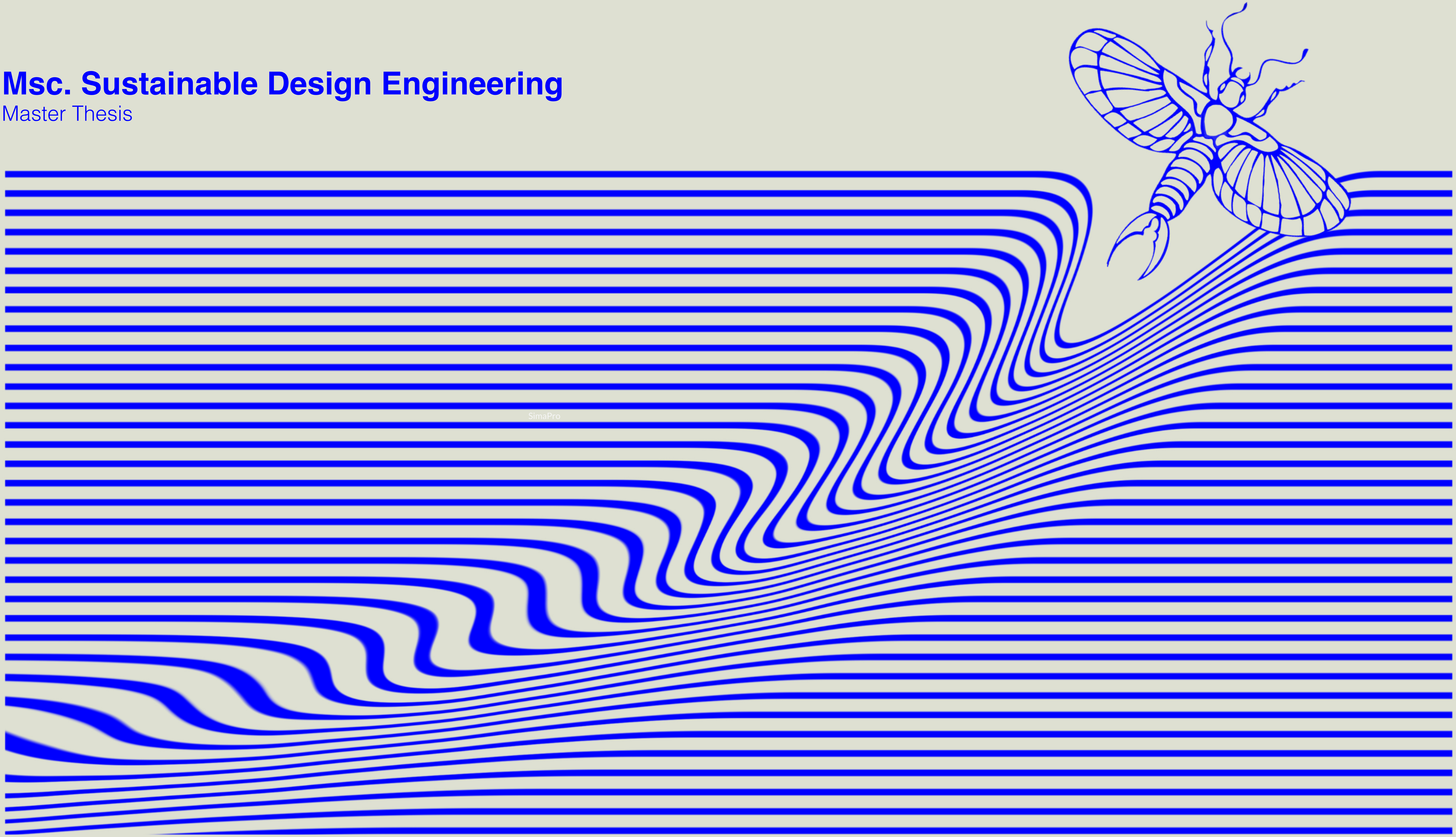
Msc. Sustainable Design Engineering

Master Thesis



Abstract

This thesis is conducted in the fourth semester of the master's program of Sustainable Design Engineering at Aalborg University in Copenhagen, where the matter of consideration is Biomimetics & Product Design - Opportunities and Innovation Creation. The project takes a multidisciplinary approach to design, drawing inspiration from materials as a design tool concept and biomimetics as a design practice rooted in observing nature and seeking answers to human-related problems.

The thesis's focal point is to find a design solution for the research-discovered problem of the lack of possibility of privacy and the occurring disruptions commonly experienced in open office workspaces. To tackle this issue from a multidisciplinary approach from material as a design tool practice was used. This gave the structure to facilitate the whole process by looking at it from three perspectives of materials, fabrication, and design concomitantly.

The design part employed a design thinking and biomimicry top-down approach. Combining both methodologies helped to develop a comprehensive solution. The use of the theoretical frameworks taught during the Sustainable Design Engineering degree guided the multidisciplinary design process where an idea for a folding complaint mechanism drawn from the folding pattern of an earwig insect emerged.

