision of a sustainable future and what I believe technologists and designers can do. In this thesis, I have reflected on this vision and hopefully have provided an iota of inspiration for the readers to contribute in their own way to a sustainable future.

Sincerely grateful,
Mrinal Chaudhury

Acknowledgement

A mere acknowledgement would not suffice the kindness, support and guidance to me, of so many individuals during this thesis assignment. I however wish to make a humble attempt.

I have genuine gratitude for my supervisory team comprising of Dr Ruud Balkenende (Chair) and Dr Elvin Karana (Mentor). Without any doubt, their immense expertise in the subjects of my research led to invaluable guidance. However, I was pleasantly surprised by how they pushed me to assert myself as a designer, reflect out of my comfort zone and embrace unpredictability. Their ability to engage me in critical analyses and their remarkable insights nudging me into new directions will surely have a long-lasting impact on me as a person & professional.

I also wish to extend my sincere gratitude to Dr Jelle Joustra, who first introduced me to this case and also facilitated the lectures & workshops of the Circular Aerospace Interdisciplinary Thesis labs by LDE CFS. Apart from facilitating, his knowledge of the associate subjects was crucial to this thesis. I met Dr Camille Carre, a polymer scientist at Airbus Central Research & Technology, who kindly set the preliminary case brief that is the basis of this thesis assignment. Throughout the thesis, she nudged with subtleties of the aerospace industry, helping me validate my process and results at each step. Through her, I got the chance to interact with Dr. Christian Weimer, Marie Sanou, Marloes van Put, Andreas Schuett from Airbus who were inspiring to say the least, in this entire process.

Some of my sincerest acknowledgements go to Mr Richard Groen, Mr Joren Wierenga, Mr Pietro Marchese, Ms Mascha Slingerland and Mr Roy Awater, whose technical support in bio-design and materials laboratories formed the backbone of this assignment. None of the results of this project would have come to light without their support. Not to forget, the PMB and the SDE Secretariat, who have had to bear with my continuous requests throughout this period. I really admire their patience and apologize sincerely.

Most importantly, my gratitude towards my support system - my family, my partner and my friends, in my home country and in the Netherlands extend beyond just this semester.
They would ensure at all times, that I was physically and mentally healthy to direct my energy towards my graduation. Oftentimes, this was achieved by literally taking over my human functioning. They also surprised me with their curiosity and relevant opinions regarding this project. My friends & colleagues in TU Delft, fondly referred to as the 'Graduation Gang' was the light in the lowest moments as we huddled behind the IO canteen in the afternoons or hunched over our laptops late at night in the library. Graduation can take its toll, and my friends and family always managed to lift my spirits up, be it with fun activities on weekends or simply the most cheerful and inane conversations.

I hope this project does justice to each of your efforts as well as it does to mine.

Abstract

This graduation project (Hyfen) elucidates opportunities for mycelium-based innovations in circular aircraft cabin design with a focus on material properties, applications and comparative environmental impacts.
Aircraft cabin interior elements account for 10% of an aircraft's empty weight, and are replaced 4-5 times during the lifetime of an airframe. Thus, cabin elements are responsible for a significant portion of an airliner's environmental impacts due to operational emissions and improper waste handiing. An understanding of the need to apply circular principles to the cabin led to heightened interest in mycelium-based materials which are lightweight and biodegradable.

The design goals where 1) Understanding the material properties of mycelium-based materials based on aircraft cabin requirements 2) Identifying optimal applications of mycelium-based materials in an aircraft cabin and developing selected demonstrators & detailed designs 3) Assessing the circularity and comparative Life Cycle Impacts of selected applications.

These goals were achieved through an adaptation of the Material Driven Design methodology. The final outcomes of this project included conceptual design and demonstrators of two applications An optimized bionic partition for the interiors of Airbus aircraft, and a versatile packaging cum meal tray for airlines. These specific applications were detailed to highlight the temporal & versatile properties such as competitive insulation (acoustic & impact), damage-resistant textures, foam-like compressive properties, mouldability into complex shapes and also comfortable tactile interactions for passengers. They also have a high potential to mitigate the environmental impacts of an aircraft cabin due to weight savings in the bulky interior panels, as demonstrated by a final circularity and fast-track life cycle assessment.

Takeaways from this thesis also include insights into the family of optimal applications which included hot & cool cases, galley, business class & first class seat shelving systems, cushions and upholstery for seats and even decorative filler material for armrests and accessories. These applications to different degrees, leverage the unique material properties (e.g. low weight, mouldability, apparent sustainable advantage, warm & comforting textures etc.) of pure mycelium and myco-composite materials. It also adds to an understanding of the design requirements for circular applications using mycelium derivatives and aims to inspire further research & development for deployment.

This thesis provided conclusive foundational qualitative evidence on the potential environmental advantage of mycelium applications over plastics, composites and other petroleum-derived materials in an aircraft cabin. Future recommendations include looking into standardization, commercialization, usability and acceptance. Project Hyfen aimed to be visionary and embolden the stringent aerospace sector to seek solutions in nature for its circularity transition - with biobased materials like mycelium being the building blocks, literally and figuratively.

Glossary

Mycelium	Mycelium is the root-like network of fungal threads or hyphae, which is the vegetative part of a fungi
Bio-based	Broadly refers to materials derived from biomass, such as plants and microbes
Mycelium Based Materials	Materials that are produced by the growth of mycelium on suitable mediums
Aircraft Cabins	An aircraft cabin is the section of the aircraft in which passengers travel. It is also commonly referred to as aircraft interiors
Circular Economy	The circular economy is a system where materials never become waste and nature is regenerated (Ellen MacArthur Foundation)
Substrate	The surface or material on or from which an organism lives, grows, or obtains its nourishment.
Incubation	Microbiological incubation refers to maintenance of the controlled environmental conditions necessary for supporting the growth or development of a microbe or cell.
Inoculation	The process of introducing microorganisms into a new substrate
Myco-composites	Solid lignocellulosic substrate bound by mycelium to make a solid mass or composite like material
Life Cycle Assessment	LCA is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service (Wikipedia)
Material Tinkering	To work with materials in a hands-on manner to search or understand properties and behaviour of a material with a designerly intention
Bionics	The study of mechanical systems that function like living organisms or parts of living organisms

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Project Introduction

This chapter provides the readers with an overview of the motivations of the author for this project. It goes on to introduce the initial assignment of understanding the challenges, opportunities and needs for deploying mycelium-based materials in aerospace. A brief overview of the contextual research on the environment these innovations are being sought is followed by a better understanding of the research questions. These research questions are filtered to the key challenge and sub-challenges that are within the scope of this project

1.1 Motivation

The global aviation industry, including both passenger and freight emitted approximately 900 million metric tons of CO_2 in 2019 pre-covid (CO_2 Emissions of Airlines Worldwide 2004-2022, n.d.).

As a designer and innovation management intern in the aviation industry, I have witnessed firsthand the conundrum the aviation industry faces - becoming net zero whilst catering to the growth demand. Airbus, the prime commercial aircraft manufacturer in the world, projects that demand for air passenger traffic will grow annually by 3,6% (2019-2042 CAGR) over the next 20 years (Global Market Forecast I Airbus, 2021). It accounted for 3.8% of the total CO_2 emissions in 2017 in the EU. Before the COVID-19 crisis, the International Civil Aviation Organization (ICAO) forecasted that by 2050 international aviation emissions could triple compared with 2015 (Reducing Emissions from Aviation, n.d.).

Without rapid and disruptive changes, this growth will only result in magnanimous growth in the CO_2 and non CO_2 emissions, cabin material waste generated from each flight and material waste generated upon decommissioning of aircrafts and it's cabin interiors.

The sight of the scale of most material waste like single use plastic and composites from an aircraft being incinerated or landfilled pushed me to strive to find alternative sustainable material sources in previous endeavours. It goes without saying that weight reduction to support transition to clean fuel systems is always aimed for.

Air traffic has brought a lot of growth, joy and connectivity to the world, yet it's circular transition is one of the hardest. As a designer with circularity and sustainability as my key driver, I wish to apply my basic knowledge and understanding of biobased materials and biodesign towards easing this transition.

I believe in the potential of inspiration and sourcing of knowledge firsthand from nature, especially for materials holds the answers to the most pressing issues of our times.

Source: AELS.nl

1.2 Initial Assignment

This thesis project is based on a case provided by the Airbus Group Central Research & Technology, to explore the application of mycelium-based materials in aviation. The aviation industry is looking frantically for developments to increase fuel efficiency by incorporating lightweight components in the fuselage of aircraft. Conventional petroleum composites with high strength-to-weight ratios satisfied several of the requirements but proved incredibly difficult in being circular. At this juncture, lightweight, highly performant bio-based materials are offering engineers exciting possibilities for improved environmental performance. (Future Materials | Airbus, 2021).

Mycelium-based materials have shown a huge potential to replace conventional petroleum-based materials towards a more sustainable and circular economy. However their application is still limited and some key challenges have to be solved to implement fungi biotechnology and mycelium-based materials in the aerospace industry.
This initial assignment as agreed, intended to address some of the following broad challenges.

| *Mycelium-based products are produced at a small scale. What are the challenges to upscale the technology and make mycelium-based products the materials of choice for our tomorrow's cabin materials?*

| *What are the aerospace needs? What can mycelium be used for and how can this be practically realised?*

| *What are the Challenges and Opportunities, e.g. viable waste streams identification and if car industry is also interested, as well as leather for fashion (bags, etc.).*

| *Are there any economies of scale benefits? How to scale-up biological manufacturing processes?*

| *What is the environmental impact of mycelium-based applications in a life cycle assessment?*

1.3 Context & Background

1.3.1. 'Forces for Change' for Aviation

The inspiration to explore new materials in an industry often is a result of the push for change from varied directions, termed 'Forces for Change' by researchers (Ashby, 2011).
'Forces for Change' refers to influences for the industry to design for and deploy new and unique material applications. Here we are asking, what are the forces that are inspiring the aviation industry to explore mycelium-based materials.
Forces for change for new or changed materials as shown in (Ashby, 2011)
One can find this through a quick scan of the literature and current affairs that 'legislation' targets the aviation industry for the reduction of its environmental impacts. (Reducing Emissions from Aviation, n.d.).

Improvement of performance, especially lightweight applications for reduced fuel consumption is another crucial force. Bio-based materials for the aerospace sector have been explored and proven to provide considerable benefits by researchers of the EU-funded ECO-COMPASS project (Bachmann & Yi, 2016).

Increasing consumer consciousness about their transport provider's sustainability, (albeit not explicitly evident by the growing number of flyers) is another factor pushing the aviation industry towards using materials that mitigate their negative environmental and social impacts. (Baumeister et al., 2022).

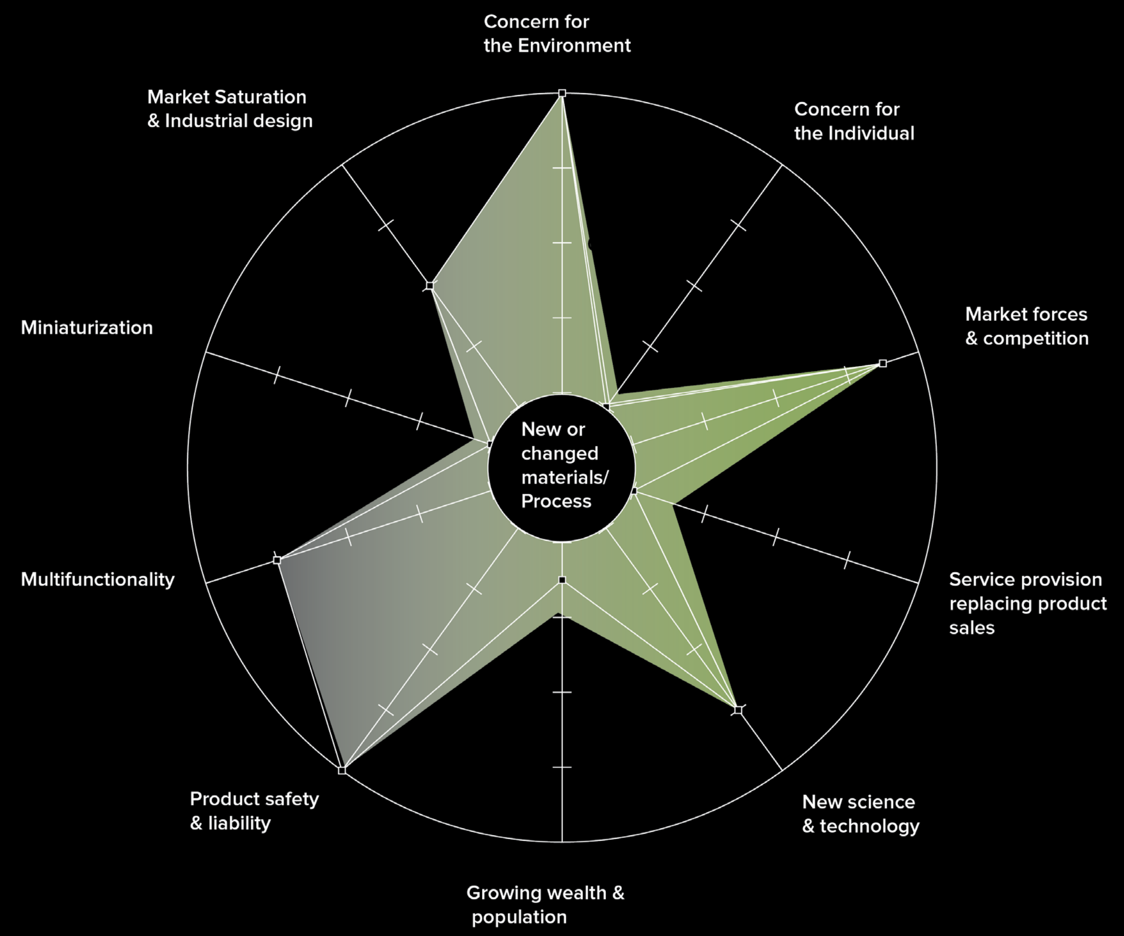
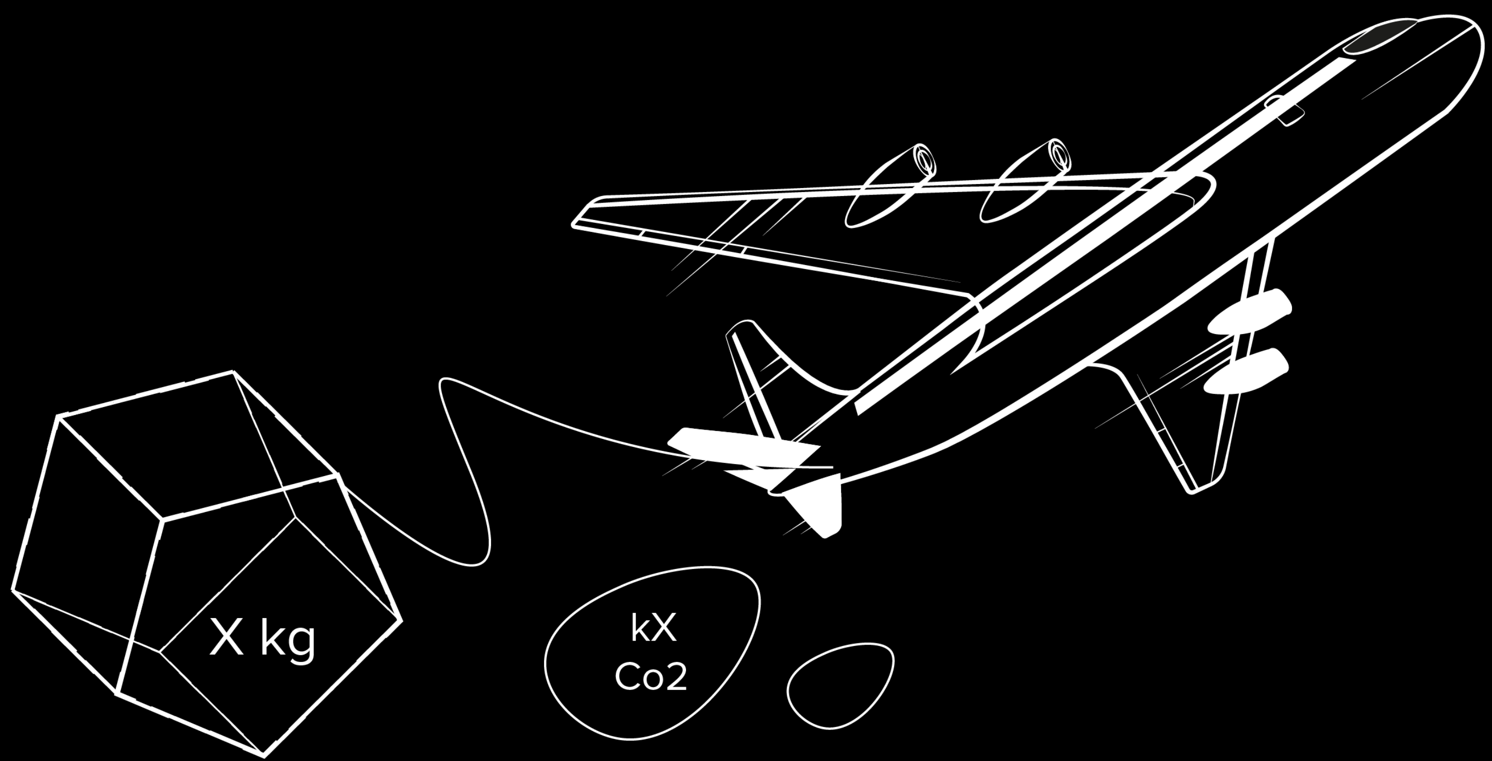


Fig.1. 'Forces for Change for aviation industry to look for new materials & processes, adapted from (Ashby, 2011).



However, the process of introduction of a novel material and deployment with certification in an aircraft is a long drawn process involving a designing and testing pyramid (Smart Certification for Sustainable Aviation, n.d.). It took nearly three decades to advance both carbon fibre composites and fibre metal laminates from first tests in the laboratory to their introduction in aerospace.

The steps of a novel material's introduction and deployment are briefly described here after consultation with the caseholders and readings. They are as shown in Fig 2.

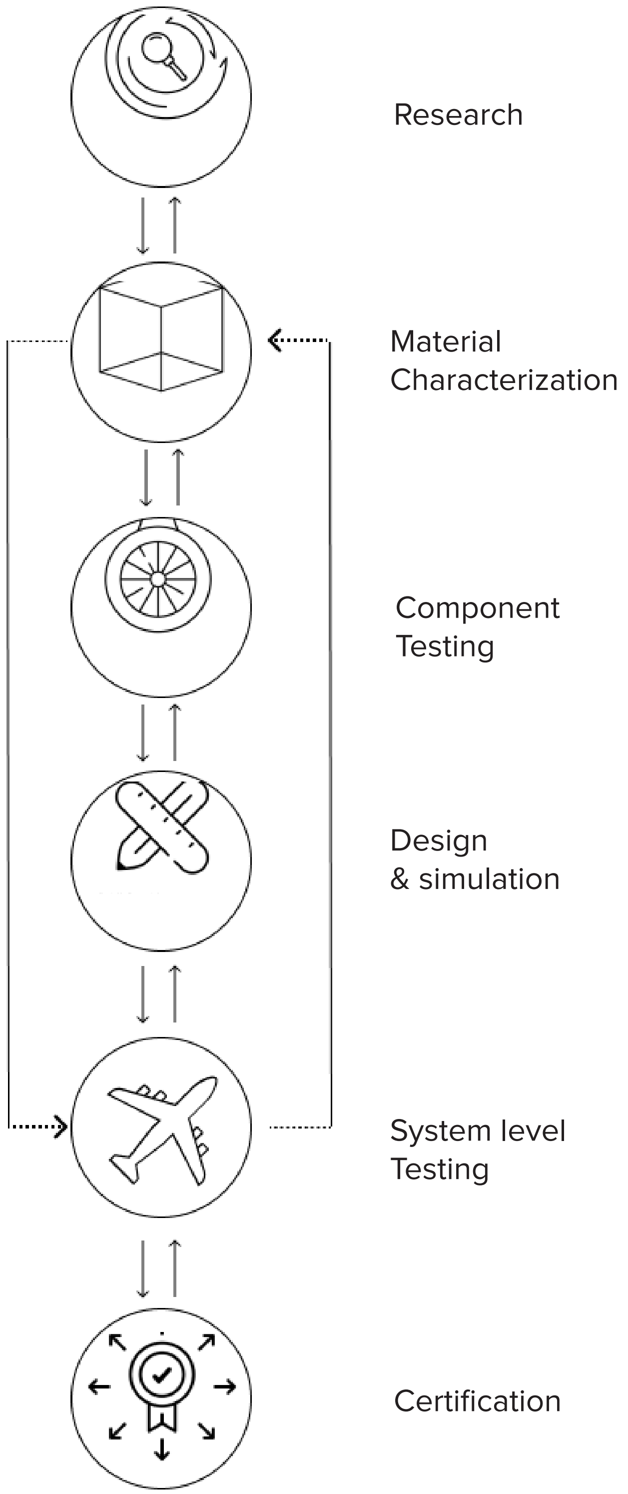


Fig.2. Overview of general steps for introduction of a new material in aviation

1.3.2. Circularity in Aviation: Key Issues

Some approaches associated with circularity have been a part of aviation intrinsically - such as designing products for aircrafts with a long service life (in the order of magnitude of several decades) and maintenance, repair and overhaul (MRO) is an area of significant expertise in aviation.

However, when it comes to cabin materials and interiors, elements are not designed to last an aircraft's entire lifespan. Interior panelling, upholstery, seating and galleys etc. are updated or replaced 3-4 times in an aircraft's general 30 year lifespan.
The discarded components made of composites, plastics and synthetic fabrics, along with copious amounts of single use plastics after each flight, land up in landfills or incineration by airlines.

Up until now, aviation stakeholders have put very limited focus and effort into the end of life of aspects - namely degradation, recycling or reuse of components. Considerabley difficulty is encountered when these principles are applied to products in the aircraft which were not originally designed to be circular. An effective way to incorporate circularity is to implement circular design principles when developing new products, at the conceptual design phase.

Publications of key aerospace organisations have identified certain priorities regarding design and manufacturing activities to aide the circular transition for commercial aviation. However, the ground reality of implementation is a bleak picture, with circularity assessments being relatively new to the industry and profits still being a preceding consideration.

Regardless, some suggested potential priorities for design and manufacturing in aviation are as follows:

Circular design solutions - A focus on extended durability, ease of repair and disassembly, reuse of components, eco-design and recycling. Design practices, manufacturing processes, related practices and frameworks specific to applications in aviation are desired.

Choice of materials - Resourcing and environmental considerations must be a part of material selection for applications. Bio-based materials and recycled materials are being favoured and harvesting of critical materials must be minimised.

Resourcing of (recycled) materials - The limited use of recycled materials in aviation is linked to the lack of feasible recycling methods and uncertainties about the qualification and safety of such materials, as regulations on the topic are still being developed. However, urban mining activities, already introduced in cities and communities, can be phased in airports and aircraft boneyards as a starting step in combination with qualification activities.

Circular Manufacturing - Developing, validating and integrating first-time-right solutions for the manufacturing of aircraft parts are promising. In addition, manufacturing facilities envisioned as close systems with local renewable energy production and treatment of waste contribute to ambitions of zero waste, zero GHG emission and minimum energy consumption facilities.
(Circular Economy - NLR, n.d.), (Future Materials | Airbus, 2021)

1.3.3. Bio-based & Sustainable Composites in Aviation Interior and Secondary Structures

The most notable of the extensive research and demonstration of ecological composites and bio-based materials in aviation has been the ECO-COMPASS project, a consortium between 8 EU partners and 11 Chinese partners. This project, albeit examining a different material, can take several notes from the results and discussions of the ECO-COMPASS project due to similar anticipated challenges.

Thus this section largely summarizes this landmark project's aims and results, which can serve as an inspiration for this thesis assignment (Bachmann et al., 2021), (Bachmann et al., 2017).

Aim:
The ECO-COMPASS partners developed and assessed ecologically improved and multifunctional composites for application in the aviation sector.

Challenges:

The challenges addressed by the ECOCOMPASS project are summarized as follows:

1. Identification of applications for Eco and multi-functional composites.

2. Development, characterisation and simulation of ecologically improved and multifunctional materials and further development based on requirements of the applications.

3. Manufacturing and validation by representative aeronautical demonstrators

4. Assessment of ecological impact by Life Cycle Assessment

The relevant outcomes of this project are as follows:

Material development: The ECOCOMPASS project developed various green composites such as pure plant fibre & bio-based resin honeycombs, hybrid non-woven flax and recycled carbon fibre composites and green honeycombs made of hybrid between natural fibres & classic aramid fibres. Rosin acid and itaconic acid-based curing agents with approximately 30–40% bio-based content were also synthesized and examined.

Material properties: Composites using purely natural fibre reinforcements showed poor mechanical properties due to poor interfacial properties between the hydrophilic plant fibres and the hydrophobic polymeric matrices. Mechanical properties, fire retardation and even anti-microbial properties show improvement with some component hybridization (e.g addition of recycled CF), nanoparticle grafting and nano-modification. The addition of flame retardants on fibre and matrix levels shows positive effects on flammability. Heat release and smoke density requirements could not be fulfilled so far.

Modelling & Demonstrators: The project achieved satisfactory Adoption of modelling & simulation tools with specific applications for bio-materials with their divergent and complex characteristics. Several interior and secondary structure demonstrators, such as an elevator panel and interior side panel, showed the potential of many eco-materials to be processed in a similar way compared to the state-of-the-art composite material.

Preliminary Life Cycle Assessment: A first overview of environmental impacts of the ramie natural fibre and bio-based epoxy curing agent and compared to generic datasets of glass fibres respectively epoxy resin. A potential improvement in ecological impacts for bio-based materials is visible for impact categories such as global warming potential, mainly due to lower energy consumption.

Fig.3 Conceptual projects in aviation about mycelium applications

1.3.4 Interest in Mycelium based materials for Aircraft Cabin

There is currently no publication (atleast very easily available) that has explored the application and commercialization of mycelium based materials in the aviation industry, clearly highlighting the need for the exploration. All endeavours mentioned in this section have been one-off instances of trials or have explored mycelium for decorative purposes.

A pioneering interest in Mycelium based materials for aircraft interiors was shown by the client - Airbus, with a few standalone demonstrative pieces and design concepts. At the Floriade expo, in collaboration with Inholland, Economy aircraft seating demonstrator with mycelium based foams was developed. It was part of the project Stichting Innovatie Glastuinbouw Nederland (SIGN project). Fig 3. Mycelium based aircraft seating demonstrators as part of the SIGN Project

At the Hamburg Aircraft Interior Expo 2023, Airbus also unveiled the C-Suite business class seat as part of it's Airspace 2035 vision (https://www.facebook.com/airbus, 2023). The seat developed by the Advanced Cabin Design team at Airbus proposes the utilisation of mycelium leather for upholstery and as armrest covers. No openly accessible record of demonstrators was found yet.

An observation of relevance for this thesis is that none of these applications have leveraged the versatile or the more unique properties of mycelium materials such as low-weight, acoustic damping, textural & shape complexity or biodegradability.

Most of the explorations till now have utilised mycelium materials more decoratively, signalling underutilisation of this novel material's capabilities. This presents a key challenge and opportunity for this project.

1.3.5. Commercial or artefact-based mycelium applications in other industries

The aerospace industry may not have had a lot of examples yet, however researchers, architects and designers have demonstrated few impressive products and temporary constructions made using mycelium-based materials. These are usually single artefacts of installations.
However, in a context such as an aircraft cabin where feasibility and commercial viability is of utmost importance, inspiration can be sought from established fungal biotechnology-based companies.

One of the oldest and most established companies with a wide range of mycelium applications is Ecovative started in 2007 by Eben Bayer and Gavin McIntyre. Their high-performance foams (Forager) produce applications for beauty, furniture, the fashion industry and more. Mogu, in San Francisco, produces acoustic wall and floor panels made of mycelium composites as sustainable interior panelling for homes. Mycoworks has been popularized for its low-carbon natural leather called Reishi.

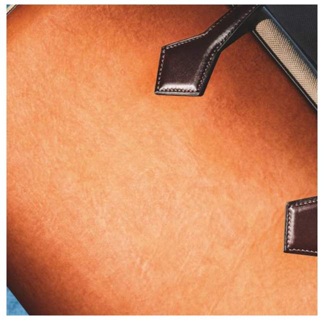
Interesting applications have also been demonstrated by designers, engineers and biotechnology companies as well. The following section is a brief overview of some mycelium based applications in other industries and the properties of mycelium they have used to it's advantage.

Commercial & artefact based mycelium applications

A list of applications of mycelium based materials in other industries and the mycelium properties they take advantage of.

Low-carbon and low energy production

Grown Bio
Pavillion
for DDW 2019



Hermes
Bag made of Reishi
mycelium leather

Ecovative
Myco-composite
packaging

Biodegradability

Loop Biotech
Mycelium Coffin

Mycotex
Mycelium textile

Shapability & Mouldability

Blast Studio
3D Printed living
mycelium column

Grown bio
Mush lume lamps

Eric Klarenbeek
Mycelium living chair

Ecovative
Myco-foam based disposable footwear

Acoustic & Thermal Insulation

Ecovative Forager
Myco-foam based
cushioning

Mogu
Acoustic panels

Grown Bio
Hot & cool cases

Studio MOM
Mycelium helmet

1.4. Problem Definition, Scope & Research Questions

In this section, the conclusions derived from contextual research are used to reframe the initial problem definition & define the research questions.
Mycelium composites are lightweight, bio-based, sustainable and naturally biodegradable, making them a seemingly lucrative choice for applications within an aircraft. Despite bio-based materials and living composites having found commercial applications in several industries, the aviation industry has exercised reasonable caution because of some challenges.
Some of these broad challenges include:

1. Lack of knowledge on material properties & performance for the specific needs of an aircraft cabin.

2. Lack of identified and demonstrated applications of mycelium within aircraft cabins to have a foundational basis to inspire further research and targetted development.

3. Environmental & circularity assessment of mycelium materials to find conclusive proof of it's environmental advantages before substantial investment & usage.

4. Lastly, design, development and optimization of fungal biotechnology processes for scaling up mycelium for the life-cycle of products and services for aircraft cabins.

Table 1 outlines these key identified challenges and their sub-challenges or research questions through a cause-effect analysis method.
These research questions are further identified as in-scope or out of scope due to limitations over resources and knowledge at this juncture of the project.
A guide to the right of the research questions is used to inform the reader of the chapters where these research questions are answered and the stage of the research & design methodology (Material Driven Design based) that was used to answer it.

1.5. Approach & Methodology

This thesis project aims to design to design & assess applications for an aircraft cabin context with mycelium based materials as a point of departure. The most well defined and well understood methodology by me, which can aide meaningful design is the Material Driven Design method developed at the Faculty of Industrial Design Engineering, TU Delft (Karana et al., 2015). Broadly, it follows the order of understanding & characterizing the material, distilling it's unique properties , defining a vision and designing products to manifest material experience patterns and realise the vision.
A detailed account of the research & design methodology that has been adapted for this thesis assignment to incorporate the research questions, is provided in Chapter 2.

1.6. Final Deliverables

An overview of mycelium based material properties of significance and advantageous to the aviation industry.

1. A list of requirements and desired attributes to guide a generalised design of circular applications for aircraft cabins using mycelium materials and similar bio-based materials.
2. An overview of a family of cabin applications that utilise mycelium materials to it's advantage.

3. Concept design, demonstrators and development process of selected applications to enable further research, commercial development and optimization.

4. Preliminary comparative circularity and life cycle assessment of the selected application as a reference.

Table 1: Table of Research Questions & Scope

Key Challenge	ID	Research Questions	Chapter	Methodology Stage
Lack of knowledge on material properties & performance for the specific needs of an aircraft cabin	RQ 1.1	What are the factors that determine the material profile of mycelium materials? How can variations in these factors result in desirable profiles for aircraft cabins?	3-4	Understanding the Material
	RQ 1.2	What are the requirements or desired properties of materials used in an aircraft cabin?	3-4	Understanding the Material & Creating Material Experience Vision
	RQ 1.3	How do mycelium materials (pure & composite) compare to current aircraft cabin materials?	3-4	Understanding the Material
	RQ 1.4	What are the properties of mycelium based materials which can be the most desirable or beneficial in an aircraft cabin?	3-4	Creating Material Experience Vision
	RQ 1.5	How can mycelium materials be processed to prepare them for compliance & certification by Aviation Safety Agencies?		
Lack of identified and demonstrated applications of mycelium within aircraft cabins to have a foundational basis to inspire further research and targetted development	RQ 2.1	What are the range of applications which are desirable and feasible for mycelium usage in cabins?	5	Manifesting material experience patterns
	RQ 2.2	What properties of mycelium materials do these applications benefit from?	4-5	Manifesting material experience patterns
	RQ 2.3	How can these applications be produced and assembled in an aircraft cabin?	6	Designing material/product concepts
	RQ 2.4	What are the intended impacts of these applications in the aircraft cabin?	5-6	Designing material/product concepts
	RQ 2.5	What are the usability and ergonomic concerns that arise over the lifespan of use of the products?		
	RQ 2.6	How does the material qualities, visual, technical or others alter over the course of time if the usage lifespan is in years?		

Research Question in Scope

Table 1: Table of Research Questions & Scope

Key Challenge	ID	Research Questions	Chapter	Methodology Stage
Environmental & circularity assessment of mycelium materials to find conclusive proof of it's environmental advantages before substantial investment & usage	RQ 3.1	How does the environmental footprint of mycelium based applications compare to the current conventional applications?	7	Designing material/ product concepts
	RQ 3.2	What are the end of life strategies suitable in the controlled aviation context, for mycelium based applications?	7	Designing material/ product concepts
	RQ 3.3	What are the environmental hotpsot processes in the lifecycle of produce, use and end-of-life of mycelium applications?	7	Designing material/ product concepts
	RQ 3.4	How can these environmental hotspot processes be optimized for climate neutral or climate positive life cycle processes?		
	RQ 3.5	How will the aircraft interior supply chain for these circular applications look like?		
Lack of identified and demonstrated applications of mycelium within aircraft cabins to have a foundational basis to inspire further research and targetted development	RQ 4.1	How can laboratory processes of mycelium product production be scaled up to cater to annual demands of aircraft manufacturers?		
	RQ 4.2	How these industrial processes handle the uncertainty that accompanies production using a living organism?		
	RQ 4.3	What is the viability of the production, use and end-of-life of these applications?		
	RQ 4.4	How can the production facilities and airlines cater to needs of maintenance, repair, refurbishment and recycling efficiently?		

Research Question in Scope

Research & Design Methodology

In Chapter 1, the problem statement, the research questions and the scope were redefined in light of this thesis project. To go forth in a systematic manner to achieve the goals set, a research & design methodology inspired by existing methodologies was required. This chapter begins with an introduction to inspiring methodologies and frameworks such as Material Driven Design (Karana et al., 2015), Material Ecology (Oxman et al., 2015) and strategies for finding applications for materials (Landru et al., 2002).

An adapted design methodology specific to this thesis assignment and context with the Material Driven Design methodology as the foundation is described in detail. The aim of a specific chapter on this methodology is to be able to allow other researchers to understand, replicate or reconstruct it for material-based design or bio-design in aerospace and similar contexts.

2.1 Existing methodologies & frameworks

In a standardised modern industrial design, architecture or engineering process, the design and development of the form & function precedes material selection and is largely independent. However, in certain situations, the material is the point of departure for design and development. It may happen for example, when a novel material is created and catches the attention of people, or applications are being sought to prevent the loss of value of a material in circular economy. In this thesis, the prior happened.
Three key publications were studied to seek inspiration to develop a suitable methodology for this project.

Strategies for finding potential applications of materials (Landru et al., 2002) :

3 strategies are defined. They suggest substitution based on properties, matching design requirements and lastly, making a selection by function.
A reflection of these strategies suggest it might be a bit obsolete for a complex material like mycelium where one cannot discard potential applications based on absolute values of material properties.

Material Ecology (Oxman et al., 2015) :

Both a design approach and an associated collection of tools and techniques, Material Ecology seeks to bring the built environment closer to the natural and the biological environment. By integrating digital design research, environmentally aware computational form generation and digital fabrication, the method seeks to create objects that are alive, responsive to the environment as they age.
While this method was found to be modernist, it is more suited for a singular specific application and can be used when a rather advanced idea of the desired application design is fixated upon.

Material Driven Design (Karana et al., 2015):

This methodology, developed at TU Delft equips designers and researchers with tools to design meaningful applications with emerging materials which have unfamiliar, unusual or novel properties and experiences. It allows the designer to qualify the material beyond what it is, to what it does and how it interacts with it's environment and user.

This method was the most well understood and perceived as suitable for the current challenge of application design for this thesis assignment. Thus, it was decided to use Material Driven Design as the foundational methodology. It is described in detail in the following section.

2.2 Material Driven Design

The MDD Method has four main action steps in the following sequence:

1. Understanding The Material: Technical and Experiential Characterization

This step focuses on articulating the product's unique role (in contrast to alternative materials) when applied in products. It implies tinkering with the material to understand the forms that can be achieved, methods to shape and process it and its technical/mechanical properties. It also includes benchmarking to position the material amongst similar and/or alternative materials, to generate insights on potential application areas. Exploring the aesthetic and experiential qualities through user studies is also part of the step.

2. Creating Materials Experience Vision

The step involves articulation of the design intention, called the Material experience vision in this method. The Materials Experience Vision expresses how a designer envisions a material's role in creating/contributing to functional superi-

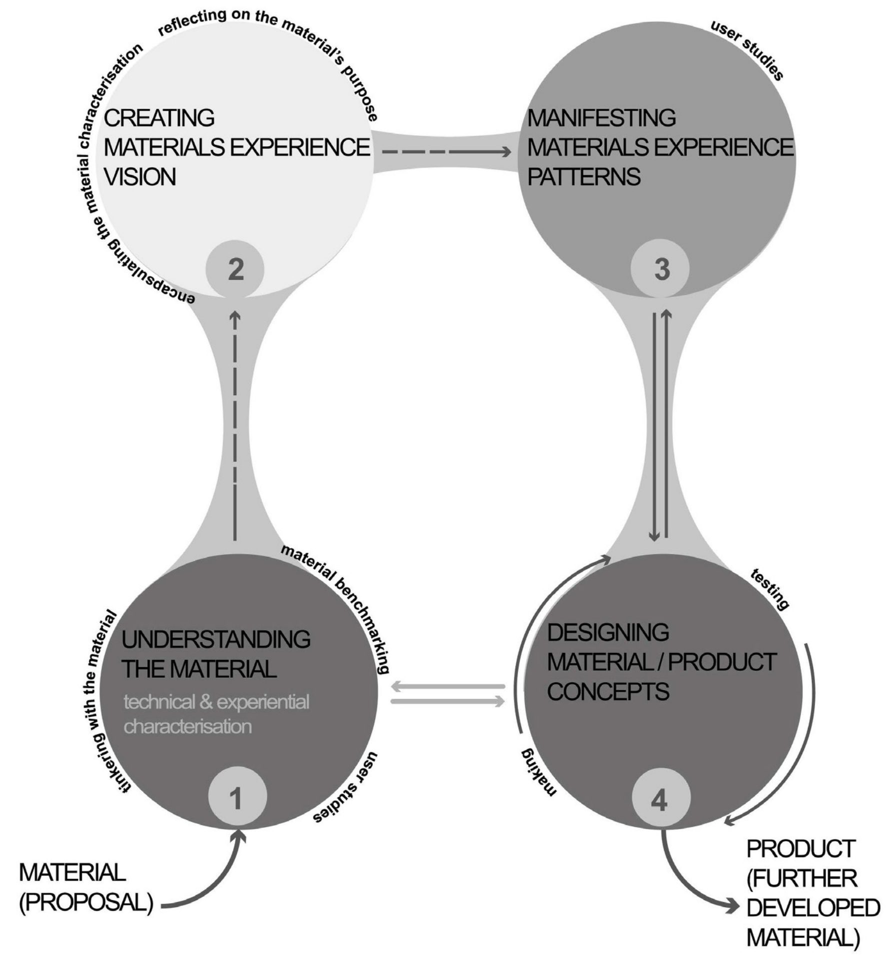


Fig 4 Material Driven Design Methodology (Karana et al., 2015)

ority (performance) and a unique user experience when embodied in a product, as well as its purpose in relation to other products, people, and a broader context (i.e., society and planet) (Karana et al., 2015). A metaphor showing the interaction between the user and the material is also created.

3. Manifesting Materials Experience Patterns

In this step, the materials' experience vision and interaction are analysed to link them to the formal qualities of new materials and products. The analyses provide 'meanings' (such as feminine, familiar, high-tech, etc., under the interpretative level of materials experience), which can be more easily operationalised in user studies. As a conclusion, the designer is expected to summarise the findings of the study, use his/her own intuition to interpret the findings and formulate the relationships between the formal properties of materials/products and the explored meanings.

4. Designing Material/Product Concepts

In this stage, the designer integrates their main findings into a design phase. The method mentions that this step doesn't necessarily need to be the ultimate step and contemplation of product ideas can go hand in hand with other steps. In this particular situation, an application domain has already been specified, which triggers ideas from an early stage. However, the ideas need to be translated into the product (or product service system) concept incorporating the results & conclusions of the previous steps.

5. Embedding Circular Thinking in Material Driven Design
As stated in the scope, this project aims to design circular applications. Thus, inspiration is taken from the tools suggested by (Vogel et al., 2020) to embed Circular Thinking in Material Driven Design.

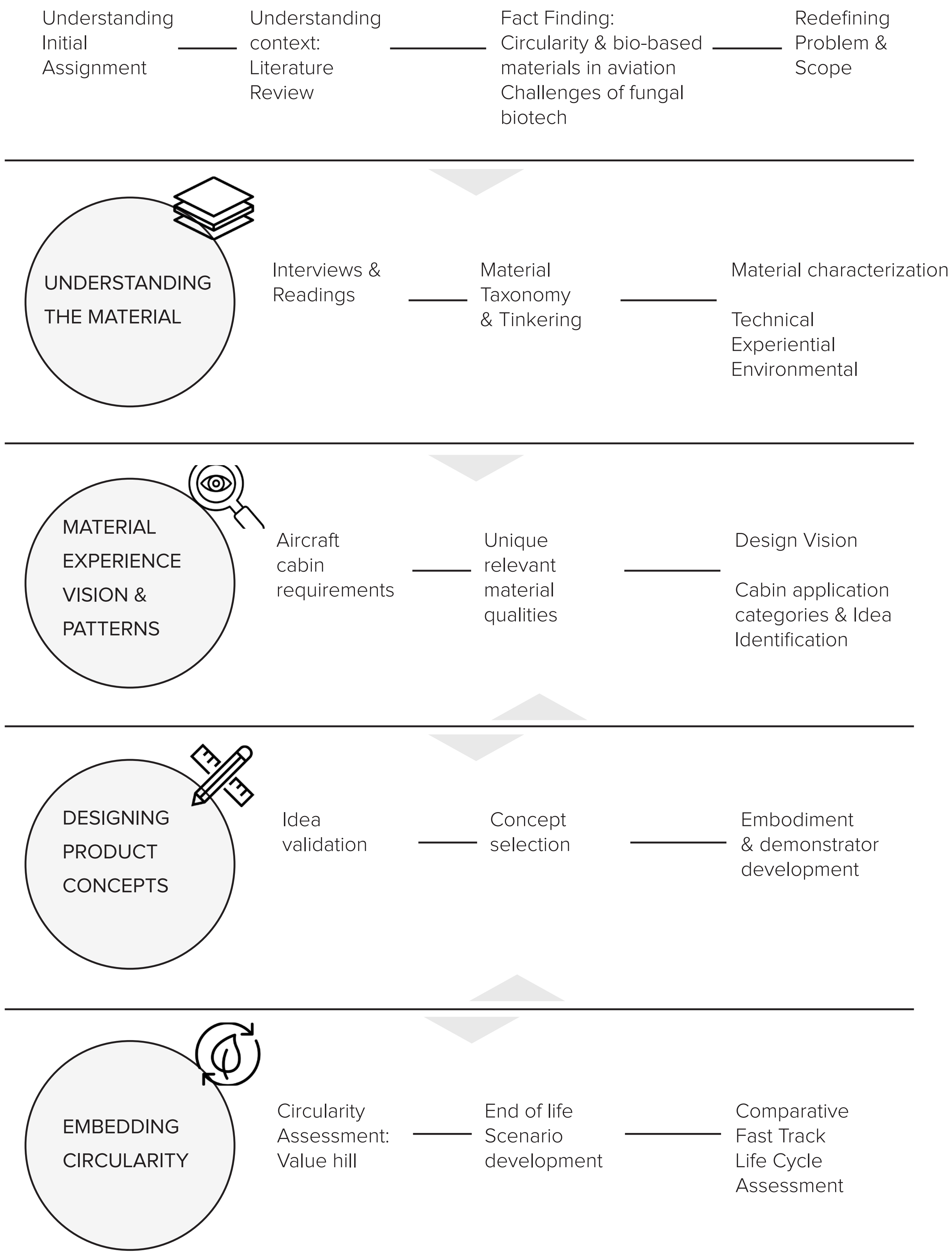


Fig 5: Research & Design Metholodology of this project

2.3 Research & Design Methodology : Project Hyfen

In this graduation thesis project titled Hyfen, existing methodologies serve as the foundation on which a detailed adapted methodology is outlined. This adaptation was necessary to tailor the process to design in the unique situation for Material Driven Design, that the material - Mycelium and the broader application context - Commercial Aircraft Cabins, are both provided.

The specific processes in the methodology are broken down and shown in fig 5, to enable researchers and designers to reproduce or adapt this work for their own endeavours in this field. The process in practical life was not linear but iterative.

Takeaways

1. Form preceding materialization as a principle had gained precedence and become a norm for industrial design, architecture and engineering in the modern world (Oxman et al., 2015). As these professional communities began revisiting the principles of nature and aimed to build products symbiotic with or derived from nature, the material regained its importance as the progenitor of form.

2. In this case, the material - mycelium, is the starting point for design instead of the form or function. Intuitively, the select pioneering methods in the 21st century, namely - Material Driven Design & Material Ecology, provide methods, frameworks and toolkits for design dependent on material knowledge & experimentation. All of them had set the material as the point of departure.

3. The Material Driven Design developed at the Faculty of Industrial Design Engineering at TU Delft, was the most thoroughly available and understood by me as a designer and author. It stood out in its completeness for me where it not only allows a design engineer to qualify a material's constituent characteristics but also for its affordances in functions, its meanings & expressions and lastly its interactions with users. It is also a method adaptable to incorporate circularity from the outset and build unique scenarios.