Combining all the knowledge gained through the design thinking and biomimicry top-down process resulted in the prototyping/fabrication phase that entailed the innovative Tailored Fiber Placement (TFP) technique in the VR-Lab at Aalborg University in Copenhagen. The prototypes were tested for usability, compliant mechanism properties, and materials attributes.

Materials used in this process were chosen deliberately to be sustainable, natural, and manufactured to the highest quality standards. Furthermore, a Life Cycle Assessment (LCA) was conducted for the chosen prototype for the sustainability promise validation and to align the design with the principles of sustainability. The assessment highlighted how the design contributes to fulfilling the three pillars of sustainability and promotes sustainable and innovative manufacturing practices.

Throughout the multidisciplinary design process and experimentation with multiple techniques, the biomimetics principle was used to create a concept of partitioner that contributes towards all pillars of sustainability and provides the possibility of seclusion in the open office workspace. The process in this report presented, that this thesis contributes to the field of biomimetics, sustainable design engineering, and the creation of innovative solutions for enhancing privacy in contemporary work environments.

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Introduction

While people's privacy and seclusion are found to be essential in many settings, such as airports, schools, and hospitals, this master thesis focuses on privacy in open office workspaces. The open office workspace has become increasingly popular in recent years, but it presents challenges in maintaining privacy and concentration for employees.

The current trend of creating open office workspaces was initiated in the 1980s and has gained immense popularity among company owners. Such workspaces promote collaboration, communication, and teamwork among employees, which is vital for success. Open office concepts also come with challenges, including the need for more privacy and the possibility to decide when to withdraw from people by the employee itself. Humans often need help concentrating on their work due to the constant noise and visual distractions in the workspace. This lack of privacy can reduce productivity, lower job satisfaction, and increase employee stress (Piccard & Westin, 1968). To address this discovered problem, a multidisciplinary approach of materials as a design tool was chosen because it promotes using multiple disciplines and creativity to foster a deeper understanding of the problem (Dahy, 2019). Combining knowledge and skills from different fields from biomimetics, design, and tailored fiber placement fabrication to Life Cycle Assessment (LCA) and sustainability, makes solutions more innovative, effective, and comprehensive.

Numerous studies and literature reviews have already been conducted by companies and other researchers on employee work behavior, needs, and privacy in open office workspaces. They highlighted the importance of workplace privacy, comfort, and productivity. Those findings provided sufficient information to form the design solution. Therefore, the design process did not require employee participation, as the research provided a comprehensive understanding of the challenges and needs in the open office workspace. While employees understand their desires and preferences uniquely, they probably may not have the exact knowledge and expertise to design an optimal workspace. For instance, they are unfamiliar with novel design methodologies and their usages, such as biomimicry, (LCA), or Tailored Fiber Placement (TFP), which are increasingly used to create sustainable and functional designs.

Biomimicry, or biomimetics, is the design practice of looking deeply into nature and gaining solutions for human-related problems (Benyus, 2009). This approach was chosen because its application has proven to solve many already existing design challenges in the most efficient way. It allows learning, synthesizing, and later applying those solutions in the real world. This approach often results in more sustainable and efficient designs that can improve human well-being while minimizing environmental harm (Hwang et al., 2015). Leveraging the earwig folding pattern, facilitated biomimetic design that promotes privacy and reduces distractions for the employees. Doing this is essential in order to achieve the social sustainability of the product in the office space. Specifically, the thesis will focus on developing a foldable, biomimetics-inspired partitioner, which employees can use to decide the intensity of human connections and interactions while creating their own private seclusion within the open office environment.

The foldable, biomimetics-inspired partitioner prototype will be designed to mimic the natural folding patterns of an earwig insect wing. The partitioner will comprise a lightweight, flexible material that can be easily folded and stored when not in use. Using biomimetics-influence design will not only aim at providing privacy to the employees but also at creating an isolating and comfortable environment, which is extremely important when tackling social sustainability. Improving their work experience while allowing them to withdraw from people when needed is predicted to help them focus on their work without leaving the workspace entirely. The partitioner will be easy to unfold, allowing employees to set up their private space quickly and effortlessly whenever needed.

The product will be developed using an innovative and young Tailored Fiber Placement (TFP) fabrication discipline. Previously used primarily in the aircraft and automotive industry, this technique is already being explored and proving very beneficial for sustainability and efficiency in the design world. BioMat Institute (Biobased Materials and Materials Cycles in Architecture) Research Department at ITKE (Institute of Building Structures and Structural Design) in Faculty 01–Architecture and Urban Planning, University of Stuttgart is one of the examples where this technique is being developed and explored on a more significant scale (BioMat Department, n.d.). This high-performance manufacturing technique will allow for the exact placement of fibers in a complex three-dimensional shape without having excess waste during production. This principle is fundamental to sustainability and its economic and ecological pillars by not having additional costs of the excess materials and not producing waste.