4. In this thesis, the method was detailed at each stage with activities that are specifically relevant to bio-based material-driven design for aviation and aircraft cabins. Variations from a general case for the method mainly include the following:
Introduction of aviation-specific technical characterization steps

5. Developing material experience cum design vision based on both unique material properties and aircraft cabin performance requirements
An iterative product-service design combining circularity & life cycle assessment with the design vision.

Science of Mycelium Based Materials

Chapter 3, serves as the starting point of research using the methodology outlined in Chapter 2. It is the preliminary phase of 'Understanding the Material' (Stage 1 of the methodology) wherein the basic science of mycelium materials and how they can be manipulated to manifest a wide range of material properties is outlined. Mycelium materials can be a large family of materials which are analogous to certain conventional materials. Factors that determine the resultant mycelium material category and afforded functionalities are described briefly. A conclusion is drawn about the factors that will be experimented with and those that will be considered constant for the span of this project.

3.1. Understanding the Material: Methodology

In order to initiate 'Understanding the Material' for the design of aircraft cabin applications, I resorted to literature research on the biology & fabrication of the material (Appels et al., 2019), (Vandelook et al., 2021), (Ng et al., 2022) and its resulting properties and ultimate performance.
In addition, semi-structured interviews were conducted with 3 experts.
The experts had expertise listed on the right.

The interviews resulted in an understanding of the list of factors that can be varied to tailor the mycelium materials for generalised & specialised requirements for aircraft cabin materials - for example, material integrity,waterproofing, fire retardancy or sustainable visual properties.
These insights were supplemented with readings about the material development of mycelium materials to material taxonomies developed by other designers and researchers like (Karana et al., 2018), (From biomass to mycelium composite. An exploration on cellulose and weed residues, 2020) and (Appels et al., 2019), amongst others.

These interviews and readings helped the creation of a broad material taxonomy of factors that can be varied to create unique profiles of mycelium-based materials tailored for aerospace and cabin applications. While this taxonomy (fig 9) can be used as a basis for further projects (with verification), a revised taxonomy with only factors for material tinkering in this project is shown later.

Key insights of this research and a part of the material tinkering are described in further sections of this chapter. Analysis of the material performance is detailed meticulously in Chapter 4.

Expert ID: MT1

Education & Research Technician developing a Biolab at Faculty of Aerospace Engineering, TU Delft. He is a biotechnologist by education specialising in fungal isolation, taxonomy and biochemical characterization.

Expert ID: MT2

Associate Professor and Head of Shaping Matter Lab at Faculty of Aerospace Engineering, TU Delft. Specialised in developing hierarchical bioinspired materials with contradicting properties

Expert ID: MT3

Bio-design PhD candidate at the Faculty of Industrial Design Engineering exploring design potentials of mycelium-based materials.

Expert ID: MT4

Polymer Scientist at Airbus with a specialisation in developing biobased materials for the automotive, building and aerospace industries.

3.2. Introduction to Mycelium-Based Materials

Fungi are a member of the group of eukaryotic organisms with more than 1.5 million species discovered (an estimated six times more species than plants). Mycelium is the vegetative part of fungi, a network of hyphae, which spread throughout their environments, secreting enzymes that dissolve their food so that it can be absorbed into their cells (Mycelium 101: What Is Mycelium — Ecovative, n.d., p. 101).

Mycelium-based materials most commonly refer to materials which require as their primary constituents Mycelium (the vegetative part of fungi, a network of hyphae) and substrates.
Mycelium-based materials can be broadly classified into pure mycelium materials and mycelium composites.

Pure mycelium materials

Pure mycelium materials are the result of the complete degradation of the substrate. They are often harvested by a liquid culture of the mycelium to make materials resembling cushion foams, leathers, fabrics, paper or even bacon. The properties of pure mycelium materials depend on the substrate, the type of fungi, and its growth conditions (Appels et al., 2019), (Karana et al., 2018).

Myco-composites

Mycelium composites or myco-composites are produced when fungal colonization occurs on a cellulosic or lignocellulosic material such as hemp, straw, cotton waste etc. The fungal composite is obtained when the fungal growth is stopped by heating the material at 60 -70-degree Celsius in an oven for 1-1,5 days (Appels et al., 2019).

Fig 6. Examples of pure mycelium materials (Left to right) a. Foam b. Textiles c. Leather
Sourced from producer webpages (Ecovative, Mycotex and Mycoworks)

Fig 7. Examples of myco-composite materials (Left to right) a. rigid foam b. pressed panels c. brick
Sourced from producer webpages (Ecovative, Mogu)

3.3. Factors in Material Development of Mycelium-Based Materials

The most important factors involved in the fabrication of finished mycelium-based materials are briefly described in this section. These factors are of relevance in eventually deciding factors to vary to develop applications with desired properties.

3.3.2. Material Ingredients

A. Fungal Strain: The filamentous hyphae or mycelium that grows on the substrate can vary in density and growth rates, in turn affecting the coverage of the substrate and its technical properties. The most widely used strain for growing mycelium composites is Ganoderma Lucidum. High growth rates and stable resultant composites have led to its widespread use even commercially (Jones et al., 2020). Other species with high strength, stiffness and thick fungal skin growth in final products are, Schizophyllum commune, Trametes Versicolor and Pleurotus Ostreatus.

Due to a higher assurance of successful myco-composite production, the Ganoderma lucidum species was chosen for further experimentation and demonstrator design.

Fig 8. (Top to bottom) a. Ganoderma Lucidum species b. Hemp hurd
c. Wheat flour

B. Substrates: Substrates function as nutrition providers and may add bulk. In the case of pure mycelium materials, they are completely degraded whereas, in the case of myco-composites, they are a crucial determinant of the density and even mechanical properties, acoustic properties, and thermal insulation properties. Substrates are lignocellulosic and can be granular like cellulose, granulated hemp or sawdust, providing a smoother textured composite for applications such as decorative and passenger-facing applications etc. Short-fibred hemp is well known to support and stimulate dense fungal growth supporting insulation applications, but it can produce brittle products when compressed. (From biomass to mycelium composite. An exploration of cellulose and weed residues, 2020), (Cerimi et al., 2019). Long fibrous substrates commonly used such as rapeseed straw also provide opportunities for property enhancement by spreading forces over a larger area, allowing applications such as seat backrest panels.

Thus, for further experimentation, Hemp fibres (short) and Rapeseed Straw fibres (long) in the hope of assured growth and enhanced flexural properties for applications.

C. Additional Nutrients: On occasions when the substrate's nutrients are inadequate or the growth density or duration requirements are varied, additional nutrient supplements like wheat flour or oat bran are added.

D. Coatings & additives: In the light of a context such as aviation, which requires flame, smoke and moisture-resistant properties, coatings or nano-modifications can result in desired properties as illustrated in the ECOCOMPASS project (Bachmann & Yi, 2016).

3.3.3. Growth Conditions & Material Processes

Mycelium growth is supported in high humidity conditions and the homogenization, mechanical properties and even growth rate has been shown to be sensitive to the light (intensity & directions) provided for growth, the CO2 concentration (commonly 7%), humidity in a growth chamber (commonly 65-70%) and the growth duration and packing in the mould (Appels et al., 2019),(Girometta et al., 2019), (Ng et al., 2022).
While mycelium composites have a relatively standardised procedure requiring between 2-3 weeks from inoculation to growth in mould, pure mycelium materials can have different durations and methods. Pure mycelium materials can be produced in 5-14 days using an efficient fermentation process (Vandelook et al., 2021).

Production Methods:

Mycelium composites by moulding: After inoculating grow bags with the fungal strains, followed by 7-8 days of growth, the primary shaping of the mycelium composites is done in moulds. Wooden, acrylic or vacuum-formed moulds are used to grow the mycelium over the substrate in the desired shape. After 7-8 days of growth in the mould, the mycelium composite is either dried to hibernate the fungi or heated in the oven to kill the fungi. Depending on the shape and size of the substrate and the final properties, milling, cutting, sanding etc. processes can be used for secondary shaping.

Mycelium Composites by Additive Manufacturing:
Substrates such as hydrogels and cellulosic pastes can be loaded with mycelium and extruded through 3D printers to create complex living structures, which can continue growth, self-repair or regenerate. (Blast Studio 3D Prints Column from Mycelium to Make “Architecture That Could Feed People,” 2022), (Gantenbein et al., 2022).

Secondary Processing of Mycelium Composites:
Very often, mycelium composites are usable for applications right after the drying and heating process. However, for enhancement of mechanical properties (higher rigidity, tensile strength, compressive strength etc.), they can be pressed (cold or heat pressed) or even made the core of sandwich composites. Depending on the usage conditions, lubricants, coatings and additives are added.

Active Growth Process & Processing of Pure mycelium materials:
The growth of pure mycelium biomass can be achieved on solid and liquid feedstock with carefully controlled growth conditions. Abundant aerial hyphae are produced by pumping large amounts of CO2 into the growth chamber to prevent mushroom formation. Ecovative’s forager foam, leather and bacon are produced using an active growth process. (Williams et al., 2022), (Vandelook et al., 2021).

Passive Growth Process & Processing of Pure mycelium materials:

This low carbon intensive process is used by the biotechnology company Mycoworks, for the production of their mycelium leather - Reishi. Mycelium cells are engineered into three-dimensional structures that are densely entwined to result in enhanced strength, durability, and haptics (Williams et al., 2022)

Secondary Processing of Pure Mycelium Materials:

In the case of Pure mycelium materials, flexibility is preferred over rigidity for applications such as fabrics and flexible foams. For this, different chemical treatments can be applied to the fungal tissue to increase pliability and durability. Coatings of thin films of polyurethane and polylactic acids are used to increase longevity, but in turn, also make the material not compostable naturally. Other coatings of natural origin being considered are cellulose biofilms grown from bacteria (e.g. Acetobacter xylinus), coconut oil, carnauba wax or beeswax etc. Deacetylation of the constituent chitin of Pure Mycelium can be achieved using alcohols/methanols, acetic acid etc. to confer additional crosslinking sites. Adding CaCl2 after deacetylation can confer antimicrobial properties to the pure mycelium polymers, making packaging wrappings for food a feasible application (Vandelook et al., 2021).

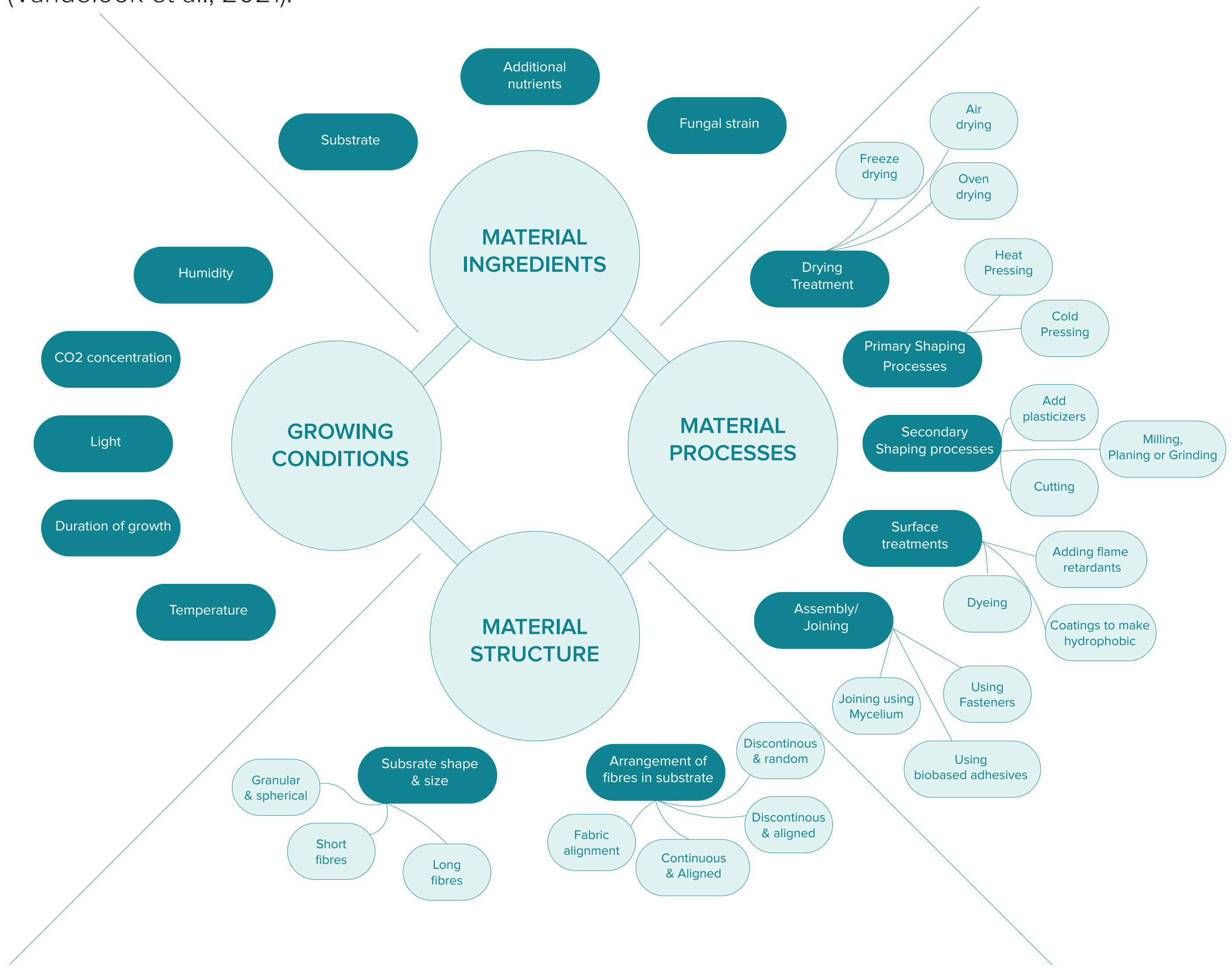


Fig 9. Material Taxonomy developed for tinkering

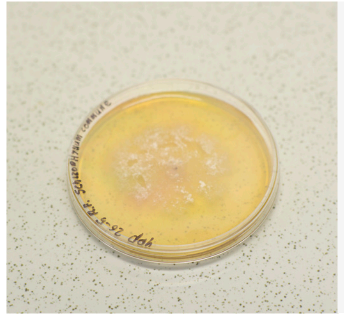
3.4. Material Tinkering & Material Prototyping Decisions

This project is one of the foundational attempts in the aerospace sector to develop applications using mycelium-based materials. Thus, for the sake of clarity and ease of preliminary assessments (technical, environmental and experiential), it was decided to limit experimentation factors that have not been tested prior in literature, to a minimum. Fig 9 shows the material taxonomy developed for this thesis, which aided the tinkering process decisions.

Prior to the development of the designed demonstrators for aircraft cabin applications, a material tinkering process described in detail in Appendix B (material diary) was followed.

The material tinkering process in this thesis enables a hands-on understanding of the behaviour of the organism, challenges of production of myco-composites and observing variations that lead to desirable material performance for aircraft cabins. A diagramatic representation of the tinkering process is shown on the right.

The resultant evaluation of the performance of the material is described in detail in Chapter 4.



1 Strain

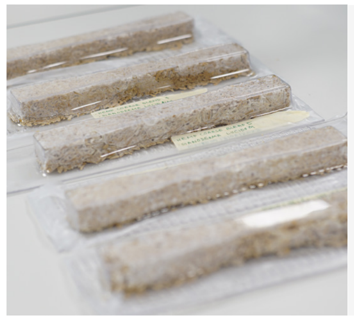
Ganoderma Lucidum from Grown Bio

2 Subsrate

4 Types
Hemp fine & Coarse
Straw coarse & Fibres

3 Autoclave

Autoclave substrate
121 degree celsius
45 min



4 Inoculate & Incubate

25 degree celsius
70% humidity

5 Drying

70 degree celsius
1,5 days

6 Processing
No pressing
Cold Pressing (Avg 0,5 Mpa)
Heat Pressing (Avg 0,5 Mpa, 150 degree celsius)

7 Characterization

Tensile test
Compressive test
3 point bending test

Fig 10: Simplified Schematic of the Material Tinkering Process

3.5. Takeaways from Material Tinkering

The material tinkering was performed with an aim to understand the form & textural differences the size and shape of substrates can confer to allow for varied visual and experiential properties in aircraft cabin applications. To gain insight into the practical challenges of production with mycelium Some observations of relevance to the design goal are as follows:

1. Out of the 8 inoculated grow bags with 4 substrates (fine hemp, coarse hemp, fine straw and long straw), 3 containing straw as substrate were contaminated. This **highlights the need for highly sterile and standardized procedures should mycelium production be undertaken by the aircraft manufacturers.**

2. 19 samples were produced at the end of the process, of which the most satisfactory growth was shown when the substrate size of hemp was small. It also resulted in better visual properties and textures. The **growth on long fibres of straw was sparse and limited, thus indicating the need for better processing if long fibred substrates are required.**

3. Laboratory conditions, instantaneous conditions and manual processes led to wide variations in resultant products. Thus, if a certain degree of homogeneity is required in the applications designed, the substrate preparation, inoculation and mixing processes and moulding processes would benefit from an **automated and industrialized process.**

4. In conclusion, the mycelium strain **Ganoderma Lucidum and hemp substrate** resulted in stable composites through a meticulous process with standard growth conditions can be chosen to develop further applications for the cabin.

These samples are processed by cold pressing and heat pressing, and subjected to technical characterization, results of which are mentioned in Chapter 4.

For further demonstrator development, variations in processing would be done for certain visual properties and technical properties that might be advantageous to aircraft cabin applications was taken. No growth conditions would be varied.

Material Performance & Requirements

As an extension of the exercise of 'Understanding the Material' for cabin application design, the material performance of the mycelium materials was evaluated for specified material property requirements in an aircraft cabin. Chapter 4 begins with a brief introduction of the required and desired material properties, for safety compliance and quality in defined application categories in an aircraft cabin. It is followed by a brief overview of the results of comparative material property analyses of mycelium materials and conventional aircraft cabin materials. This leads to an understanding of the unique material qualities of mycelium materials, their advantages and disadvantages over conventional materials, and their affordances for novel application design in the cabin.

4.1. Methodology

The methodology followed to analyse the material performance of mycelium based materials holistically, within the bounds of requirements of aircraft cabin materials is as follows:

The material performance criterias were divided into 3 categories for convenience, namely:Technical Performance, Experiential Performance and Environmental Performance. Under each category, the desired material properties and compliance requirements for aircraft cabins are briefly listed. These material requirements and further product requirements were validated with professionals from Airbus during interviews.
The professionals' expertises can be briefly described as follows:

Expert ID: RE1

Polymer scientist at Airbus Central Research & Technology specialised in developing bio-based materials for aerospace, automotives and buildings

Expert ID: RE2

Product manager for Sustainable Cabin at Airbus

Expert ID: RE3

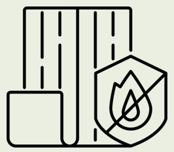
Trends and materials designers at Airbus

The technical performance of the mycelium based materials are thus evaluated for the listed properties, in comparison to conventional aircraft cabin materials. Information on the material properties are gathered from two sources - literature on technical characterization of mycelium materials, and material testing of samples developed in the biodesign laboratory in Science Centre & Faculty of Industrial Design Engineering at TU Delft. The property range values were then added as records in Granta Edupack and compared to conventional aerospace materials using Ashby Plots.

The experiential performance of mycelium based materials was analysed through desktop research of experiential characterization performed by other researchers using the **Ma2E4 kit from Material Driven Design.** The results were evaluated against the defined experiential requirements for aircraft cabins as defined in interviews with experts RE1, RE2 and RE3.

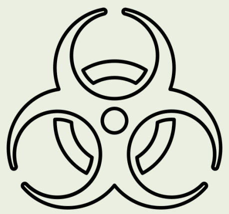
Lastly, brief environmental performance of mycelium based materials was performed through literature review of life cycle assessments of myco-composites and mycelium leath**er.** These LCAs were performed using research data collected in laboratories or through commercial suppliers.This analysis leads to a generalised identification of environmental hotspots. However, In the absence of published data on aerospace applications, no comparative information of environmental performance of the materials can be gained.

General required material properties in Aircraft Cabin



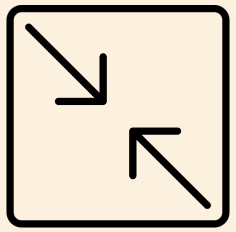
Fire Retardancy

Low Density/ Weight

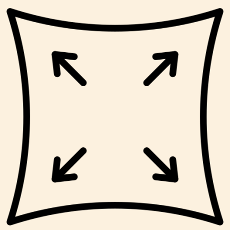


Non Toxicity

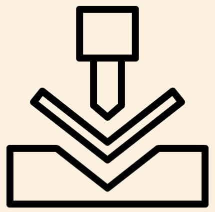
Application specific material properties in Aircraft Cabin



Compressibility



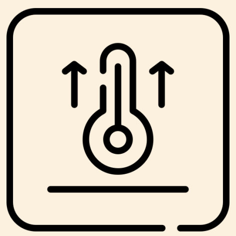
Stiffness



Elasticity

Application specific material properties in Aircraft Cabin

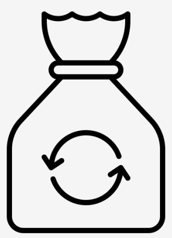
Acoustic Insulation



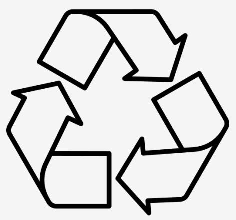
Thermal Insulation

Water resistance

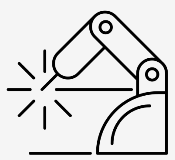
Material properties for circularity in Aircraft Cabin



Biodegradability



Recyclability



Repairabiility

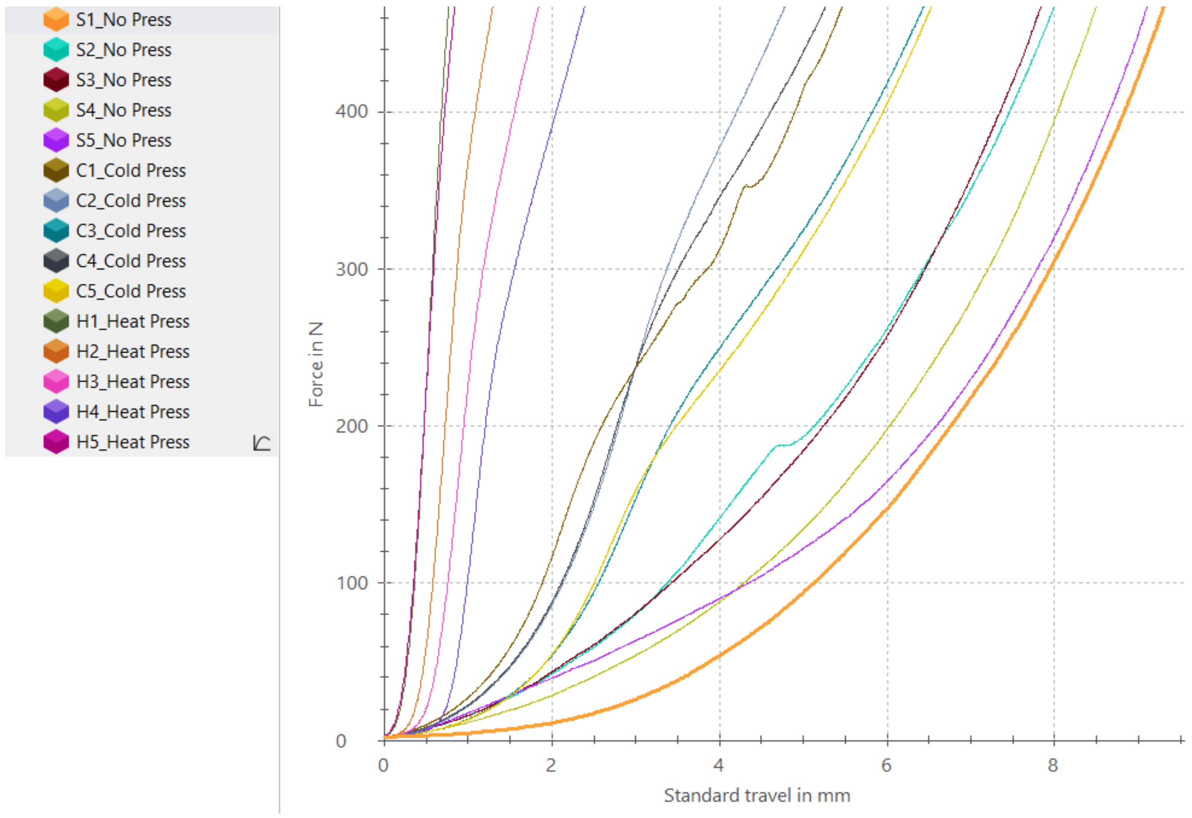


Fig 11 : Compressive test behaviour of non pressed, cold pressed & heat pressed myco-composites

4.2. Results

4.2.1 Comparative Technical Performance of Mycelium Materials & Conventional Aircraft Cabin Materials

For aircraft cabin applications, technical material properties of importance identified are density, mechanical strengths, fire safety and retardancy, acoustic and thermal insulation.