The thesis will involve a literature review of the existing privacy issue in open office workspaces and the studies showing what is crucial and essential for employees working in this environment. The paper will approach the identified problem from a multidisciplinary approach of materials as a design tool practice. This theory looks at design from three perspectives of materials, fabrication, and design simultaneously to achieve the best outcomes (Dahy, 2019). In the design section of materials as a design practice, both methods of design thinking and the biomimicry top-down approach will be combined to get a clean outcome when creating the product by extracting the best from both methodologies and fusing them into one cohesive approach. Furthermore, a biomimetic analysis with the identification of principles and later abstraction from the biological model of the wing-folding pattern will be conducted. Using another discipline of engineering and TFP machinery to facilitate a model. This method will enable creating and visualizing the final prototype in a 3D physical model and present an innovative approach to the problem. An LCA will be conducted to assess the overall environmental burden of the project and its weak points that could be improved for even better outcomes.

In conclusion, the lack of privacy in open office workspaces is a growing concern for both employees and some employers. Implementing a multidisciplinary approach provides a promising solution to this problem. The biomimetics-inspired, compliant mechanism partitioner, developed by prototyping using the TFP method, will offer an alternative approach to enhancing privacy in open office workspaces while allowing employees to control their privacy. The thesis aims to contribute to the existing knowledge and lack of privacy in open office workspaces by using biomimicry design practice to provide insights like conducting an LCA or using innovative methods of TFP, that can guide companies toward creating more creative, respectful, and sustainable work environments.

Research question

To contribute towards sustainable development, initiatives in connection to biomimicry and open office design concept, this project centers around developing a multidisciplinary solution that is intuitive in usage, fulfills three pillars of sustainability, and is less climate-burdening through its whole life cycle. This combined established the scope for the project based on this research question:

How can biomimetics foster creating a sustainable, compliant mechanism partitioner, using a tailored fiber placement method, that provides the possibility of seclusion for the open space office?

The process of answering that question will be elaborated in the following report, briefly presenting the literature review on the office design, its history, and employees' psychological behavior. Additionally, the importance of privacy and the ability to withdraw from human interactions when desired will be raised. Moreover, the definition of biomimicry and earwig insect wing design will be presented. The methodology employed in the research and design is based on the conceptualization for the prototyping stage by simultaneously incorporating design thinking and a biomimicry top-down approach in the design phase of the materials as a design tool philosophy approach. Subsequently, the paper will discuss contributing towards the three pillars of sustainability, the Tailored Fiber Placement (TFP) method, and its advantages towards a sustainable production approach in design. Additionally, an analytical Life Cycle Assessment (LCA) will be performed to understand better the design's climate burden, followed by a conclusion and discussion of the research and final prototype outcome.

Literature review

While privacy and seclusion are essential in many places, such as airports, hospitals, and schools, this master thesis focuses specifically on the issue of privacy in open offices. The open office workspace has become increasingly popular in recent years, yet it presents challenges in maintaining the level of privacy and concentration for its employees.

The Office

History Of Office Design

During fast industry growth in the United States of America, the first offices started to appear due to the emerging need in housing large numbers of employees in the same place/ building. At that same time, thanks to the industry growth, another sector also was developing- steel manufacturing. Thanks to using steel in new architecture, being able to design big open spaces with no walls inside, and span them over multiple floors with elevators that helped get there fast and reliably the "office" started to emerge in the city (Kopec, 2018)

Office before the 21st century could be categorized into four distinct design ways: Taylorism, Bürolandschaft, Cubicles, and Virtual Office (Kaufmann-Buhler, 2021).

The first design (the 1920s) was built on the hierarchy/ management that already existed in the office. It focuses on breaking tasks into smaller parts and dividing them between different employees by incorporating standardization of the procedures to achieve pure efficiency. This approach treats the employees more as robots, who need to fulfill their tasks most efficiently, not human beings Office (Kaufmann-Buhler, 2021)

In the 1950s new approach to designing office spaces emerged. It was breaking up from the currently existing office design. It understood that the Taylorism approach is better suited for simple tasks operated in linear development – like car production (Ross, 2012). The Bürolandschaft office landscape was focused on human relations (Caruso & St John, 2019). It was designed as a non-linear office promoting human interactions and collaboration. It focused on developing various work areas that connected multiple people in lounge spaces or big tables while implementing lots of natural light and small partitions (St John architects et al., 2006).

The next step in office design was created by Robert Propst, which came with the invention of a free-standing modularity system named Action Office for Herman Miller. Those modular systems (Cubicles) had the role of providing space division and providing privacy (Aardex, 2004). Unfortunately, this bright idea implemented by other companies as a money-saving approach leads to a dehumanizing aspect of this type of office and forgetting about the individual elements of the employees. By the 1980s, they had become the corporate standard (Kopec, 2018). Kupritz sees the bad qualities of cubicle design as increased visual and auditory distractions and decreased productivity (Kupritz, 1998). Moreover, although they appeal to employers as a low-cost office design strategy, they lead to a loss in employees' level of concentration and productivity, which does not benefit the company in the long run.