Mycelium composite materials and foams are porous materialis, with density ranging between 30 to 200 kg/m3.
It's tensile strengths in the range of 0,04 - 0,24 Mpa, compressive strengths ranging from 0,04 - 0,6 MPA and flexural strengths 0,007 - 0,87 Mpa (Ref)

Ashby plots in fig 12 indicate that aerospace grade materials that have similar density and mechanical property ranges as mycelium-based materials are open cell and closed cell foams and low-performing composites.

Plots in fig 11 & 13 resulted from material testing of non pressed, cold pressed and heat pressed myco-composite samples fabricated in the Science Centre and Faculty of Industrial Design Engineering. It can be inferred that the compressive behaviour of mycelium composites resembles that of foams, with non pressed composites being more compressible. The flexural properties or stiffness of the heat pressed composites can reach close to that of insulation boards.

Pressing (cold or hot) increases the density and hardness of the material, but also makes it more brittle. Thus, pressing results in shifting the material behaviour from foam like to brittle plastics and wood like. Enhancement on ability to resist compressive and bending stresses is observed upon pressing. However, the tensile properties of mycelium composites are of no practical consequence as it is not an elastic material.

It can thus be inferred, that applications of mycelium within an aircraft cabin should not be primary load bearing structures, and rather be used where there they the mechanical properties of foams, insulation boards or low-performing composites are also acceptable.

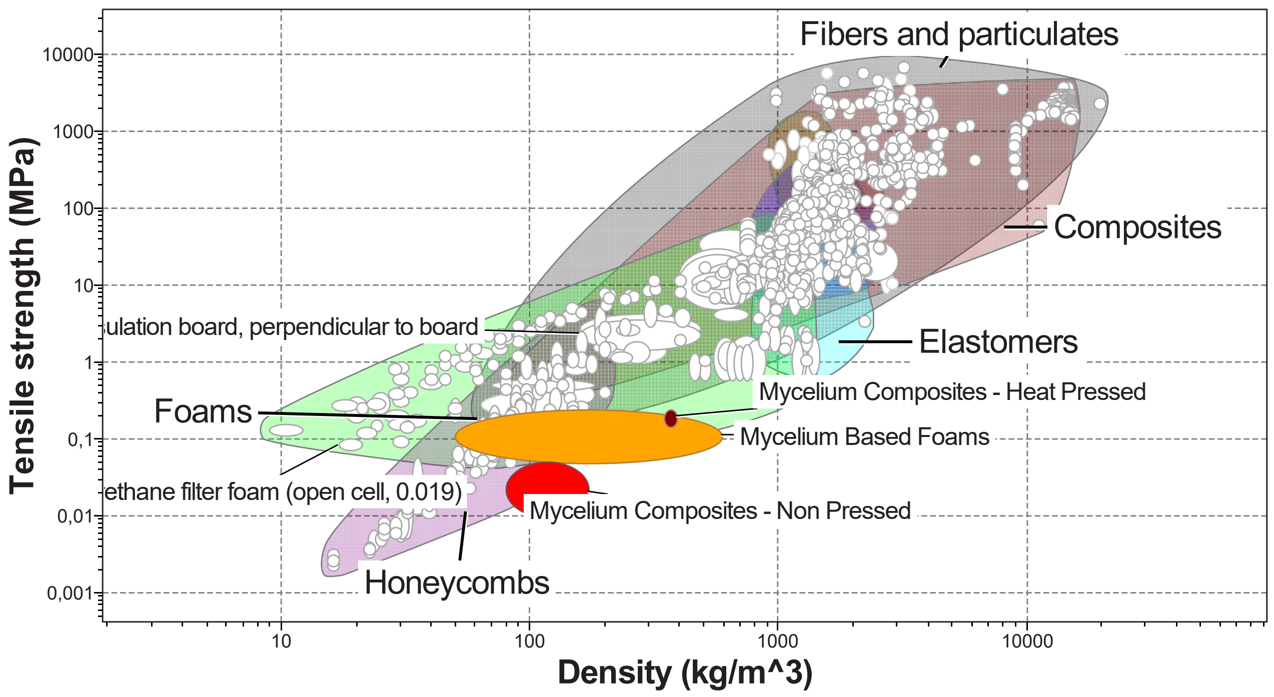


Fig 12 : Ashby plot of density vs tensile strength of myco-composites from literature against aerospace materials in granta edupack

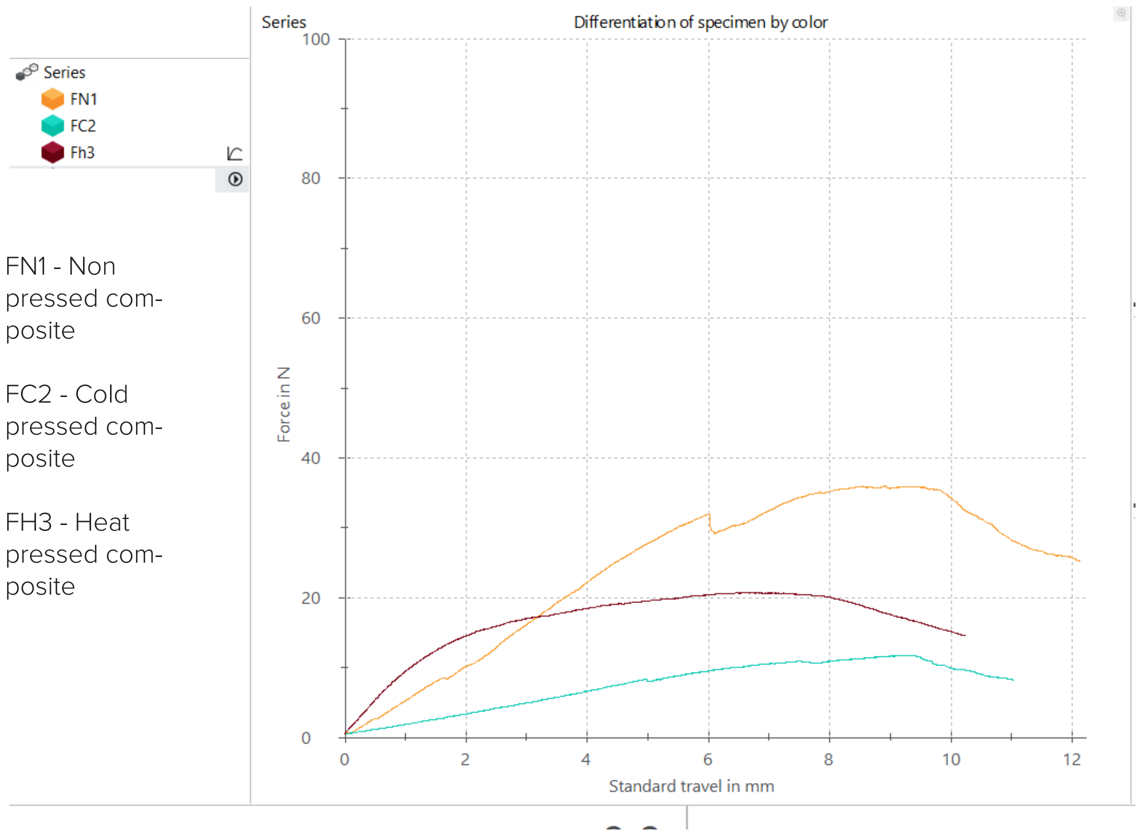


Fig 13 : Flexural behaviour of non pressed, cold pressed and heat pressed fabricated composite samples

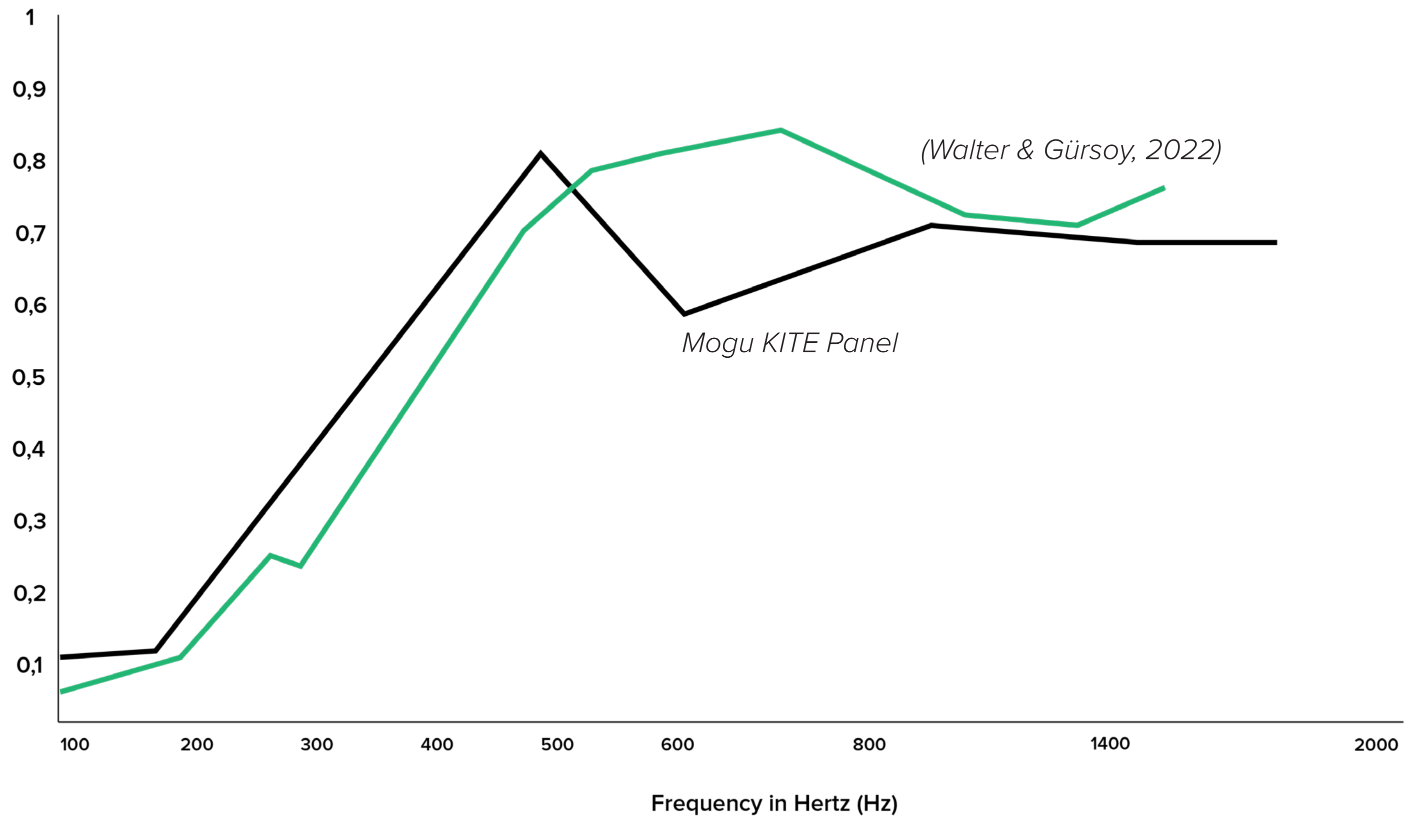


Fig 14: Sound absorption co-efficient vs frequency plots of some commercial (Mogu) & research based samples (Walter & Gürsoy, 2022)

Acoustic & Thermal Insulation

Mycelium composites have a thermal conductivity ranging between 0,04 - 0,08 W/m-K. For effective thermal insulation, lower thermal conductivity values are required and mycelium fibres bound around natural insulators such as hemp & straw fibres make myco-composite low-density low thermal conductivity materials. They can compete with conventional insulation materials such as glass wool (57 kg/m3, 0.04 W/m·K) and extruded polystyrene insulation (34 kg/m3, 0.03 W/m·K) and natural insulators including sheep wool (18 kg/m3, 0.05 W/m·K) and kenaf (105 kg/m3, 0.04 W/m·K) (Jones et al., 2020).

Mycelium applications for temperature control of food, drink, or enclosed spaces in aircraft cabin are indeed highly relevant.

Mycelium itself is an excellent acoustic absorber, exhibiting strong inherent low-frequency absorption (1500 Hz) and outperforming cork and commercial ceiling tiles in road noise attenuation (Jones et al., 2020). Mycelium composite samples in the study by (Walter & Gürsoy, 2022) outperformed commercial sound absorbing materials such as polypropylene and plasterboard panels and was only marginally less competent than fibreglass boards between 250 - 500 Hz.

Commercial acoustic panels produced by Mogu.bio (based in San-Francisco) have a sound absorption coefficient between 0,4 - 0,8 within the frequency range of 250 - 600 Hz, with a peak at approximately 375 Hz (muvobit, n.d.).

The frequency range of noise from humans is 85 Hz to 600 Hz, implying mycelium acoustic panels can be effectively used of noise attenuation and acoustic insulation in aircraft cabins.

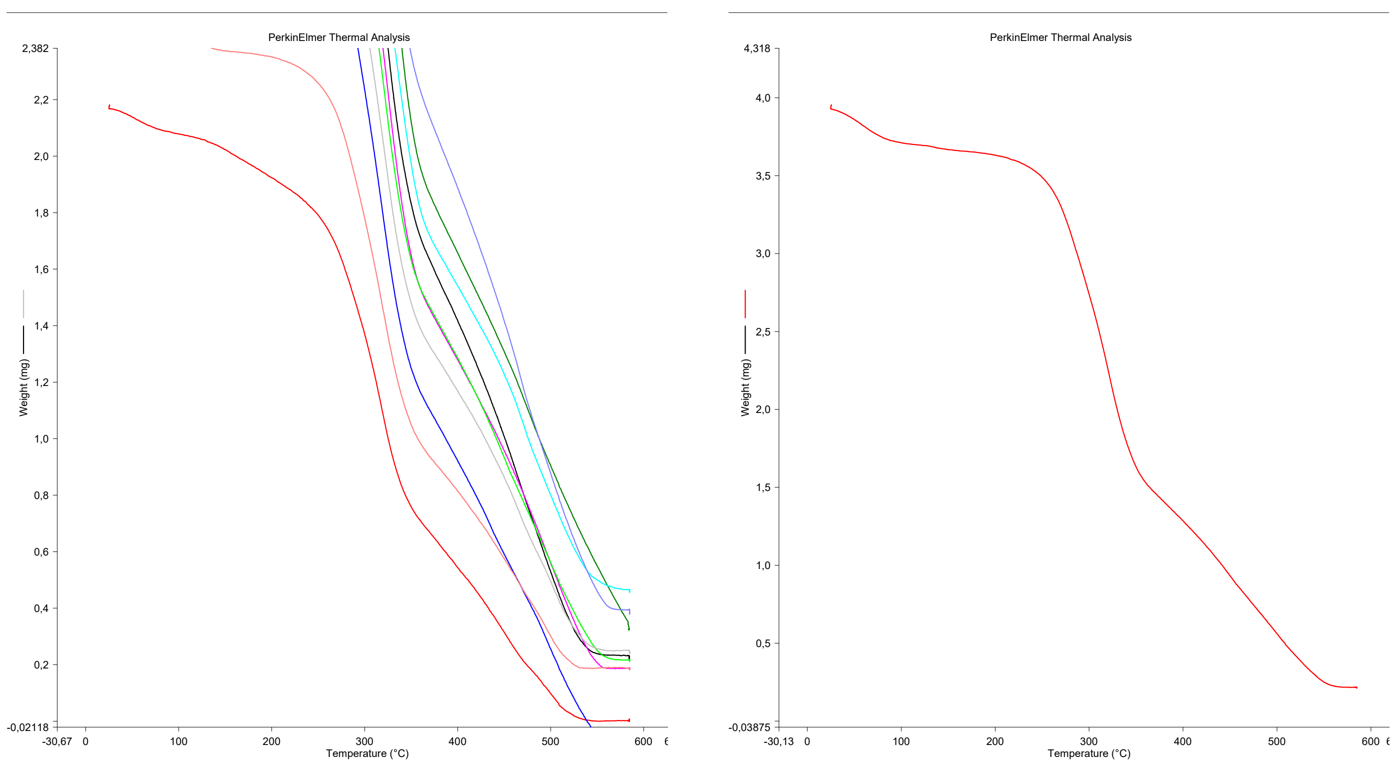


Fig 15 : Thermogravimetric analysis of fabricated myco-composites, heated from 25 - 600 degree celsius at 10 degree per min.

Fire Retardancy & Thermal Degradation Properties

Meeting the stringent fire safety regulations of an aircraft cabin, would become essential at some point of application development with myco-composites.
Limited literature is available on the fire retardancy and thermal degradation properties of mycelium materials. The study by (Jones et al., 2018) provides the most detailed account.

It is supplemented by Thermogravimetric analyses using a Pyris in a Perkin Elmer 4000, of mycelium samples produced during this project in the laboratory at Faculty of Industrial Design Engineering. A mycelial mass of approximately 5-10mg was placed in a ceramic crucible and heated from 25 °C to 600 °C at a heating rate of 10 °C/min.

Consistent with the findings of (Jones et al., 2018) , the thermal degradation of mycelium samples developed in the lab, occurs in 3 stages. In the first stage, 5-10% weight loss occurs between 25 degree celsius to 200 degree celsius. A rapid weight loss of 65-70% occurs between 200 - 375 degree celsius and is followed residual mass losses uptil 91-95%.

(Jones et al., 2018) also analyses the gases released (CO_2 and H_2O) and the heat release rate of Mycelium composites, along with PMMA & PLA. The heat release rate of a burning material is commonly accepted as the most important fre reaction property since it strongly infuences factors such as fame spread, secondary ignitions, smoke generation, etc. The peak heat release rate and total heat release rate during combustion, of mycelium samples is are significantly lower compared to PMMA & PLA as reported, indicating improved fire safety over plastics. In both experiements, a fibrous char was the result at the end of the combustion.

It can be be concluded that the fire safety properties of mycelium can be promising for aircraft cabins and the thermal degradation can also

4.2.2 Comparative Experiential Performance of Mycelium Materials & Conventional Aircraft Cabin Materials

While the passenger/target user material experience of mycelium-based materials in the context of Aircraft Cabins is not extensively published, insights about the material experience of mycelium in other contexts can be drawn.

For the sake of clarity and brevity, the material experience / experiential characterization of Mycelium composites and foams will be discussed in reference to the Ma2E4 toolkit developed by researchers at TU Delft (Camere & Karana, 2018).

Quoting the researchers:

'....The Ma2E4 Toolkit aims to support material/design professionals in understanding (1) how people receive a particular material on four different experiential levels: sensorial, interpretive (meanings), affective (emotions), and performative (actions, performances), and (2) how these levels interrelate in the experience of the material...'

Table 2 provides a brief overview of the results in literature on experiential characterization of mycelium materials.

Table 2 : Results of Experiential Characterization of mycelium by researchers using the Ma2E4 tool in Material Driven Design

Experiential Level	Most Associated actions/words	Sources
Sensorial *How does the material, with its inherent qualities impacts the human sensory system?*	Not elastic, opaque, light, stiff, brittle, soft and velvety	1. Study 1: By researcher Frida Andersson (Kjellqvist, 2023) Participants: unknown Location: Malmo Univerisity
Interpretive *What situated meanings, judgements and interpretations the user associates to the material after the initial sensory reception?*	Natural, organic, artisanal, strange, handcrafted, calm, eco-friendly, symbiotic and compostable	2. Study 2: By researcher Davine Blauwoff (Karana et al., 2018) Participants: 5 Location: Delft University of Technology
Affective *What emotions are triggered unconsciously upon interaction with this material?*	Curiosity, surprise and fascination Doubt, disgust and distrust	3. Analysis of news articles and reports
Performative *What kind of active interactions does the user wish to have with the material?*	Pressing,caressing, poking, urge to break	

Study of Acceptance:

In a study by researchers from the Faculty of Architecture at Poznan University (Bonenberg et al., 2023), the acceptance of Myco-composites in Interiors was explored. An experience test and consumer test with 80 participants with a 9-degree scale of material acceptance was performed with Interior designers & architects. In the experience test, the myco-composite cladding panels were again perceived as soft, pleasant and neutral (tending towards warn). Noteworthy is that no participant described the material as 'cold'. Despite not being aware of the production process, most of the participants could easily perceive the Myco-composite as eco-friendly upon contact.
An overwhelming 63 out of 80 participants answered in the range of 'a hesitant yes' to 'definitely yes' when asked 'Would you accept the material in interior design elements in a home that you design with an ecological aesthetic?'.

Implications:

The results are of consequence for aircraft interiors where warm, comfortable and soft are prioritised. A mapping in Fig 16 lists the experiential qualities of mycelium which are of importance to aviation interiors.