Another change in the layout and structure of the workplace came with technological advancements from the 1990s. Mobile phones and laptops allowed the employees to conduct their work not only sitting at the desk in the office building but also from home. This 'virtual office' greatly influenced the office size and design needs (Gensler, 2008).

Employees' Work Behavior

With the alterations in the office, the design also came an understanding of human behavior. Employers realized that each employee is different and requires a non-identical work environment. That is why there has been a differentiation between individual types of employees.

Figure 1: Key zones in the office space

Figure 1, (Steelcase, 2012) Created an interconnected workplace model that sees an office as a dynamic ecosystem that should adapt to changing current needs and environment. The model presents four key zones: the Focus Zone for individual, and personal work, the Collaborative Zone for community work, the Learning Zone for training and developing new ideas, and the Social Zone for relaxation and socialization. These zones in this framework are designed to support different work styles and activities, with various furniture solutions to facilitate collaboration, communication, and individualism.

(Johnson et al., 2020) created its framework based on the cultures emerging in current office social interaction: Collaborate, Create, Control, and Competition. Collaborative space is provided for social people. Create zone focuses on strategic thinking. Control focal point is an element of tactical work. Compete for culture is based on tactical work with aspects of presenting (Haworth, 2011). Both frameworks acknowledge the need to curate the office space for different employees. It ensures that by having multiple adaptive ways of facilitating work, the outcome will be effective and will not drain people by the end of their shift.

Figure 2: Jahnson Framewoek

A workplace survey (Gensler, 2008) shows that around 53% of workers are disturbed by other people surrounding them when they try to focus. Additionally, 42% of them makeshift solutions to adjust themselves and adjust their work to their needs- figure 3. To support his research. Johnson Controls (Puybaraud & Kristensen, 2011) in its survey conducted on 3,885 employees, reported that more than half of the workday of a single employee is spent focusing on distractions.

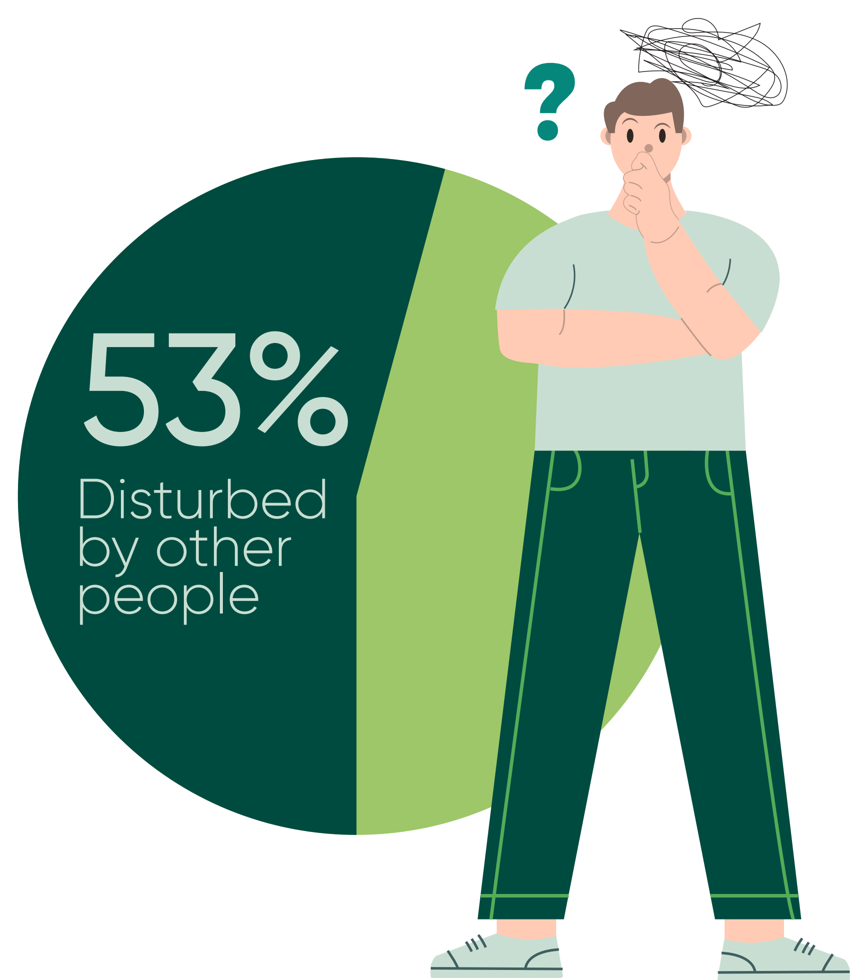


Figure 3: Survey findings from Gensler, 2008

All these surveys and studies of employee behavior prove that the distractions and lack of privacy when desired, caused by working in an open-concept environment are downgrading the employees' productivity levels and concentration.

Importance Of Privacy in A Workspace

Privacy and thinking about it is being implemented in multiple fields, and thus it might have slight variations in its definition based on the context. Looking at (Pedersen, 1999), his theory is focused on recognizing that privacy is not always based only on withdrawal from the people but mostly on controlling the amount and the intensity of human connections and interactions. He suggests there are different- 6 types of privacy: anonymity, isolation, reserve, intimacy with friends, intimacy with family, and solitude.

Visual privacy lets the employees balance their need for social interaction and communication by providing them with appropriate personal space (Kupritz, 2011). Additionally, looking at the work (Bellingar & Kupritz, 2011) shows that privacy can be divided into two categories

Being visible to co-workers | **Being able to see co-workers**

being visible to co-workers and the second of being able to see people and co-workers. This is linked to the privacy concerns defined above.

Here the visibility for other co-workers has shown that the employees feel like they are being constantly watched, which was taking a significant portion of their time focused on just thinking about it, not being productive and in the workflow (Piccard & Westin, 1968). Additionally, seeing other co-workers and not having any boundaries to cross (walls, doors, windows, etc.) lead to more interactions/ distractions by people simply intruding to say hello or have a small talk (Oseland et al., 2011).

To sum up, it is visible that there are many studies done on the constantly more and more emerging open offices and the issues they are creating. Despite the increasing emphasis on collaborative work environments, employees still spend a significant portion of their work time concentrating primarily on individual tasks in their workstations. Furthermore, it has been revealed that the lack of desired privacy can significantly impact employees' job efficiency. With a growing trend towards higher desk/ workstation density in work environments, it becomes crucial to identify privacy factors that positively contribute to employees' perception of their work satisfaction, leading to better outputs and efficiency, contributing to overall company growth and growth success.

State of the art

The previous paragraph focused on the office and its problems emerging from forming the open office concept through the years. With the growing need for flexibility and adaptability in workspaces, creating private and semi-private spaces that provide employees privacy while promoting collaboration and communication, office dividers have become an effective solution. Here the currently existing solutions created by many companies for that issues will be presented and discussed.

Office partitions have been a staple in open offices for decades. Traditional partitioners, such as solid walls or standard cubicles, can make an office space feel closed off and uninviting. There has been a shift in the design of office spaces, with companies moving away from traditional office partitioners and towards alternative and unconventional options. These new partitioners offer a range of benefits, including increased employee productivity levels, improved health and well-being, and an addition to a unique aesthetic (Bautista, 2021).

There are various of different approaches to designing office space and the dividers that are embedded into it. Some of the more innovative approach divider types are based on design ideas like:

• Green walls, also known as living walls, are made up of plants grown vertically on a surface, such as a wall or a frame, and can benefit employees and the environment. One of the main benefits of green office walls is their ability to absorb carbon dioxide and other pollutants from the air, releasing oxygen in the process and improving indoor air quality. Green walls can also help reduce the noise level in office spaces. Plants on the wall absorb sound waves, reducing the amount of noise that bounces off hard surfaces like walls and floors. They provide a visually appealing and calming atmosphere, which can help to reduce stress and increase the productivity of the company employees (Hailstone, 2022). Looking at all the positive aspects, we must remember the downsides of this design choice. A significant concern is the cost and maintenance required to install and later sustain this green wall. They require significant water and nutrients, contributing to water scarcity and mold issues if not properly maintained. Additionally, the plants may thrive if regularly sustained, creating unwanted design aesthetics. Finally, some employees may have allergies to a particular type of plant, which can create discomfort, allergies, or health problems (Manso & Castro-Gomes, 2015).

• Water walls. Water is one of the most potent biophilic elements and incorporating it into office design through partitioning provides several employee benefits. It incorporates water elements, such as fountains, aquariums, and water walls, into the built environment. Looking at (Browning et al., 2014) research shows that having water nearby reduces stress and lowers heart rate and blood pressure. Additionally, it increases feelings of tranquility and positive emotional responsiveness. It improves concentration and perception, and memory restoration. The takeaway from that research is that a frequent multisensory experience of clean water is perfect for the human psycho-physiological well-being of workers. Unfortunately, this solution also presents limitations or obstacles that sometimes take work. Some of the most common concerns regarding that design choice are high first cost and later the cost of continuous maintenance requirements that are unavoidable in this design. Another one is water scarcity, especially in water-poor regions, and sanitation toward human health. All those issues can be overcome, but they need to be addressed right from the beginning in planning that water feature in the office (Browning et al., 2014).

• Inflatable privacy screens. Looking at new Google Office designs, they implemented innovative creations like inflatable privacy screens. These privacy screens are large, inflatable structures made from translucent cellophane that can be easily inflated, moved, and placed in different locations within the office. They are designed to provide employees with a private workplace without distractions or interruptions. By providing a private space for employees to focus on their work, these screens can help to reduce distractions and improve overall productivity in the workplace. Unfortunately, cellophane is not a natural material that contributes to plastic pollution when the product is discarded. Additionally, the inflation time takes several minutes, making this process long and keeping the employee from changing the state of it quickly, depending on the situation (Wakabayashi, 2021).