Another result of great significance for aircraft cabin interior manufacturers is the ease of interpretation of mycelium composites as natural and eco-friendly. Manufacturers wish, as a strategic choice that the ecological aesthetic and material be easily perceived by passengers

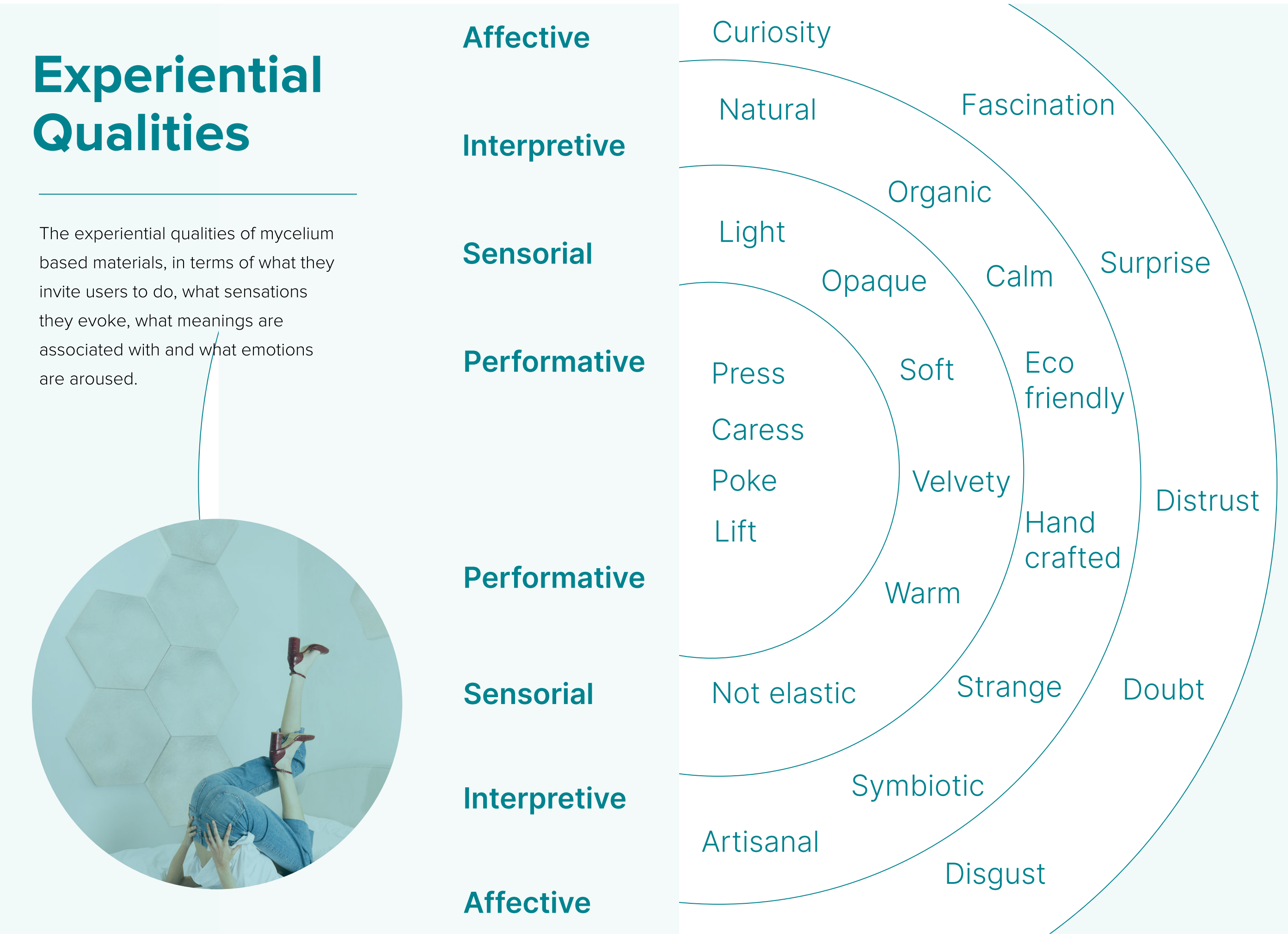


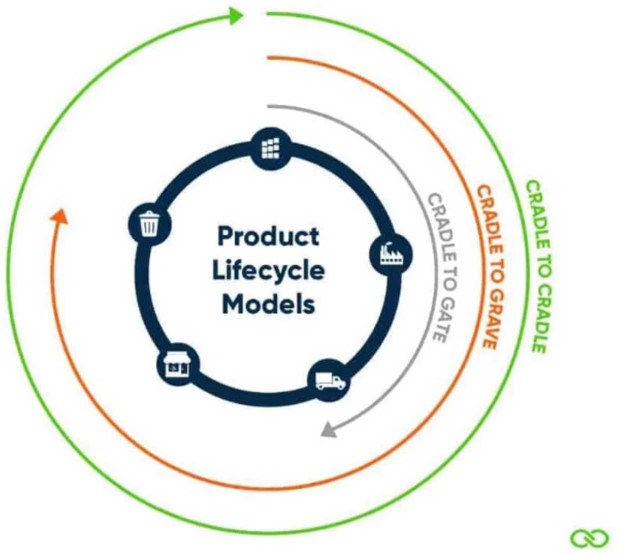
Fig 16. Experiential Mapping

4.2.3 Comparative Environmental Performance of Mycelium Materials & Conventional Aircraft Cabin Materials

An attempt to understand the comparative environmental performance of mycelium materials was made through review of Life Cycle Assessments in literature. Yet again, due to no application in the aerospace context yet, there were no truly comparative LCAs for the context. Thus, the selected LCAs studied could yield only preliminary insights on environmental impacts of production of mycelium materials.

4 LCAs based on on ISO 14040/44 were studied, 2 out of which were performed on laboratory scale samples by researchers (Stelzer et al., 2021),(Livne et al., 2022). Both of these LCAs were carried out based on research data.

2 other LCAS were carried out by researchers on commercial samples and data from established companies, namely - Ecovative's mushroom packaging and Mycowork's Reishi leather (Williams et al., 2022).



Source: Ecochain

Fig17: Myco-brick sample (Livne et al., 2022)

Fig 18: Reishi mycelium leather (Williams et al., 2022)

Table 3. Summarized results of literature review of LCAs

LCA	Functional Unit	Goal & Scope	Inventory	Outcomes
LCA of Myco-composite brick (Stelzer et al., 2021)	Functional (declared) unit of one fungal-based brick standardized to the German 'Normal format' (NF) brick (24 × 11.5 × 7.1 cm) made out of hemp shives	Intended application of this LCA is to determine the potential environmental hotspots of the lab scale production of fungal-based bricks. Cradle to Gate Study	The primary data for the production of fungal-based bricks were collected during lab cultivation Secondary datasets were taken from the databases of Sphera (with SP 40) and Ecoinvent 3.5 using the GaBi software for modeling	Hotspot 1 : Electricity usage for sterilisation & drying (high climate change potential) hotspot 2 : Hemp cultivation & procurement (impact categories – land use & acidification) Environmental hotspot 3: Polypropylene grow bags (impact category climate change & water scarcity)
LCA of Myco-composite brick (Livne et al., 2022)	Functional unit was defined as 1 m3 of the myco-composite made with rapeseed straw, cellulose and fungal species Trametes Betulina	The goal of the cradle-to-gate LCA was to evaluate the environmental impact of fungal mycelium material production focusing on the Embodied Energy and Embodied Carbon	The life cycle inventory (LCI) reported here is based on EE and EC coefficients taken from the work of this study, data from the scientific literature, the Ecoinvent 3 database, and reasoned engineering assessment when no other option was available	The LCA resulted in an EE value of 860.3 MJ and an ECof−39.5 kg CO-2eq per cubic meter for the "mycoblock". Hotspots: Electricity consumed in incubation/growing stage of mycoblock. Maintenance of incubator temperature & laminar flow hood. Production of the bags and molds, which are made from fossil fuel-based polymers

Table 3. Summarized results of literature review of LCAs

LCA	Functional Unit	Goal & Scope	Inventory	Outcomes
LCA of Ecovative Mushroom Packaging	Not Available	Cradle to grave LCA The LCA purpose was to: evaluate the impact of competing Ecovative internal inoculation processes	Primary data was collected directly during multiple process runs in the company	Inoclum type had an insignificant impact ecologically The part drying process was shown to contribute over 50% of the entire life cycle carbon footprint. Ecovative is testing an alternate drying process that uses about 1/3 the energy and dries in minutes instead of hours.
LCA of Mycelium Leather - Reishi (Williams et al., 2022)	Functional unit of this study is 1 m2 of Reishi™, i.e., post-processed*, finished, and packaged leather-like** material with natural haptics, satisfying similar performance, quality, and hand feel as animal leather. In the case of Reishi™, this means dyed and lubricated	Cradle-to-gate Life Cycle Assessment (LCA) following the ISO14040/14044 standard is used to quantify the environmental footprint of Reishi	Ecoinvent 3.6 was used as the main background database], with use of processes from Agri-footprint 4.0 (economic allocation)	Reishi's™ carbon footprint is as low as 2.76 kg CO2-eq per m2 , or 8% of the value of the bovine leather benchmark modeled Hotspots: Process's sterilization of raw material inputs via autoclave tools. Energy use for sheet production & heating the facility are biggest contributors of CO2 emissions.

The contribution of these LCAs for this project's goals are as follows:

1. Identification of Environmental Hotspots in production: All 4 studies identify the electricity required for the sterilization, drying and processing the materials as environmental hotspots for the production. Land use for production of certain specific substrates (e.g hemp) is also a hotspot. Lastly, for mycelium composites, fossil fuel based polypropylene grow bags also contribute to negative impacts.

2. Limited Comparision with Conventional Materials: As these LCAs were performed for an objective understanding of the material's environmental without specific application context, only the analysis of Reishi leather (Williams et al., 2022) mentions that mycelium leather by reishi is has a substantially low carbon footprint (merely 8% as that of bovine leather).

Work required in this thesis

All of these LCAs looked into solely the production (cradle to gate) since there wasn't a clear application. It is thus imperative that an attempt cradle to cradle Life Cycle Assessment attempt be made once application design is finalized in this project.

It is essential for decision making on deployment in the context of aircraft cabins that comparative LCAs quantifying the environmental performance advantage (if any) mycelium-based materials give against conventional fossil fuel-based nomex honeycombs, thermoplastics, foams and leathers provide.

Takeaways: Observations Key to the Development of Design Vision

1. Mycelium-based materials stand out for their low density, superior insulation (thermal & acoustic) properties, cushioning, and conferred environmental advantages. Their material experience is characterised by words such as soft, organic or natural, warm, and velvety. They are easily moulded into complex surfaces. Mechanically, an as-grown myco-composite resembles open-cell foams such as Polyurethane or rigid & high-density foams based on mycelium network density and even scale. Cold pressing during processing increases density, and heat pressing increases density, hardness and also brittleness. Thus heat pressed composites can often resemble functional plastics like ABS or particle boards but may have lower tensile strengths.

2. Hence, going further and in developing a design vision and product design requirements, it is imperative to focus on the advantageous properties. It widens the possibilities and shifts the focus from structural applications.

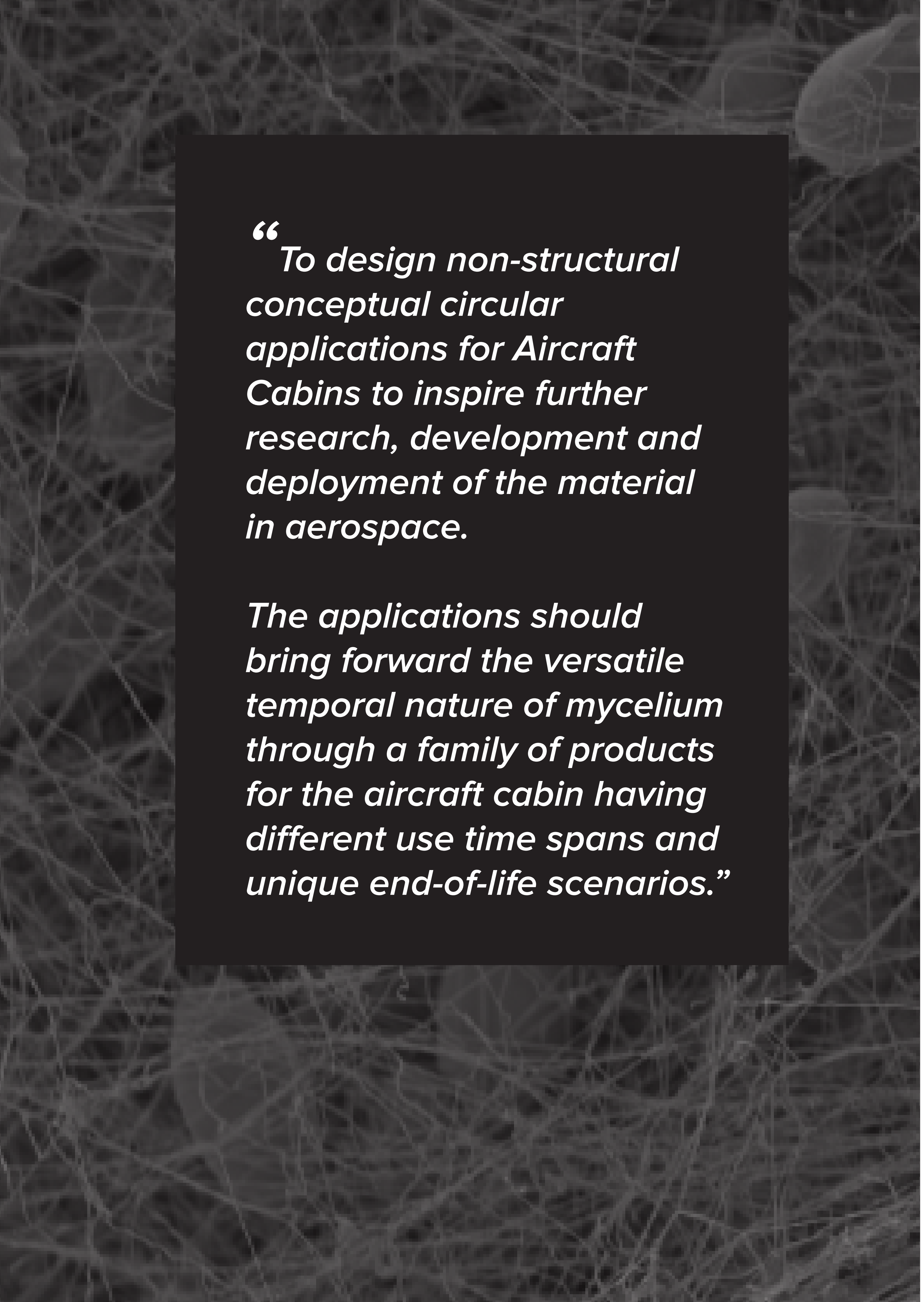
3. Mycelium-based materials are easily perceived as sustainable and as ecological composites in their natural states - thus hiding the material unless deemed necessary due to airline restrictions was decided against.

4. Aircraft interiors having surfaces facing passengers and crew benefit from having a calm, warm and pleasant nature. Thus applications for decorative mouldings and surfaces are pragmatic choices as well.

5. The mycelium-based materials can have different temporal qualities depending on their processing and use case, making them a versatile choice. As a designer, my design vision and design concepts realised in this thesis have the potential to highlight these facets of bio-designing with mycelium, showcasing the potential impact of it and hopefully inspiring other designers & researchers in the Aviation design field.

Identifying Applications for Aircraft Cabin

This chapter marks the juncture of the initiation of application design. It begins with a defined design vision. It looks deeper into a conventional aircraft cabin's application categories and requirement specifics (functional & material). Materials used conventionally are also briefly analysed and then compared to mycelium material categories, seeking requirement satisfaction. This leads to design concepts of a few optimal applications for the cabin, which were further evaluated by professionals in the aviation industry. A concept selection at the conclusion of the chapter is based on criteria to align with my design vision, my intention of demonstration and outlined requirements. These few selected concepts are further detailed and subjected to technical & environmental evaluation in Chapter 6.



"To design non-structural conceptual circular applications for Aircraft Cabins to inspire further research, development and deployment of the material in aerospace.

The applications should bring forward the versatile temporal nature of mycelium through a family of products for the aircraft cabin having different use time spans and unique end-of-life scenarios."

5.1. Design Vision

The design vision is a the outcome of the combination of understanding the context and the material. In the sections pertaining to the science of designing with mycelium and it's material performance in the light of requirements in cabin applications, certain advantages and disadvantages were highlighted.

Through material tinkering as well desktop, the versatility and variability of the material for different use cases stood out to me. As mentioned in my design vision, I wish to demonstrate that mycelium materials in sustainable cabin design can have impacts beyond decorative additions. It's mechanical properties may not allow for structural applications, but it's insulation properties, experienced comfort and environmental advantage can be leveraged for several inspiring and functional applications. In addition, this thesis project was initialised with the intrinsic aim of designing for circularity, thus designing these applications to be circular from the outset is embedded in the design vision.

5.2. Application categories in an aircraft cabin and potential ideas

Materials used in an aircraft cabin can be broadly divided into those that are used and discarded during each flight, and those that are part of the cabin and airframe for atleast 1/3rd or the whole of an aircraft's lifetime. Among those that are part of the cabin, seating and accessories have different functionality and requirements than interior panellings.

Materials used for all these applications need to have different lifespans and satisfy different requirements.

Thus, for further identification of mycelium applications, these clusters were used to seek better matches.

Infight Service Products

Meals & Catering equipment, amenity kits, toys, trays, blankets, hot & cool cases, earmuffs and earphones etc.

Seating & Accessories

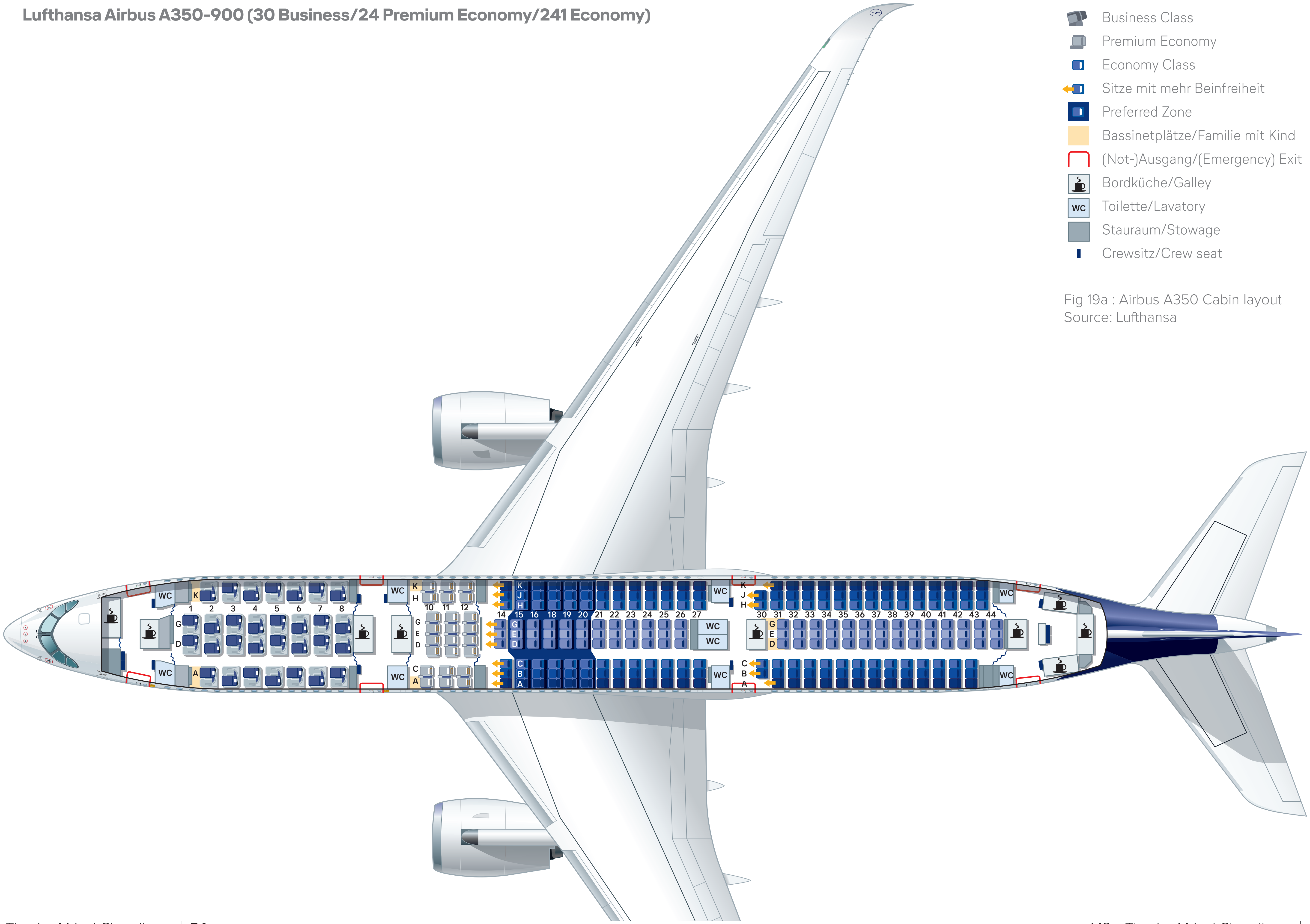
Seating upholstery, foam, seat pans, armrest and headrests, shelving for storage, tray tables etc.

Interior Panels & Structures

Partition walls, galley walls, lavatory walls, inflight bars etc.

In fig 19, through the reference of an Airbus A350 cabin, the positioning of these application categories in a cabin and their requirements are listed, and the specific mycelium materials that can satisfy those requirements are connected. This exercise aids narrowing down the optimal application design ideas.

Lufthansa Airbus A350-900 (30 Business/24 Premium Economy/241 Economy)



- Business Class
- Premium Economy
- Economy Class
- Sitze mit mehr Beinfreiheit
- Preferred Zone
- Bassinetplätze/Familie mit Kind
- (Not-)Ausgang/(Emergency) Exit
- Bordküche/Galley
- Toilette/Lavatory
- Stauraum/Stowage
- Crewsitz/Crew seat

Fig 19a : Airbus A350 Cabin layout
Source: Lufthansa

Seating & Accessories

Seating upholstery, foam, seat pans, armrest and headrests, shelving for storage, tray tables etc.

Requirements

Soft & warm textures

Comfort & Lightweight

Temperature control

Recyclable / Refurbishable

Possible mycelium materials

Foam

Leather

Interior Panels & Structures

Partition walls, galley walls, lavatory walls, inflight bars etc.

Requirements

Lightweight

Acoustic & thermal insulation

Comfortable textures

Repaiability & structural integrity

Possible mycelium materials

Myco-composites

Myco-composite panels

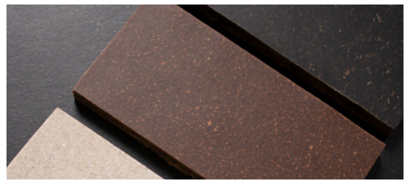


Fig 19b : Application categories, requirements & possible mycelium material application locations in a cabin

Illustration credits: Vicente Quintana Arntz

Infight Service Products

Meals & Catering equipment, amenity kits, toys, trays, blankets, hot & cool cases, earmuffs and earphones etc.

Requirements

Lightweight

Compostable

Insulation

Muliifunctional

Possible mycelium materials

Myco-composites

Foam

5.3. List of Requirements & Criteria for Designed Products

The list of product design requirements has been developed as an extension of material requirements, for current and future product design and development. It was validated by the professionals listed in Chapter 4, i.e experts RE1, RE2 and RE3.

In this section, I define the current product attributes/ requirements to realise the design vision of this thesis, and future requirements for commercially deployable products in the cabin.

The requirements are again separated under the Technical, Experiential and Environmental categories for convenience. Those which were deemed most important as criteria for evaluation are emboldened.

Table 4. Design requirements/attributes for application design

Technical Attributes

The **current desired attributes** or requirements for this case pertains to the **demonstrative concepts** being developed to form the backbone of further detailed research and development for commercial aircrafts. The **future attributes** are the **requirements a finished product** for commercial aircrafts using mycelium materials would have to satisfy.

Current Desired Attributes

T1 **The weight of the designed function should not exceed the weight of the existing application (or function it is replacing)**

T2 Any mycelium-based material application if has load bearing components or even minor structural functions (parts of partitions, galley walls, stowage compartment doors, etc.) should be able to withstand equal stresses or more than the conventional material component they replace or repurpose.

T3 For equipment, cargo in the passenger compartments and any other large masses, the following apply:
These items must be positioned so that if they break loose they will be unlikely to
(i) Cause direct injury to occupants;
(ii) Penetrate fuel tanks or lines or cause fire or explosion hazard by damage to adjacent systems; or
(iii) Nullify any of the escape facilities provided for use after an emergency landing.

Future Required Attributes

TF1 The applications, when researched & developed further for fitting in a commercial aircraft must comply with FAR/CS 25.853 and 25.855 guidelines for Flammability, Smoke & Toxicity.

TF2 If the mycelium-based application is a part of an aircraft seat component assembly, must not deform under any loads up to those specified below in any manner that would impede subsequent rapid evacuation of occupants.

TF3 The occupant experiences the following ultimate inertia forces acting separately relative to the surrounding structure:

(i) Upward, 3.0g
(ii) Forward, 9.0g
(iii) Sideward, 3.0g on the airframe; and 4.0g on the seats and their attachments.
(iv) Downward, 6.0g
(v) Rearward, 1.5g

Experiential Attributes

Current Desired Attributes

E1 **Visual & tactile perception of the material should be warm, calm and comfortable**

E2 The material applications should look clean and hygienic.

E3 The material applications should mitigate concerns about association with fungal material.

E4 The applications should be easy to clean and disinfect for the crew.

E5 **The sustainable advantage of the material should be perceived easily by the users.**

E6 The product should be easily shapable for variations of the application.

E7 The aging of the material should not negatively impact passenger experience

Future Desired Attributes

EF1 The product, when being designed for commercial aircrafts should be resistant to damage from beverages, biological and chemical fluids it comes in contact with.

EF2 The look and feel of the materials should be customizable for different airlines who are customers

EF3 The applications should highlight the material as being a low carbon, sustainable choice alongside being a clean and luxurious material option desired in aviation.

EF4 The usage of mycelium based materials should not imply a degradation in communicated design value.

Sustainability Attributes

Current Desired Attributes

S1 The mycelium-based material for a specific application, through its entire life cycle (production, use, end of life) not have a higher carbon equivalent than the conventional material used. The weight is an important driver of sustainability & fuel efficiency.

S2 The raw materials used such as the mycelium strains & substrates should not be easily exhaustible. Other raw materials required in the overall production process should not be subject to critical material risk.

S3 **The end of life of the product must lead to a circular pathway**

S3.1 If the application is one-time use, the disposal method should release toxins or highly polluting elements.
S3.2 If the application is for long term use, the material must be designed for durability during it's service span & maintenance cycle.

Future Desired Attributes

SF1 If the applications are for long term use (fitted in the cabin interiors), repairable elements will be much desired.

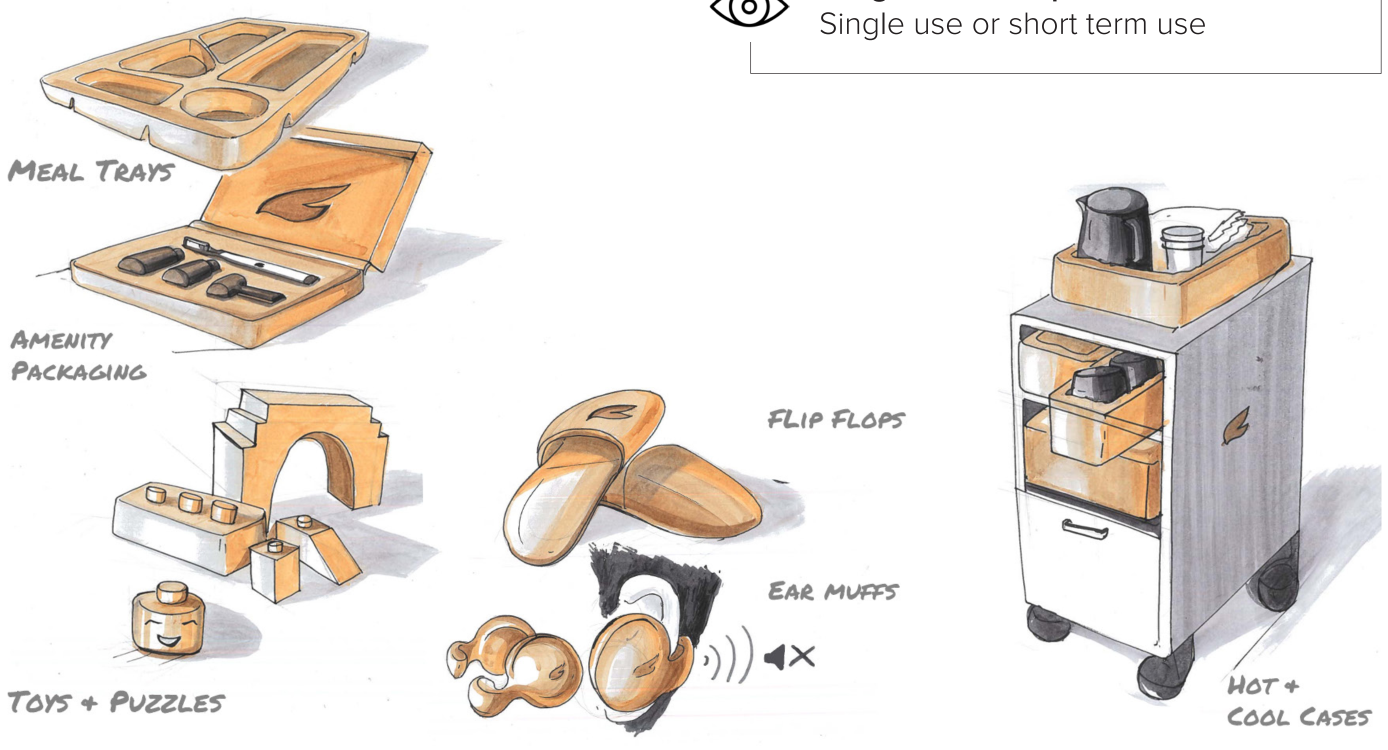
SF2 Coatings or chemical processing applied to the finished products should not ideally hinder the planned end of life processes like composting, incineration or recycling.
SF2.1 The toxicity of any additives used should be in accordance with the REACH regulation

SF3 The life cycle analysis of the mycelium based products show some environmental hotspots.
The developed commercial processes for the applications should be able to mitigate the effects of the hotspots.

For Ex. The dehydration/drying process process should use sustainable energy mix if permitted by the location of production.

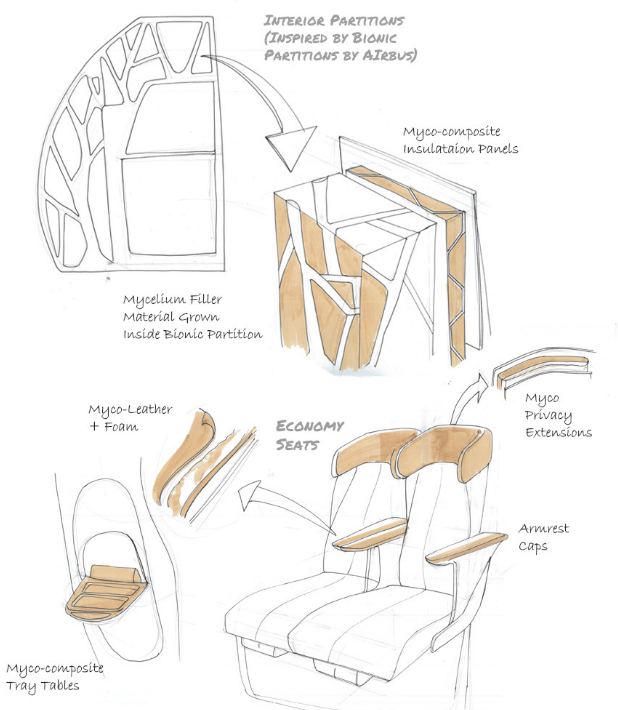
5.4.Ideation of Potential Cabin Application Concepts

Inflight services products
Single use or short term use



Interior Panels & Structures

Seating & Accessories



AIRCRAFT INTERIOR COMPONENTS

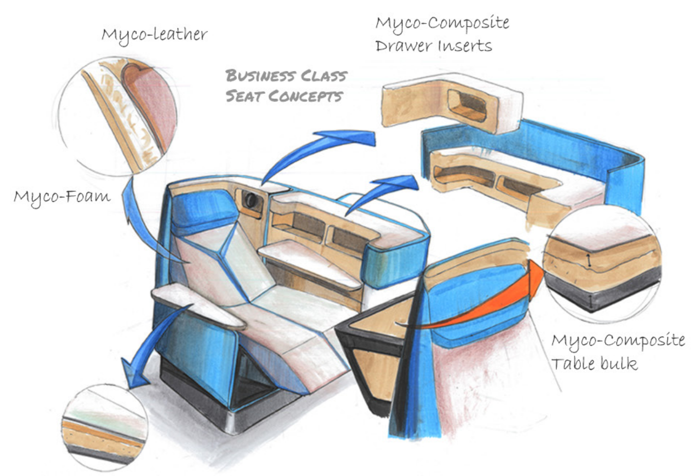


Fig 20: AI generated visuals with prompts to generate mycelium based applications in a cabin

5.5.Idea validation & Analysis

The concepts were subjected to a brief open validation session with professionals responsible for cabin design and development to different degrees i.e RE1, RE2 and RE3.

Some highlighted insights from thee validation are mentioned here:

RE2, a product manager for sustainable cabins, mentions it is key to identify the aviation stakeholders responsible for production and end-of-life of the proposed products for a circular design.

RE3 (Trends & materials designer for cabins) & RE2, suggest that applications that are in close contact with passengers' bodies, may have acceptance and maintenance concerns. In addition, having opportunities to customize product forms for different airline customers is advantageous.

RE1 (Polymer scientist at Research & Technology) mentions, that keeping the aim of inspiring through impact in mind, it is key to select product ideas for demonstrators which provide advantages that other materials cannot and also have a high potential to mitigate the negative environmental impacts - through either weright reduction, superior technical performance or awareness.

All experts agree, that masking the natural appearance of the mycelium materials with coatings in any of these applications goes against the strategic choice of aviation stakeholders of letting the sustainability advantages be apparent to users, and also may hinder end-of-life processes.

5.6.Concept Selection

While each of the applications depicted in section 5,4 hold promise, for the sake of demonstrator development and environmental assessment in this thesis, a basic 3-degree scale evaluation was performed. The criteria of evaluation were derived from the design vision, suggestions from experts and corresponding requirements.
Table 5 enlists the 12 criterias and scores the concepts.

The concepts selected to detail further, develop into demonstrators and assess are the amenity packaging/meal trays and the optimized mycelium composite based bionic partitions.
Apart from it's satisfaction of criteria, the rationale behind this selection relates to my aims as a designer in this project, to inspire further development.
The optimized mycelium composite based bionic partition was chosen as conventional partition walls are one of high weight components in a cabin, built using materials and composites which are by no means easy to recycle, or return to the loop. A demonstrator of the partition can also be adapted for other interior panelling and large scale furnitures. It is thus a versatile and high impact choice which can easily demonstrate the benefits of mycelium deployment, thus inspiring further development.

The amenity kits cum meal trays on the other hand, allow me to demonstrate impact and the opposite end of the range of lifespans of mycelium materials. These products are not required to have a lifespan of years, yet they have assured interactions with most passengers in aircraft. Clever design, can thus allow me to use it also as a vehicle of raising awareness about bio-based materials and circularity, inspiring not only the researchers but also users. It aids in tackling the issue of single use cabin waste from airlines, due it's sheer volumes.

In chapter 6, these chosen concepts are detailed further.

Legend

2 = Material quality highlighted well/ Criteria satisfied well
1= Material quality satisfactorily noticed / Criteria met
0 = Material quality not highlighted at all / Criteria not met

Table 5: Concept selection table for application ideas

	Criteria / Quality	Application Concepts					
		Amenity Packaging & Meal Trays	Hot & Cool Cases	Earmuffs & Flip Flops	Business Class Seating	Economy Class Seating	Bionic Partitions
1	Apparent Sustainable Advantage	2	2	1	2	2	2
2	Thermal Insulation	2	2	1	0	0	1
3	Material Versatility	2	0	1	2	2	1
4	Acoustic Insulation	0	0	1	1	1	2
5	Reduced Weight	2	2	1	2	2	2
6	Hygienic Feel	1	2	1	2	2	2
7	Percieved comfort	1	0	1	2	2	2
8	Mouldability	2	1	2	2	2	2
9	Customizability	2	1	1	2	1	2
10	End of life Potential	2	2	2	1	1	2
11	Environmental Impact Potential	2	0	0	2	2	2
12	Cabin weight reduction potential	1	0	0	1	1	2
	Total	19	12	12	19	18	22

Takeaways

1. My design vision defined intends to inspire researchers & designers to continue their interest to make commercial deployment of mycelium in aircraft cabins a reality soon.
Thus, to realise my vision, I proceed with the identification of applications & products, and conclude this section with a selection of 2 product service concepts.

2. These selected concepts should help me realise my vision by allowing me to demonstrate the range of temporal qualities of mycelium, its maximal weight-saving or environmental impact reduction potential and allow passengers to perceive these sustainable material choices.

3. Using reference to the Airbus A320, A330, A350 and A380 passenger aircraft family interiors, application categories in an aircraft cabin could be defined for the convenience of design with mycelium. These three categories, namely - inflight service products, seating & accessories and interior panels & walls differ mainly in their lifespan of use.

4. Mycelium materials, in this context can demonstrate varying durabilities and hence be used for these different lifespans for each of these categories - Inflight service products, seating or panels. Examples of specific products in these categories that can use the mycelium properties to their advantage are briefly illustrated in this chapter. All these products & services can become a family of mycelium applications in future aircraft cabins, with varying ease of introduction into the aircraft.

5. As mentioned in point 1, a selection of two concepts - a modular meal tray cum amenity kit packaging and an optimised interior bionic partition (skeletal design by Airbus DE), was made. A modular meal tray/packaging tackles the two biggest uses of single-use plastics disposed of in an aircraft cabin. A design aspiration would be to make use of product messaging on the design to allow the users to understand the sustainable shift, and become involved in it.
An optimised bionic partition, on the other hand, can use mycelium's insulation, textural qualities and weight-saving potential to mitigate the impacts of GFRP & CFRP composites which pose immense environmental challenges at the end of life.

Details on these designs are presented in Chapter 6.

Concept & Demonstrator Design

In this chapter, the two chosen design concepts to develop into demonstrators are detailed.
The design of their form, their aesthetic features, product messaging, functions and assembly methods (if any) are described. The material development process and their list of materials are defined. In the conclusion, their potential impacts and their user scenarios (if relevant) are briefly discussed.

6.1 Concept & Embodiment Design : Myco-composite based Bionic Partiton

6.1.1 Form & Function

This design uses the aluminium alloy bionic partition skeleton developed by a collaboration between Airbus, Autodesk, APWorks and the Living. The skeleton is optimized through a rigorous generative process inspired by slime moulds with the best possible strength to weight ratio. The skeletal framework, however needs filler material and coverage to become a passenger facing component.

This proposed design uses mycelium foam like like composite grown as filler material with the skeletal framework as part of the mould, and provides coverage & acoustic insulation with customizable textured myco-composite panels.

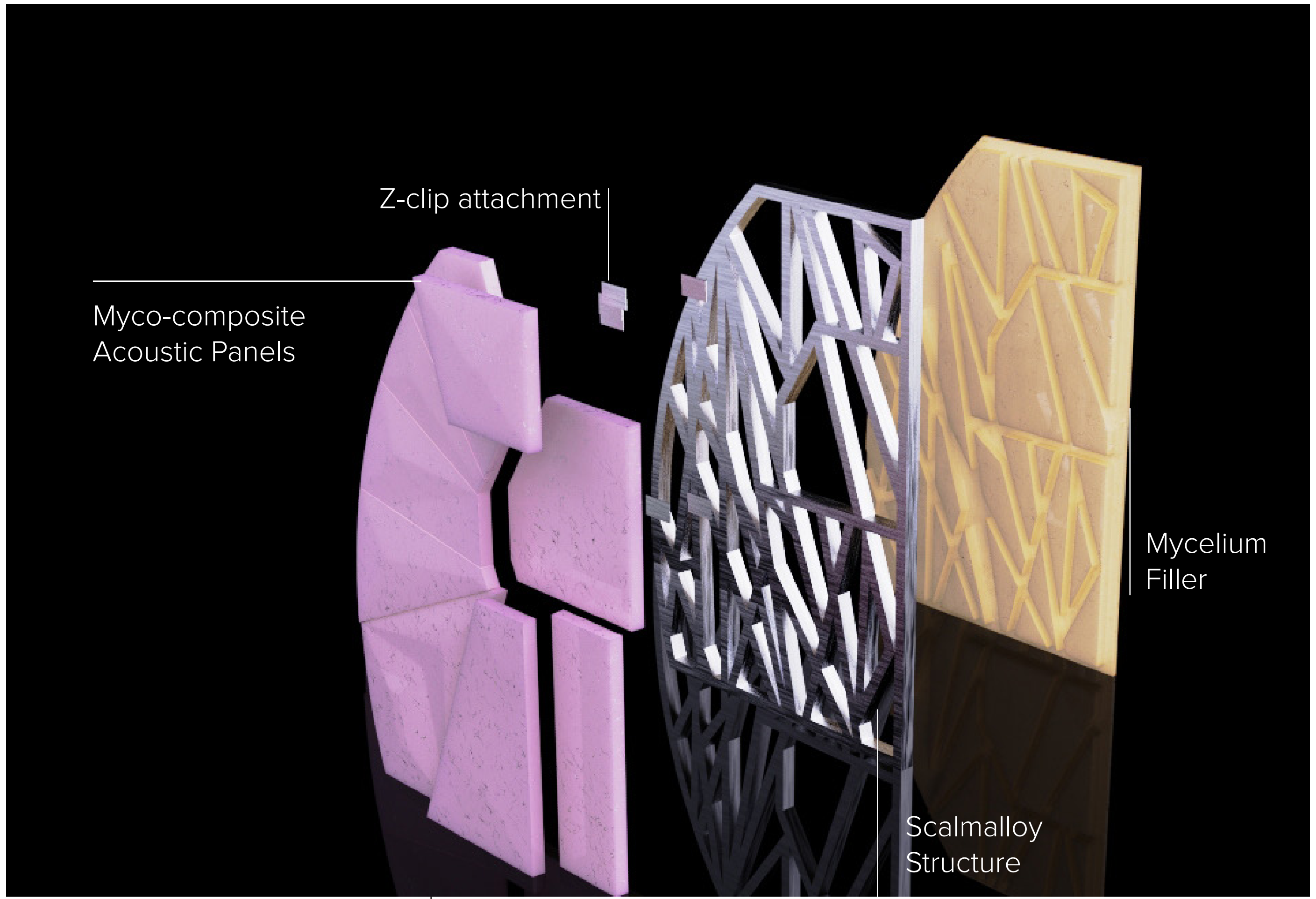
This reduces the number of materials used in a conventional partition from 5 to merely 2, with no non-recyclable or petroleum based materials. The tile based coverage allows easy installation and disassembly, using Interlocking clips/snaps or screws. A localised scratch or damange can be repaired by removing the tile itself instead of the whole partition wall.

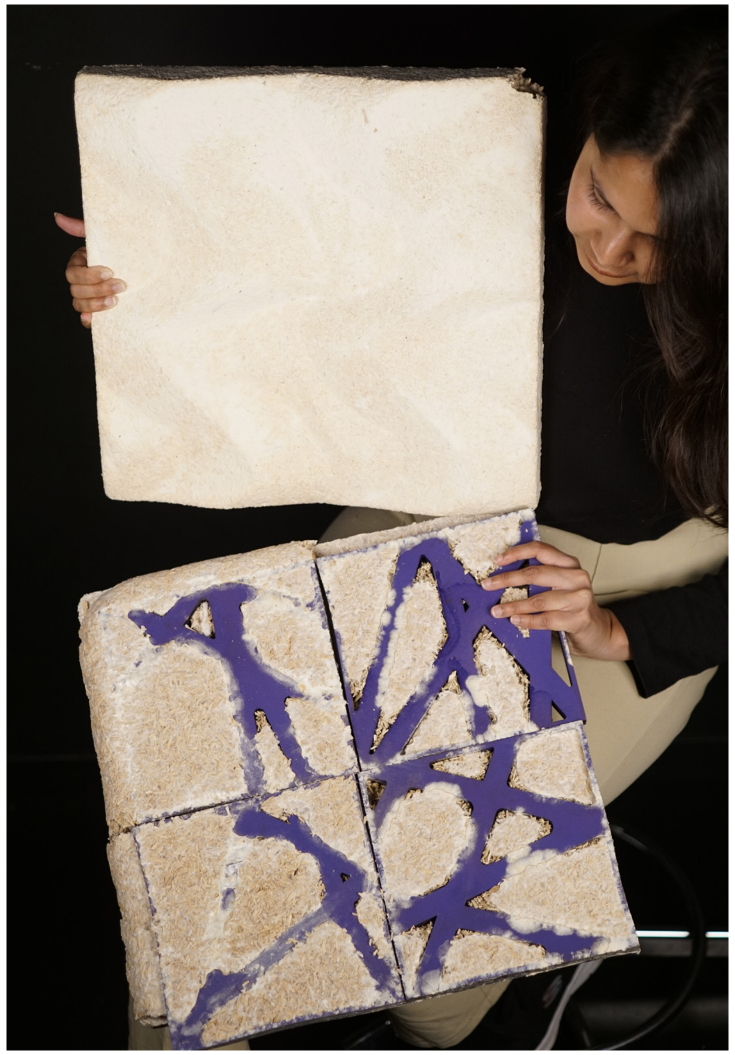
The partition wall can function similar to the conventional partition, with attachment points for crew seating, monitors or other utilities.

Impact:

This revised design at this stage weights 41,6 kg, in contrast to a conventional 67 kg partition wall - a 25% reduction in weight.

With approximately 12 - 20 walls in the cabin of the latest Airbus A380, a maximum of **500 kg** can be reduced, translating to 100 tonne Kg jet fuel saving per annum and **310 tonnes of CO2** production due to fuel combustion (Nordisk Aviation, n.d.).