Those presented, currently innovative and unconventional existing ideas are solving different needs of employers and employees regarding separation and space-dividing properties. Each approaches this topic from a different perspective presenting an innovative solution. All of those ideas significantly impact human beings and their health. However, it needs to be addressed that they also have some disadvantages or at least some points to remember when choosing them as the solution for dividing space. Additionally, none of the above or similar dividers approach the problem from a multidisciplinary design perspective, including biomimicry, engineering, sustainability, and design, with the usage of the young discipline of TFP which will be discussed in the following paper.

Significance of study

This section briefly explains the need and significance of this specific design solution.

As stated in the previous sub-chapter, there is a gap in the partitioner's world of approaching the division by implementing a multidisciplinary approach toward workers' needs by giving them more privacy when desired. Research presented that jobholders working in the open office concepts are grappling with concentration, productivity, and creativity while being distracted by other workers who are passing by. Creating a divider that will help minimize the stimulants for the laborers is predicted to boost their productivity and satisfaction by letting them decide when they are in focus mode and open for collaborative, interpersonal contact.

In the previous sub-chapter, it was presented that multiple partitioners deal with the level of partition and division on various levels and methods of achieving that. Nevertheless, none is designed with a multidisciplinary approach of combining biomimetic design practice, novel manufacturing methods of TFP, and fulfilling all three pillars of sustainability in mind. This leads to a creation of a partitioner that will solve the issues from a multidisciplinary approach. A first design approach is the TFP method, which was previously used by aerospace manufacturing and is now being implemented in the product design field as a young discipline. The method was utilized due to its high efficiency and automation, which is critical for the mass production of the solution (Khaliulin et al., 2015). It is a new method and discipline allowing the translation of calculated paths into textile reinforcements. The reinforcement has locally variable fiber orientations and layers, which help strengthen the material (Konze et al., 2017). Additionally, this method helps lower the resources used for production to the minimum. It lowers the excess leftover materials because technology only uses the amount of thread needed. Having no waste material is beneficial for sustainability, its three pillars, and the economy of the product in the future production and market (Uhlig et al., 2019). The TFP methodology chapter will further discuss this design methodology used in designing the partitioner.

Another discipline applied in creating this partitioner is biomimicry, which helped extract the folding performance of an earwig insect wing and later translated it into technical words of engineering by making the design a compliant mechanism design synthesis. Biomimetics is also a multidisciplinary design method (Ilieva et al., 2022) that combines engineering, biology, and other sectors to achieve the best results from all worlds. More biomimetics will be elaborated on in the biomimetics methodology chapter.

Looking at the sustainability discipline, the three pillars (Brundtland, 1987) are being explored and accomplished by creating a design that fulfills all pillars. By using production time and energy wisely, being considerate of the environment and its impact, and being concerned for human health and work behavior, the design takes all advantages of designing with sustainability in mind.

Creating a divider within a multidisciplinary approach is valid for employees and employers. It presents itself as a product designed within the unconventional practice of getting design inspiration and later synthesis from nature. It is curated toward satisfying humans with the possibility of seclusion and privacy in a workspace without degrading the environment while using contemporary production techniques.

Biomimetics

The term "biomimetics" is borrowed from the Greek words "bios" and "mimesis," which can be understood as "life" and "imitate," respectively (Hwang et al., 2015). Otto Schmitt introduced it in 1982 (Vincent et al., 2006). Later Janine Benyus popularized it in the context of Design for Sustainability (Delmotte, 2007).

Looking at history, it is hard to pinpoint when humankind started to look deeply into nature for solutions to address design problems. Nevertheless, multiple well-known examples exist of using biomimicry through the ages (Aziz & El Sherif, 2016). One of the first was Leonardo Da Vinci, who studied birds and their flying methods to construct flying machines (Jakab, 2013). Another example can be an architect- Filippo Brunelleschi, who, by looking at the eggshells, got inspired to create a famous dome for Florence Cathedral (Remy, 2021). However, only during the mid-20th century, it becomes a widespread practice between designers and architects to transfer the concepts found in nature to the engineering world (Niebaum, 2017).

Biomimetics is a 'meeting' and 'merging' form of biology, technology, and other innovative sectors to create an end solution (Dahy et al., 2022). It focuses on finding, learning, and grasping nature principles to apply them in current technologies and improving them as an end goal. Therefore, it is not an imitation of nature but rather an understanding of nature and its principles for future implementation and improvement of human lives (Amer, 2019) Figure 4.

In recent times, the deterioration of the environment due to climatic changes has been experienced globally, resulting from years of human interference with the natural environment through the excellent extraction of fossil fuels. It has led to a call for more sustainable approaches to modern living conditions. Hence, the adoption of multiple systems to sustainability for improved climatic conditions. Many of these approaches and ideas point to one fact; nature has been the ground of sustainability, thus being the best designer. One such idea is the concept of biomimicry, also known as biomimetics. The following chapters will present more of the biomimetics methodology (Bright & Brisibe, 2021).