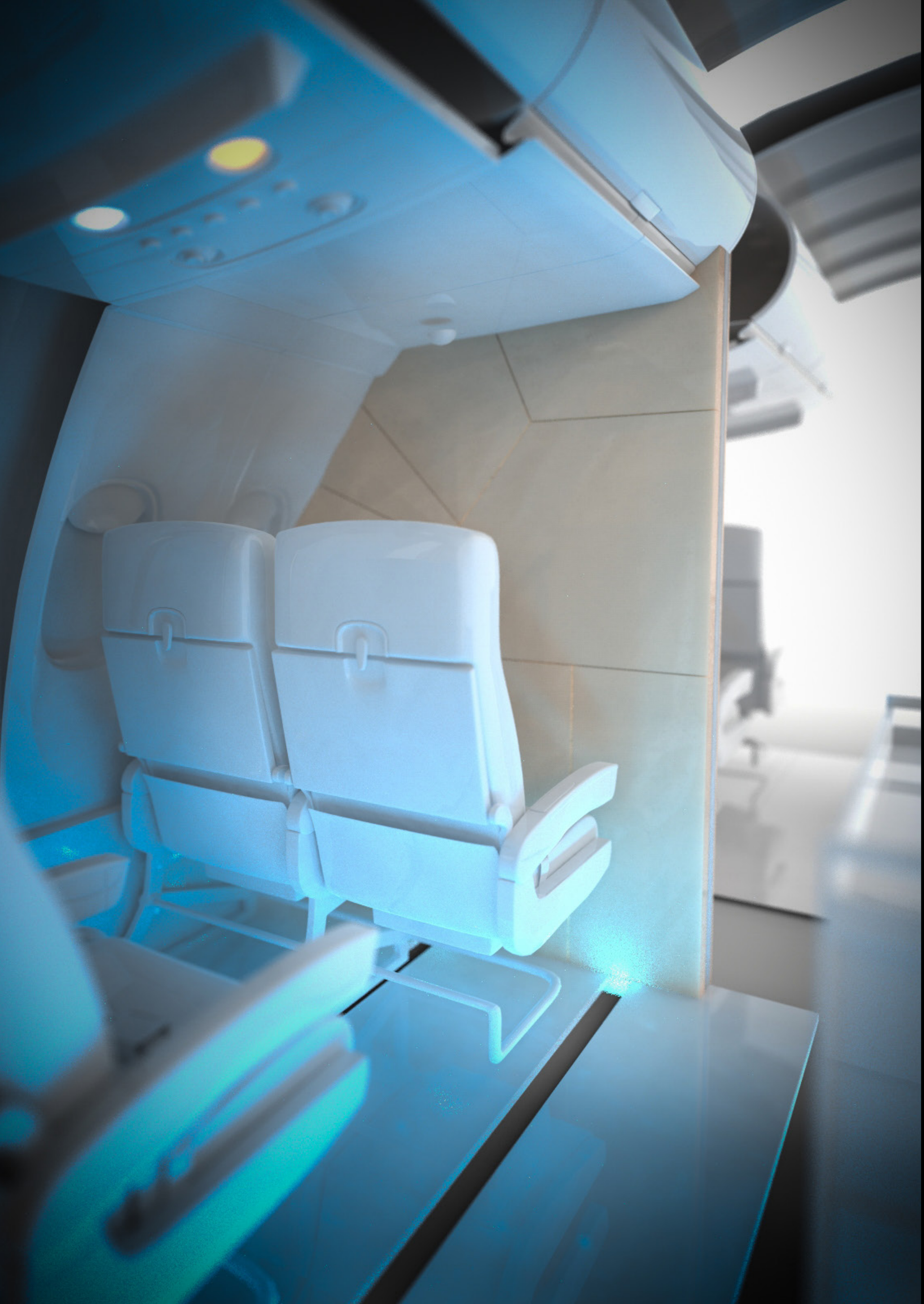


DEMONSTRATOR
Partition section

Acoustic panel from Grown Bio

Filler & skeletal structure built at Biodesign lab & PMB,

Faculty of industrial design Engineering TU Delft



40%
Lighter than conventional partition

41,6 Kg
Total Weight

11,6 Kg
Mycelium weight

0
Petroleum based materials

6.2 Concept & Embodiment Design: Meal Trays & Amenity Packaging

6.1.1 Form & Function

Meal serving trays in aircraft cabins are conventionally made using BPA-Free polypropylene, and used to arrange and serve dishes and cutlery. Amenity kits on long haul flights typically come in the form of plastic or synthetic fabric bags with travel sized hygiene and dental products.
The proposed dual function design comprises of a meal serving tray that can be transformed to an amenity packaging through the use of puzzle like modular blocks. The tray component is used for serving, and when fitted with internal blocks, can be used as customizable storage and cushioning for hygiene products, dental products and other amenities.

The puzzle like blocks also enable product messaging and easy end-of-life processing, either realised through the passenger or by the airline

Dimensional match allows for this dual usage, and also helps airlines minimize the no.of tyes products purchased.

6.1.2 Product Messaging

According to IATA, in 2018, airlines generated around 6.7 million tonnes of cabin waste (Discarded Plastic And Uneaten Food, 2020). About 80% of this waste is comprised of single-use plastics for meal trays, cutlery, amenity kits, toy bags, bottles etc. which are landfilled or incinerated by the airlines.

This product has been designed to subtly highlight the single use cabin waste issue and efforts of alleviating it through circular materials. Thus, through moulding to emboss or engrave the product messaging, the exterior of the product mentions that it was
'Grown with fungi, plant fibres and care'.

The puzzle like 3D blocks provides surfaces which signify the end-of-life process options for the product, in which the passenger can choose to take part. Faces of the blocks read 'reuse', 'grow' or 'compost'. While they are self explanatory, simple instruction pamphlets can accompany the product as chosen by the passenger.

DEMONSTRATOR
Amenity kit

Fabricated at
Biodesign lab & PMB,
Faculty of industrial
Design Engineering ,
TU Delft

DEMONSTRATOR
Meal ServingTray

Fabricated at
Biodesign lab & PMB,
Faculty of industrial
Design Engineering,
TU Delft

Takeaways

At the conclusion of this chapter, the reader can see the results of the design & production of the demonstrators.

1. The modular meal tray/amenity kit packaging concept has been designed to engage the user and as a vehicle for material awareness. The amenity kit's modular design with small blocks of mycelium and product messaging about the end-of-life options encourages the passenger to take the kit home, reuse it, compost it or use it as fertiliser blocks.
2. An alternate user scenario simply informs the passenger about the end-of-life pathways that the airlines might use. Product messaging could also allow airlines & cabin interior manufacturers to mention the uses of mycelium in the cabin.

3. The optimised bionic partition builds on the skeletal design of a slime mould-inspired generative design of a Scalmalloy skeleton by the Advanced Cabin Design team at Airbus. The designed demonstrator replaces layers composites (GFRP or CFRP), plastic coatings, wool and decorative mouldings in a conventional partition, with mycelium composite processed in different ways. The Scalmalloy skeleton provides structural load-bearing capacity, while the mono-material filler & panel of mycelium composites provides insulation, resists damage and is a lightweight visual barrier.

4. With mycelium's acoustic insulation properties, it is theorised that it can effectively reduce sound pressure in the cabin environment due to speech. A sound absorption coefficient ranging from 0,4-0,9 is observed from frequencies between 50-600 Hz (range of soft speech to baby's cry) for acoustic panels made with mycelium.

5. This design also saves about 25kg per unit of partition, and with the use of approximately 20 such panels in an Airbus A380 cabin, a weight saving of 500kg per aircraft, translating into approx 100,000 or 100-ton jet fuel saved and 316,000 kg of CO_2 emission due to fuel saved (Data source - IATA).

6. While that may constitute only a fraction of an aircraft's CO_2 emission, the advantages & cost savings in the raw material production and end-of-life of the mycelium-based partition panels add up substantially.

In Chapter 7, the assessment of the end-of-life strategies and life cycle impacts of these designs is presented to validate the assumptions surrounding the environmental impact of the designed products & mycelium-based materials in aircraft cabins.

Circularity & Life Cycle Assessment

In this penultimate chapter, one of the key motivations of this thesis is revisited - to understand the environmental impacts, advantages, disadvantages and potential of mycelium-based materials in applications in the aircraft cabin. A brief report of the analysis of its circularity & circular end-of-life strategies afforded by the material & context is presented. It is followed by the results of a comparative fast-track life cycle analysis of a conventional aircraft interior partition and the mycelium-based optimised bionic partition. The intended outcome of this chapter is to understand the scale of impact of mycelium partitions and to identify environmental hotspots in their life cycles for future optimization strategies to minimize negative impact.

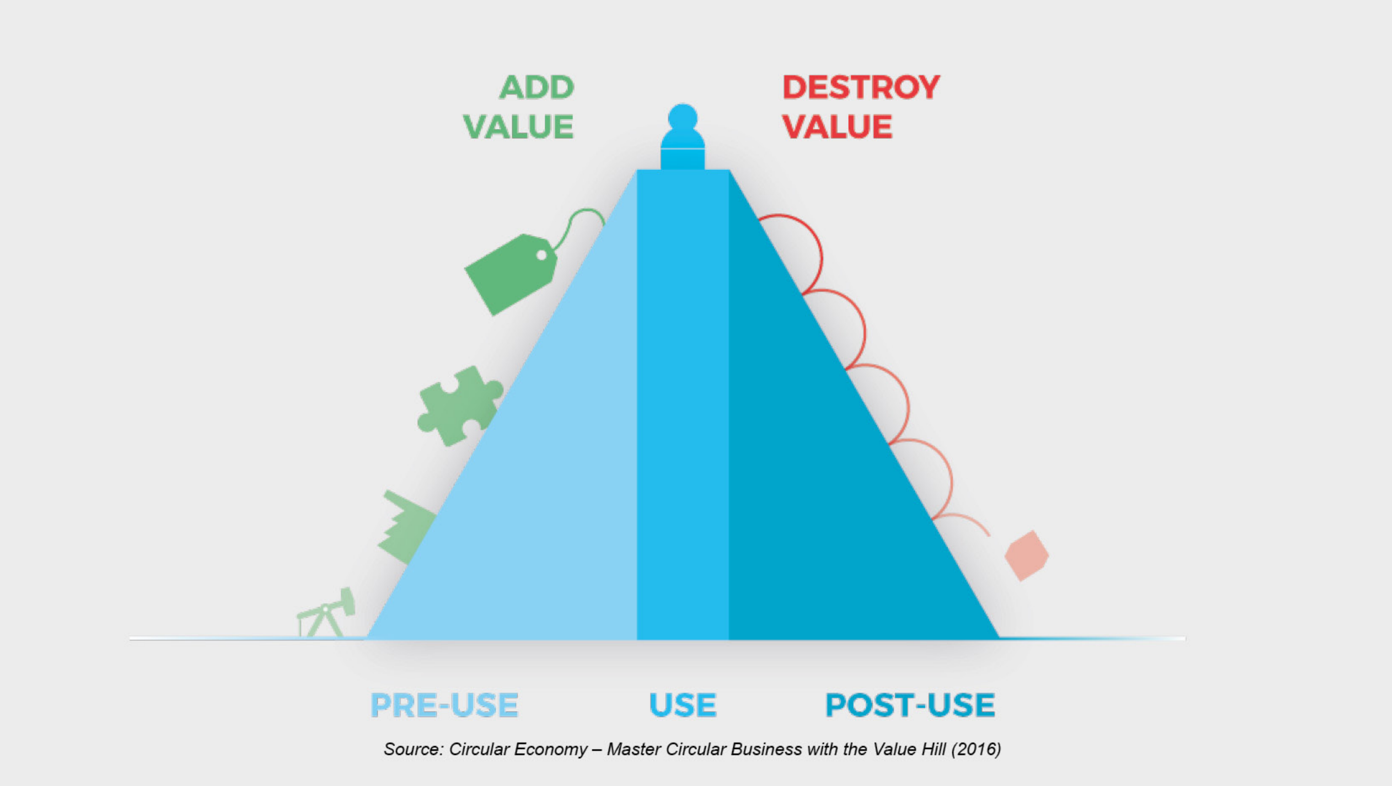


Fig 21. Value hill methodology for circular strategies (CIRCO)

7.1 Circularity of Proposed Application Design

As stated in the personal motivation, for a successful circularity transition, circularity should the foundational consideration instead of an afterthought. Thus, as one of the conclusion of this design endeavour, it is essential to propose a circular product service system and strategies for mycelium applications in cabins.

To devise these strategies, a combination of theoretical and experimental analysis was used. Decisions about optimal end-of-life strategies for mycelium materials in the controlled aviation environment are taken through the use of Value Hill (Master Circular Business with the Value Hill - Insights - Circle Economy, n.d.) as a business strategy tool.

The value hill in a circular economy proposes a categorisation based on the lifecycle phases of a product: pre-, in- and post- use of a product. Value is added at each stage of the production process, but in a linear economy, once a product has reached the end of its life, it is sent to landfill or is incinerated without energy recovery, quickly losing its value. For a circular model, it proposes the following strategies for businesses to retain value within the closed system during each life-cycle phase:

Pre-use : Circular design of products, materials and services for long term retention of value.

Use : Support optimal usage and product productivity

Post Use : Value recovery or capture resource value after product's life.

Inspiration for a preliminary framework to assess actions/processes to support circular economy strategies of the value hill is drawn from (Joustra & Bessai, 2022).

Table 6 lists the actions & processes for circular strategies that are possible and optimal with mycelium materials in the bionic partition and packaging material. Some of these actions/processes have been validated through supporting experiments and rest have been derived through subjective evaluation and understanding of the material properties over use.

Table 6: Actions & processes for circular strategies that are possible and optimal with mycelium materials in the bionic partition and packaging materiial

Design Aim	Preserving Product Integrity			Preserving Material Integrity	
Circular economy strategies	Long Life	Lifetime Extension	Product Recovery	Structural Reuse	Material Recycling
Possible Actions/ processes for Mycelium Materials in Aircraft Cabins	Reuse packaging/ panels for purposes with lower requirements	Repair partition through self healing by mycelium Maintain by eliminating rough usage conditions	Refurbished or Remanufactured parts of the partition	Repurpose panels and filler materials for non-visible insulation applications in aircrafts	Mechanical recycling & remoulding of used mycelium composites to grow new composites
					Validated through laboratory experiments

In addition to processes listed in the table, the **thermogravimetric analysis** performed also proves that Incineration between 250 - 350 degree celsius with energy recovery is feasible.

Recycling to remould the products is supported only till a point where the substrate retains enough nutrients.
Upon reaching that stage, incineration or composting to close the loop is preferred.

End-of-life processes suitable for mycelium composites

Fig 22. Some end-of-life processes suitable for mycelium composites

7.2 Comparative Life Cycle Assessment of Myco-Composite Bionic Partitions and Conventional Aircraft Partitions

With a satisfactory level of detailed design of the product service systems, the final and some of the most crucial research questions of this thesis, pertaining to the comparative environmental assessment of mycelium application and conventional cabin materials can now be answered.

Thus, as a concluding effort, a Fast-Track Life Cycle Assessment of Myco-composite Bionic Partition and a conventional Nomex Honeycomb based partition is performed. It is assumed, that due to the scale and wide differences in materials, an comparative LCA of only the partitions would also provide some general insights applicable for other myco-composite applications. Thus, an LCA of the meal trays cum packaging is omitted at this stage.

The results are summarized in this section.

LCA Objective 1:

To understand the environmental burden/advantage of using mycelium-based materials in aircraft cabin as a filler material and insulation panels with bionic structure in class partitions and interior walls. It is compared withAircraft partitions and interior panels made of Nomex honeycomb cores and glass/CF phenolic resin. It is also an objective to note the environmental hotspots in the life cycle of mycelium composites in the partition.

Functional Unit

Comparative environmental Impacts of the materials used for 1 optimized bionic partition with mycelium filler and panelling to be used in a wide body aircraft which operates for 12 hours a day, 365 days for a lifetime of 15 years in an intercontinental flight.

System Boundaries

The product system analysed here is cradle-to-cradle, meaning it includes in the analysis of processes from raw material production, processing, product use and end of life.
In the specific context of the optimized bionic partition in comparison with the conventional partition, it involves the following high-level processes.

Manufacturing: In consideration are the raw materials, processes for production of the raw material for the substrate, electricity usage for the growth of mycelium filler and composite materials, assembly of the components of the partition, Scalmalloy for the partition skeleton and 3D printing of the partition skeleton. The environmental impacts of the maintenance of equipment used in these stages such as the autoclave sterilization, ovens for drying or metal 3D printers has been omitted for the sake of simplification and comprehensibility.

Transport & Use: The partition's use is the act of transporting it as part of an interior component of the aircraft. The transport/use stage thus focusses on fuel usage in terms of the approximate cost-of-weight in terms of the amount of jet fuel/kerosene required within the terms of functional unit.
Other transport processes include the transport of substrate raw materials to the production & assembly location. However, these transports can be assumed to have a minimal impact when compared to the usage of the partition in the aircraft.

End of Life: In line with the principles of circular economy, product life extension can be achieved by repairing damages in the partition, refurbishing or recycling the substrate to create new myco-composite panels. However, at a stage where the substrate quality is no longer suitable for growth, incineration with complete energy recovery is defined as the end-of-life process.
Recycling of the aluminium alloy is noted.

Similar system boundaries for a conventional partition are taken into account

LCA Inventory Analysis

The primary data for the production of the mycelium based bionic partition is obtained from laboratory experiments, data published by the client – Airbus and material providers.

Commercial acoustic panel provider Mogu bio's website was also used to estimate product weight and assembly methods. Similarily, for conventional partitions, primary data was obtained from the websites of OEMS and the FAA technical data sheet on aircraft cabin materials. For information on processes and energy usage for these processes, Granta Edupack 2021 was used.

The environmental footprint (pt) for the materials & processes are reported either as a direct match or suitable substitution (proxies) from the IDEMAT 2023 excel database.

Material Modelling

Appendix 2, provides detailed calculations of the material model and inventory.

Fig 23 & Fig 24 are drawn as a rough depiction of the material model of a conventional aircraft partition and an optimized mycelium based partition.

Material model of a conventional aircraft partition

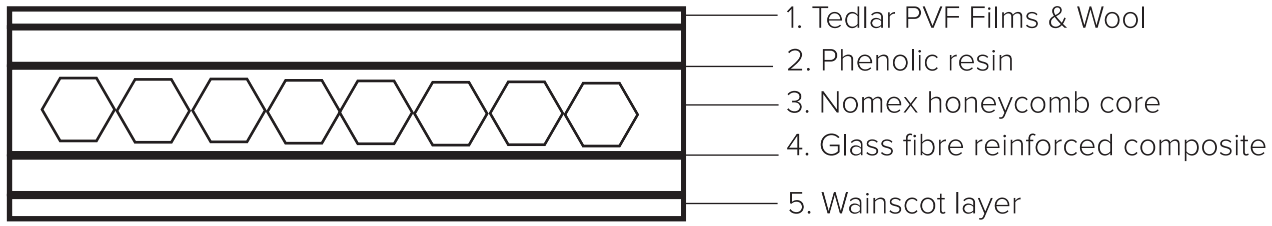


Fig. 23

Material model of a mycelium based aircraft partition

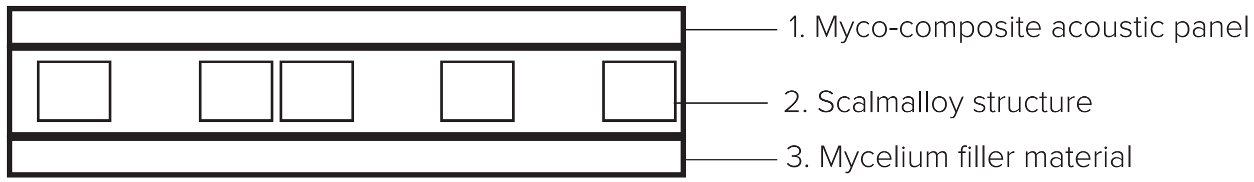


Fig. 24

Outcomes

1. The difference in the environmental footprint (Pt) due to the transport of the partitions over 15 years overshadows the impacts by the manufacturing and end-of-life processes. Thus, it is isolated and analysed. The difference in environmental footprint (pt) of transport (use phase) of the myco-composite partition is lower by approximately 40%, compared to the conventional partition.

2. The environmental footprint of the manufacturing of the mycelium composite partition bionic made with virgin substrates and virgin Al-Alloys is comparable to that of the manufacturing of the conventional partition. However, a big limitation of the excel based fast-track LCA method is that it doesn't allow easy incorporation of circular strategies such as using recycle materials. The growth of agro-residual sources of substrates such as hemp, waste cotton etc. has a considerable environmental impact in manufacturing.

Proof of concept of mechanical recycling of myco-composites indicates that this impact can be reduced considerably. Another hotspot is the additive manufacturing of the Al-alloy (Scalmalloy skeleton), and it is hypothesised that casting, as being done now, would reduce the impacts. However, it is currently beyond the scope of this project.

3. The end of life impacts were approximated for mycelium components with incineration with heat recovery of cellulosic materials like paper, cardboard and cotton.Along with recycling of the Al-alloy, the end of life impacts of myco-composites are lower than those of conventional partitions. It must be noted, that the limitation of not being able to incorporate the recycling process of myco-composite may be contributing to inaccurate results.

Total impacts in environmental footprint (Pt) in the LCA of the two partitions

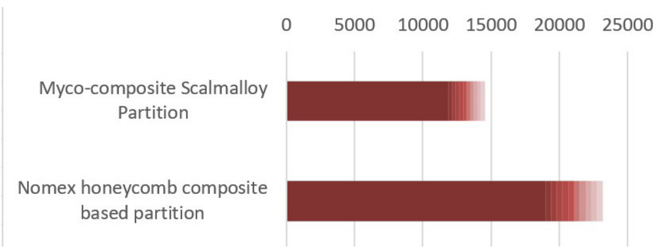


Fig. 25

Transport stage impacts i.e environmental footprint (Pt) in the LCA of the two partitions

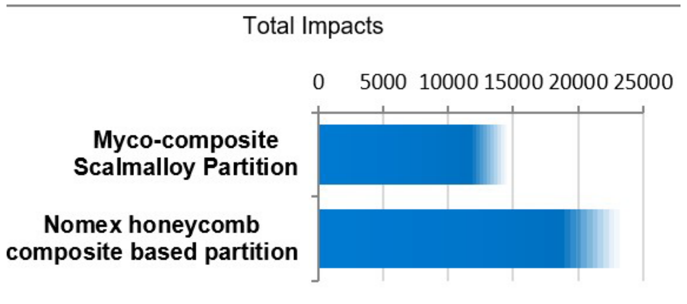


Fig. 26

Impacts in (Pt) of manufacturing and end of life stages of Myco-composite based partition

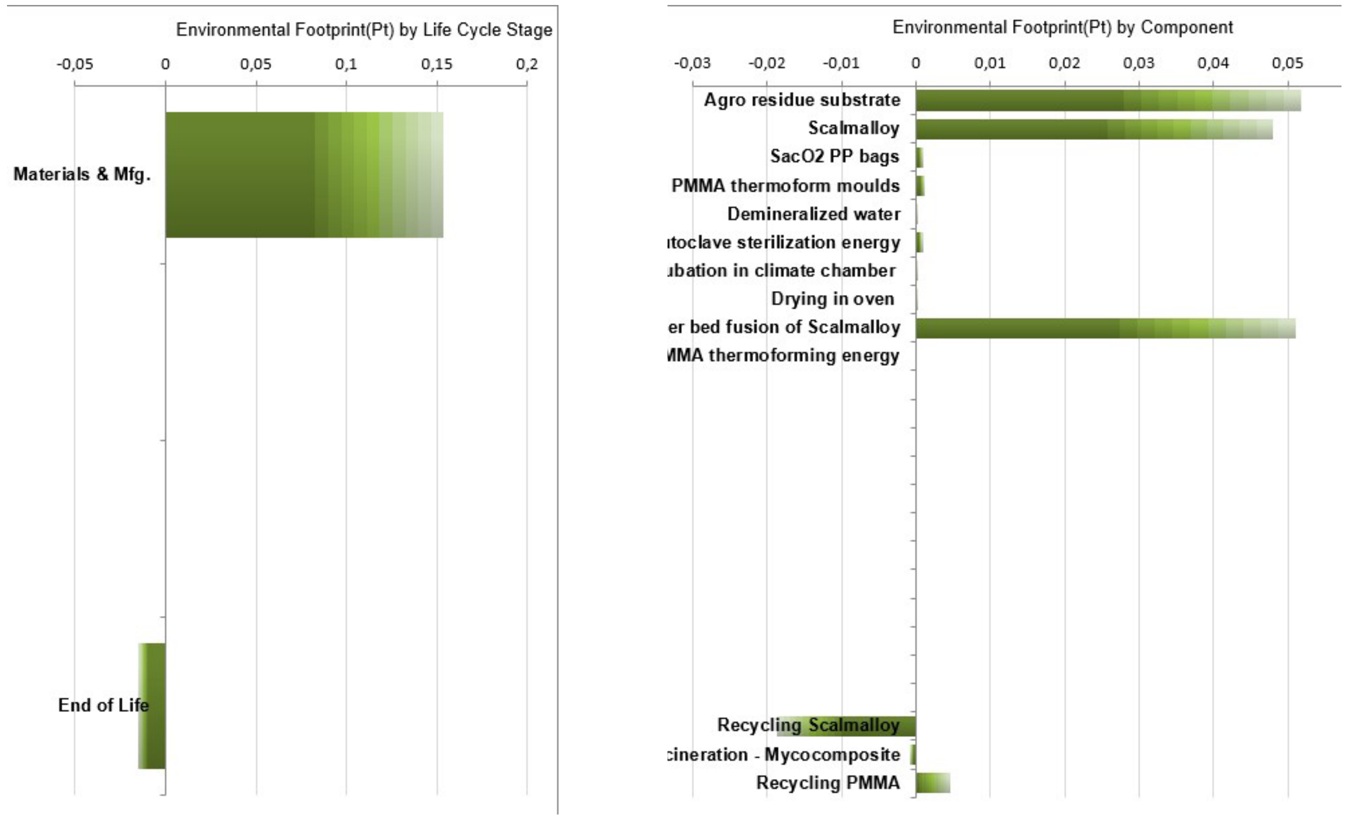


Fig. 27

Impacts in (Pt) of manufacturing and end of life stages of a convention partition

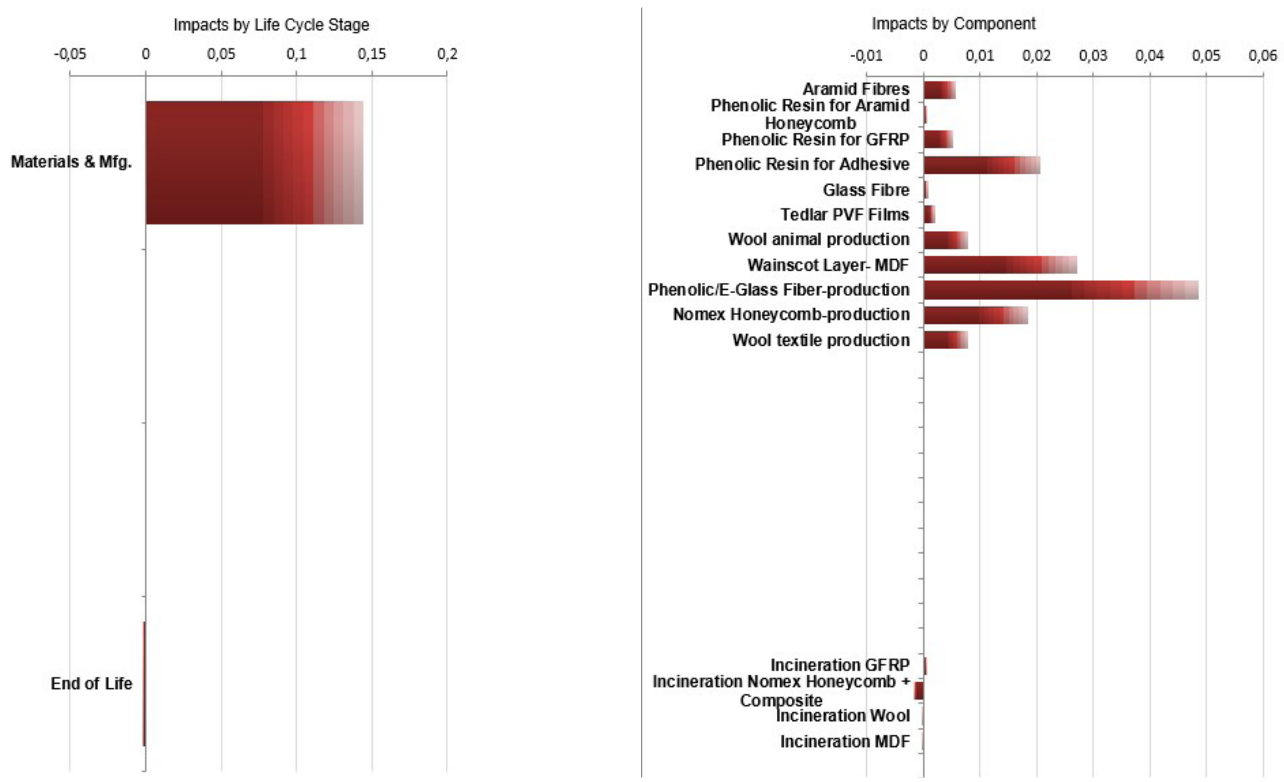


Fig. 28

Takeaways

1. Mycelium-based material in a controlled system like aviation can have desired end-of-life pathways. The value hill tool (Master Circular Business with the Value Hill - Insights - Circle Economy, n.d.), (The Value Hill, n.d.) is used to analyse specifically the actions/processes required to realise circular economy strategies for mycelium in the aviation context (Joustra & Bessai, 2022). These analyses were supported by experimentation to identify which value recovery strategies & processes were most relevant.

2. It can be concluded that modularity, repair or refurbishment by self-healing mycelium are effective for product life extension & product recovery. For preserving material integrity and lowering the impact of raw material production, recycling the myco-composite by grinding and remoulding the product was demonstrated in an experiment successfully in this project.

3. It is thus suggested as part of the design by the designer to recycle the myco-composite material of the bionic partitions or trays into the substrate and mix it with a predetermined percentage of the virgin substrate to reduce life cycle impacts during the raw material growth stage.

4. In the occasion that hygiene concerns or loss of nutrients in the recycled substrate finally occurs, both decomposition by anaerobic composting or incineration with energy recovery are valid processes. However, a quick look at the impacts of both processes in the IDEMAT 2023 database prompts incineration with heat recovery as a desired strategy by the designer here.

5. The fast track LCA of the conventional partition & myco-based partition clearly indicates the major differences in Life cycle impacts over the lifetime of use occur due to fuel savings resulting from 40% weight savings. The environmental footprint of the production of required weight myco-composites is remarkably lower, confirming the assumption. Production impacts are increased because of the casting or additive manufacturing process of the scalmalloy skeleton, the optimization of which is beyond the scope of this thesis project.

6. Environmental hotspots in the lifecycle of mycelium-based components include the electricity consumption for the sterilization, incubation and drying processes. Albeit small compared to that of Glass fibre reinforced polymer & Carbon fibre reinforced polymer production, one should aim to optimize processes for zero carbon production. While using renewable sources definitely help, a climate-positive process impacts everyone positively.

Thus, as future research opportunities, it is suggested to examine extensively how the fungal biotechnology processes for commercialization can minimize energy use and environmental footprint in all stages.

Conclusion

This chapter recaps the research questions and aspects of the problem addressed in this thesis and to which extent in terms of the findings and design proposals. It also discusses the potential implications of the introduction of mycelium-based materials as a sustainable commercial aircraft cabin material, from the perspectives of applications. Further, the limitations of this thesis and recommendations for future work in designing for aviation by leveraging fungal biotechnology are described. The thesis comes to a close with a personal reflection on the process followed in this very interesting design project.

8.1 Conclusion

Research & Design Problem
Mycelium-based materials are a family of materials of biological origin, providing several apparent advantages such its lightweight nature, biodegradability and its low carbon production process. These primary properties make it of considerable interest to the commercial aviation sector for which weight reductions and circular end-of-life of materials provide substantial sustainability advantages. However, there are gaps in knowledge, research and demonstrated design & development that stand in the way of the deployment of these mycelium-based materials. These gaps formed the foundation of the research questions and problem definition of the project Hyfen. In a nutshell, the key challenges addressed were as follows:

Challenge: The project Hyfen aimed to assess the mycelium-based materials at their current stage of development, and develop conceptual applications leveraging the most optimal material properties for within aircraft cabins.

Sub Challenges addressed:

1. Understand material properties of myco-composites and pure mycelium materials from the specific lens of identification of requirements and advantages in an aircraft cabin.

2. Identify potential applications within a commercial aircraft cabin of mycelium-based materials based on the understanding of their material profiles.

3. Design and develop demonstrators for selected applications to demonstrate low-level material development processes and analyse impacts.

4. Analyse and propose circular end-of-life strat egies that are afforded by the materials in the controlled environment of aircraft cabins.

5. Provide a preliminary assessment of the comparative ecological impact through a fast-track life cycle assessment of the chosen application.

Methods:

The above challenges were approached through a structured methodology with the Material Driven Design method forming the overarching guiding method.

An understanding of the material was developed through meticulous literature review and tinkering. Comparisons of the material profile of the mycelium-based materials with existing aircraft cabin materials and evaluations against material requirements were performed. The tinkering also sheds light on the practical challenges of designing by growing a living material.
This exercise resulted in a design vision and refined requirements for application design, thus addressing sub-challenge 1.

Potential applications within an aircraft were subsequently identified by seeking a match between my design vision, unique material qualities and the requirements developed. 2 applications were chosen to develop into demonstrators owing to their ability to highlight the design vision, addressing challenges 2 & 3.

These example applications were used as a basis to analyse circular end-of-life strategies, supported by some technical examinations. Conclusions about suitable end-of-life strategies as desired in challenge 4 were reached through an understanding of concepts outlined in value hill model (Master Circular Business with the Value Hill - Insights - Circle Economy, n.d.) and circular strategies for composites by (Joustra & Bessai, 2022).

Finally, a preliminary fast-track life cycle assessment of the conceptual application of a partition was used to gauge the ecological impacts and comparative ecological advantage. It also resulted in the identification of the hotspots in the development of the application.

Findings & Outcomes

Some findings & outcomes that can be highlighted based on the challenge they addressed are as follows:

Understand material properties of myco-composites and pure mycelium materials

As elucidated in previous sections, aircraft cabin materials have a few required properties and other desired properties based on applications. In this contextual light, myco-composites and pure mycelium materials have the following relevance for usage.
They have a variable density range based on processing but can provide considerable weight savings. Their mechanical properties (tensile, compressive and flexural strengths) can at best resemble those of low to high-density foams, not warranting the use of mycelium materials as primary structural supports.
The most attractive properties of mycelium materials especially myco-composites for applications are the following:

Mouldability & Shapability - Ability to grow into intricate or organic shapes. The only limitations imposed are those by the technologies used for mould or growth form formation.

Insulation properties - Ability to insulate sound pressure at a wide range of frequencies. Their foam-like structure allows for the insulation of fragile materials from impact and temperature variations.

Organic & warm visual & tactile quality which is desirable in a comfortable aircraft interior

Apparent sustainability - Mycelium materials are easily perceived by users as materials of biological origin and thus perceived commonly as a sustainable alternative to synthetic plastics & composites.

Identify potential applications within a commercial aircraft cabin of mycelium-based materials based on the understanding of their material profiles

The versatile nature of mycelium materials based on its material development pathway allows for several temporal properties (physically & perceptually). Thus, potential applications based on their intended time of use and their responsible production & maintenance organisation were determined.
Single-use or short-term applications by inflight services such as packaging for amenity kits, snacks, meal trays and hot & cool cases were identified.
Applications which can be repaired, repurposed, and renewed frequently include decorative coverings of armrests, leather upholstery of seating, shelf inserts for business class & first class seats etc.
Long-term applications intended for renewal once within an aircraft lifespan include mycelium-based partitions, interior panelling and insulation batting.

Design and develop demonstrators for selected applications to demonstrate low-level material development processes and analyse impacts.

In order to develop demonstrators in line with the design vision - i,e to serve as inspiration, to achieve maximal environmental impact and to showcase several of the optimal material qualities for an aircraft cabin, 2 design concepts were chosen. Thus, the demonstrator of an amenity kit packaging cum snack tray and an optimized bionic partition was developed.

The amenity kit packaging/meal tray can aide in the the reduction of single use plastic usage age in aircraft cabin. It simultaneously lets passengers feeling involved in achieving circularity through the use of small blocks with suggestive messages on the circular potential of the material after the flight. Alternatively, they can be easily decomposed after use by the airlines.

The second demonstrator built was of minimal & effective bi-material partition in the the aircraft cabin for separation of classes, cockpit and seating sections, lavatories and galleys. The skeletal structure of the partition was adapted from Airbus's bionic partition design by designer Bastian Schaefer. Mycelium foam and acoustic panels on it act as filler material, acoustic and visual partitioning.

The intended application provides 40% weight savings, and an easy to disassemble and repair design. Mycelium's warm and soft texture renders a comfortable quality to the interiors whilst making the use of a sustainable material extremely apparent.

Analyse and propose circular end of life strategies that are afforded by the materials in the controlled environment of aircraft cabins.

Mycelium materials afford several circular product system strategies to be used in conjunction, such as easy self-healing repair, disassembly, recycling, biodegradation and incineration with energy recovery.
For applications with a short life span such as an amenity packaging or meal tray, reuse and biodegradation under aerobic conditions are optimal ways of product life extension and subsequent nutrient recovery.
For applications with medium to long life span, myco-composites, as supported by experiments, can be ground to a desired particle size, and used in combination with fresh substrate. This process is akin to mechanical recycling with low energy demand.

Provide a preliminary assessment of the comparative ecological impact through a fast-track life cycle assessment of the chosen application.

The objective of the fast-track life cycle assessment was two fold. First, to gauge the cradle-to-cradle comparative ecological impacts of a conventional aircraft partition and the optimized design. The second purpose is to understand the key processes during manufacturing, transport & use and end of life, that are environmental hotspots for mycelium-based applications. The LCA was conducted by the fast track method using the IDEMAT 2023 database in a do-it-yourself excel sheet from TU Delft.

The results indicate that the key environmental impact difference between a conventional composite-based partition and a mycelium & Al-alloy-based partition occurs due to their weights and their end-of-life strategies.

The environmental footprint due to aviation fuel combusted to carry the weights of the partition for intercontinental flying for its entire lifespan (15 years) outweighs other impacts.The environmental footprint of a conventional partition weighing 67 kgs roughly exceeds that of a myco-composite-based partition weighing 41 kgs by 40%.

The other large impact differences occur in the incineration of fibre glass & aramid composites at the end of life, when myco-composites burn with organic residues and energy recovery.

A standalone analysis of the myco-composite & Al-alloy partition also results in the additive manufacturing or casting of the metal skeleton as the major hotspot.

In isolating the life cycle of mycelium-based components, optimization points for the reduction of its impacts would be ensuring the use of a cleaner energy mix for sterilization and drying processes. A faster, less energy-intensive drying process to kill the fungi and eco-friendly alternatives to

8.2 Implications & future vision

In conclusion, it has successfully achieved its goal of demonstrating that mycelium-based materials have great potential for designing circular aircraft cabin applications. This thesis provides strong qualitative evidence that mycelium-based applications within an aircraft cabin have considerably lower environmental footprints during its lifecycle.

As the aerospace industry gears itself with transformation with sustainable fuel technologies, new configurations and new policies, mycelium materials for circular interiors can be an integral element in reinvented vision.

A future of sustainable aviation would be incomplete without interior materials which have net zero emissions and can cycle back resources and nutrients. I envision the future of aviation where elements of decommissioned aircraft can feed the production systems again and single-use products can be degraded without any toxic emissions.

Mycelium materials are a versatile family of materials, and scaling up fungal biotechnology can herald a revolution that makes petroleum-based products obsolete. In light of this scenario, the aerospace industry can and must leverage it for its transformation.

8.3 Limitations and recommendations for future work

Limitations during this project were subject to my personal knowledge & skills, time constraints, the resource & technology availability, the nature of the organism and materials and unprecedented challenges that arise. These limitations, in this thesis just like any other, provide a basis for future research & development. This section provides a general overview of the limitations of this thesis and those that might be faced by others.

8.3.1: Limited Information: early stage of environmental analysis of applications

The primary challenge was to understand how fungal mycelia-derived materials can be used in circular applications in an aircraft cabin, and what stands in the way of their deployment.

Literature reviews and contextual research revealed several sub-challenges through a cause & effect method of analysis, and each of these sub-challenges could become a single thesis topic.
The client - Airbus and my personal interests directed this thesis towards focussing largely on finding optimal & unique material properties, identifying applications and most importantly - evaluating its circularity and environmental advantage. Sustained future interest of both the parties (client & student) in this novel material hinged on these material applications being genuinely circular and providing added value over existing ones.

While the initial findings from the life cycle assessment, material profile analyses and circularity analyses have very positive indications, they should only be used as a qualitative estimate. While the versatility of mycelium is advantageous in most regards, it makes the reproducibility of results subjective. Thus, numbers and figures from this thesis must not be quoted with absolute certainty.

Depending on advancements in the design & development of fungal biotechnology for aircraft cabins, more concrete information can be furnished and used for detailed evaluations such as ISO 14044 life cycle assessments.

8.3.2: Handling uncertainty & standardizing production & processing for application

During the course of this thesis, a laboratory scale production, material testing and processing of mycelium composites was done.
A laboratory scale is mildly disadvantageous due to variations in growth conditions due to a lack of human precision or machine precision. For example, every batch of sample production can have minuscule variations in the consistency of substrates, sterility of bio-safety chambers etc, which can result in magnified differences in material property and visual quality. In my experiments, sections of a single material sample oftentimes displayed varying densities and material properties. Fungal skin formation variations rendered

varying textural and visual qualities. Contamination, despite stringent sterilization measures, was a frequent occurrence which could not be monitored round the clock.

Contrary to well-known plastics or metals, the design of industrially optimized systems with the assurance of the standardized quality of products is elaborate and complicated for fungal biotechnology-based products.

Thus, one of the most important future research opportunities comes in the form of finding methods and designing processes to make standardized mycelium-based material applications for a highly sensitive context such as aerospace. Case studies of the production systems of large-scale fungal biotechnology ventures such as Ecovative, Mogu, Grown Bio and Mycoworks are great starting points.

However, as mentioned repeatedly, aircraft cabin materials have stringent flammability, smoke, toxicity and application-dependent properties. With such high stakes, a constant quality check of raw materials, procedures such as genetic modification of strains for ensuring fire retardancy compliance, quality testing of batches of production and sophisticated contamination prevention methods are imperative.

8.3.3: Practical usability and ergonomics of applications

Since this thesis is a very preliminary contribution to the novel niche of designing with mycelium for aerospace, usability and ergonomics of the applications were not in the scope yet.
It is, however, the most logical next future challenge - to understand and redesign these applications to be easy to use, maintain and serve their function right. In an aircraft cabin, mycelium-based materials can pose a challenge to clean & disinfect without surface modifications. Ease of replacement of parts and degradation of visual and design qualities of the products such as the partitions are all concerns to alleviate.

Another key area of research could be focussing extensively on the material experience, user experience & perception and acceptance of mycelium-based applications in aircraft interiors. Once the prototypes and demonstrators can be developed with desired finishes, an interesting direction of exploration would be to gauge how to users react to the novel material.

Past experiments suggest that users react more favourably to mycelium materials when they think it is part of a more ecological & sustainable aircraft & interior, compared to a conventional one.

8.3.4: Sustaining continued interest & accelerating certification

Lastly, the nature and context in which this project was kickstarted was both a novel opportunity and a limitation. For material innovations in the crucial aerospace sector, conventionally proven knowledge is considered safer and thus resistance to new material deployment is observed. Unlike other sectors, material certification for new applications can take exorbitant time for acceptance - especially if they are structural in the aerospace sector for air safety. It took nearly three decades to advance both carbon fibre composites and fibre metal laminates from first tests in the laboratory to their introduction in aerospace. Before deployment, novel materials must undergo a range of tests – from numerous general material properties tests to several sub-component tests followed by major integrated tests on board actual aeroplanes.

This thesis aimed to form the foundation of design and research with mycelium in aircraft cabins. Thus, simple general material property tests and an understanding of the advantages of the material were developed.

This thesis project would achieve its envisioned outcome if it simply generates adequate interest in the aerospace industry to scale up efforts to push towards certification & deployment of fungal biotechnology-derived materials.

8.4 Personal Reflection

The seed of thought about this unique project was sown several nearly a year ago and evolved to a tangible form in February 2023. It began with a curiosity about why, so many unique materials of biological origin are not put to use in industries like aviation which are in dire need of sustainable transformation. This personal curiosity was validated when Airbus - the forerunner organisation in aerospace and defence, expressed interest in exploring mycelium for aircraft cabins through this case.

At the conclusion of this thesis, I wish to reflect on the process and evolution of my outlook as a designer aiming to bridge the knowledge of natural systems and industrial ventures.

8.4.1 Designing out of the box or within conventional restrictions?

In the initial phase of the project, I identified that the stringent requirements of the aviation sector as being one of the unique challenges of this project. A regular question that arose was 'If you can use mycelium materials for fashion or home interiors, why can't it be used in aviation interiors?'. A straightforward belief I started out with was that it is the unique safety compliance and acceptance requirements render this difficult.
Eventually, during the process, a realisation dawned that at the current stage of development and with resources at my disposal, if I believed that mycelium-based materials have to comply fully with industry standards, the case would be shut in no time.

The challenge was thus not as simple - there were vast knowledge gaps which this case had given me a carte blanche to explore, beyond the conventional restrictions. The material-driven design methodology was especially effective in activating my thought process and looking at the true potential in the case. Instead of simply equating the technical material properties of currently used materials in aircraft cabins or passing the material through a string of tests for compliance, I evolved to better understand its unique affordances.

It thus made me metaphorically reflect on the unique advantage I provide to society as a designer. Do I wish to continue designing by rules that have been set and reach hasty conclusions about the possibilities or do I wish to design out-of-the-box solutions for which the box can eventually be widened or adjusted?

8.4.2 Embracing uncertainty, analysing and adapting

This unique opportunity allowed me to step away from designing with predictable materials and methods, and instead interact with a living organism. I had always romanticised the idea of industrial design not just getting inspiration from biological systems, but also being symbiotic with it to create products and services of use.
However, my educational conditioning that a meticulous methodology would always yield the desired results was challenged not by humans or machines, but by the fungal organism. Over the course of my multiple trials trying to predict and understand it's behaviour through generalizations, I was forced to take into account the inherent uncertainty. A key lesson as a designer I learnt thus, came from the fungi, which helped me build patience and an attitude of questioning and adapting my methods. Through patient everyday observation and recording, I understood the factors for varying rates of growth, varying properties, varying visual characteristics and failure in achieving desired shapes. Iterative experimentations, trials and errors and finally adaption resulted in satisfactory results.

This journey I took with the organism taught me more about methods of scientific analysis coupled with creative problem-solving, than several books and lessons.

8.4.3 Achieving circular transition as a driver

As someone having grown up in a world with a ticking clock for climate mitigation,
I have believed it to be my responsibility to devote a chunk of my professional career to sustainability. However, conversations, panel discussions, explorations and in-depth analyses during the course of this thesis allowed me to face the inextricable complexity of designing for sustainability and circularity. The path is convoluted on occasions, but an understanding that circularity is not an afterthought but an embedded necessity is important.
Despite it being demoralising on occasion, it ended up building my confidence in handling the complexity. I now feel energised to further my professional career towards sustainability and circularity, for industries in dire need of transition.

I wish to thank the readers for taking the time and effort to go on this graduation journey with me. I hope it has sparked curiosity and has been an enjoyable one.

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