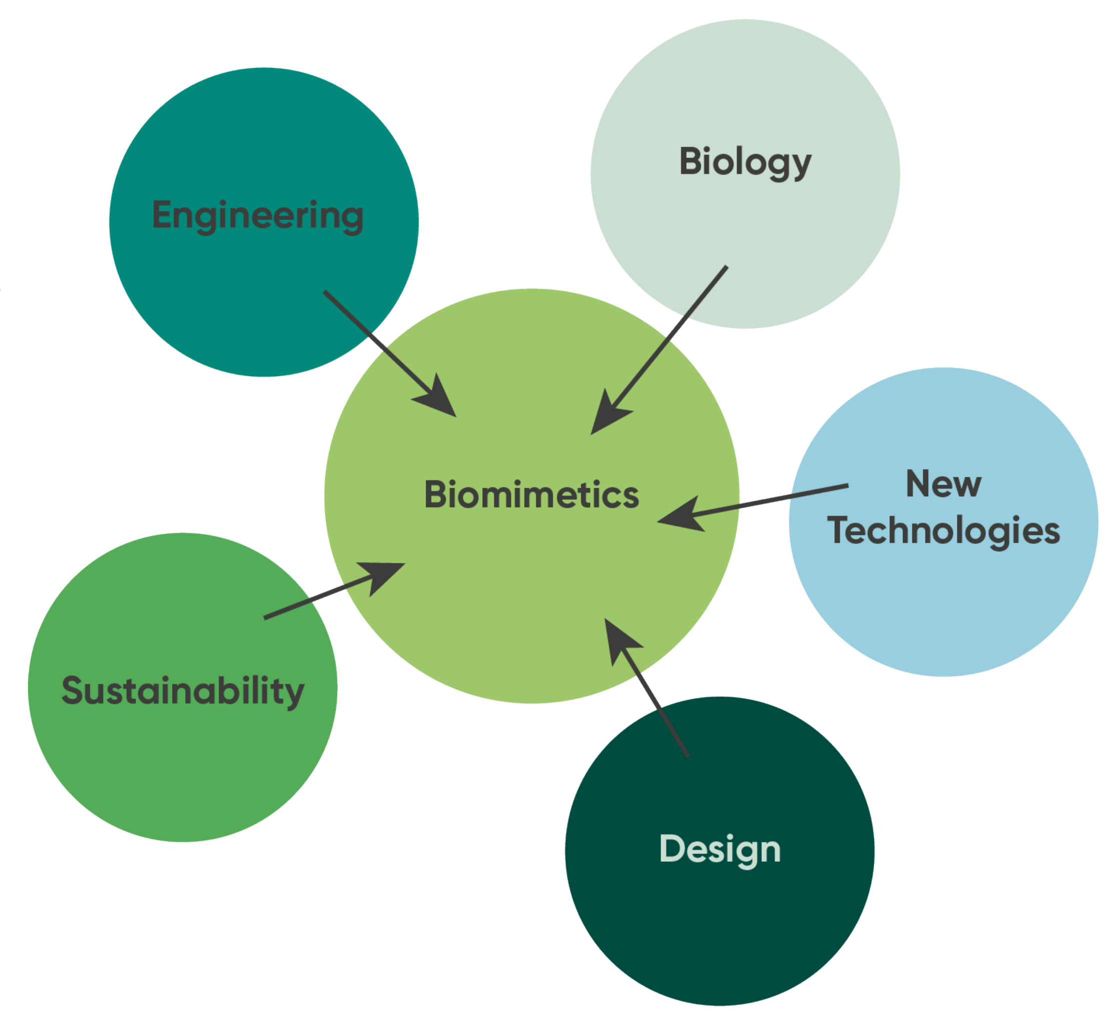


Figure 4: Representetaion of Biomimicry

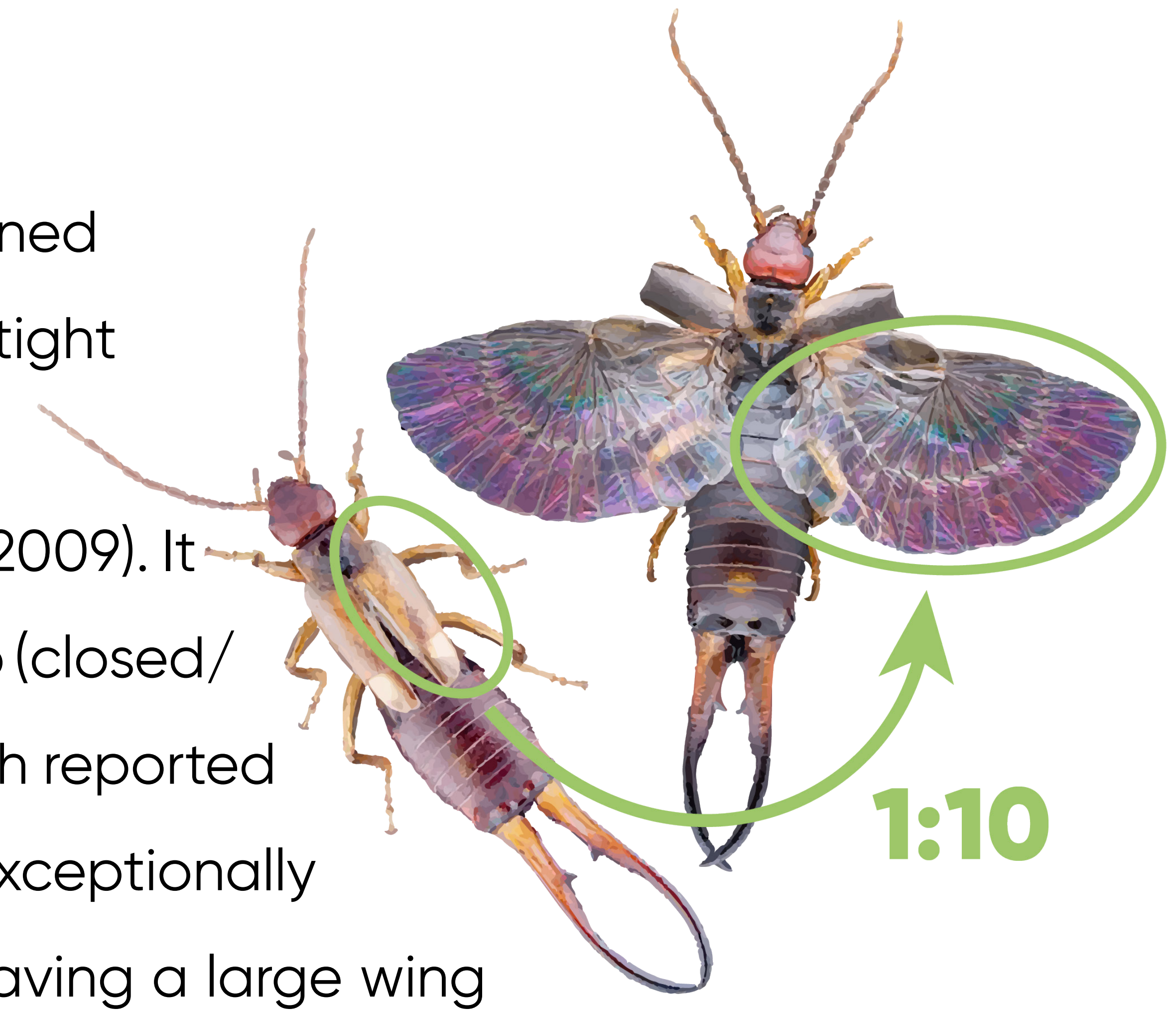
Earwig and Its principle

This section is focused on the insect Earwig and its wing principle used in the design of the partitioner.

Insects are one of the most diverse and successful animals in colonizing Earth, with over one million known species worldwide. One of the most critical factors in their success is their ability to fly, which allows them to escape predators, find food, and colonize new habitats. However, it also presented several challenges, such as developing solid and lightweight materials to support flight. The evolution of wings in insects is fascinating, and scientists have been studying it for decades (Saito et al., 2020). Wings emerged in insects around 320 million years ago. The first wings were likely simple flaps of skin that allowed insects to glide short distances. Over time, these flaps became more complex, and insects developed the ability to flap their wings and generate lift (Prokop et al., 2005).

The earwig is a member of the order Dermaptera, which means "skin wings." (Britannica, 2023). Unlike most insects, which have four wings, earwigs have two sets of wings - a pair of forewings, or elytra, which are complex and protective, and a pair of hindwings made from a sort of membrane and used for flying. The hindwings are folded elaborately towards a compact and streamlined shape ideal for passing through tight spaces and maneuvering around multiple obstacles (Rankin & Palmer, 2009). It is a tiny insect with a wing folding ratio (closed/open), one of the world's biggest, with reported values of 1:10 (Haas et al., 2000). This exceptionally high folding ratio is responsible for having a large wing area during the flight and a small, packaged form when not in use and entering its underground habitat (Doroftei & Doroftei, 2014). Figure 5

Figure 5: Folding ratio of Earwig



The earwig wings are folded in a specific pattern with curved creases and specific angles that are not sufficiently described with current origami models. Its wings are folded neatly beneath the elytra in a configuration that resembles the letter "Z.". Additionally, the wings' evolution made them self-folding without using any muscles. All of this is thanks to the resilin pre-trained joints, which are arranged asymmetrically and are pre-programmed (Faber et al., 2018). Resilin is an elastic

Figure 6: Earwig wing

biopolymer that storages the energy in the wings and lets them fold/unfold when needed (Haas et al., 2000). The last principle is the possibility of locking the wings to resist the aerodynamic forces during flight (Faber et al., 2018) Figure 6.

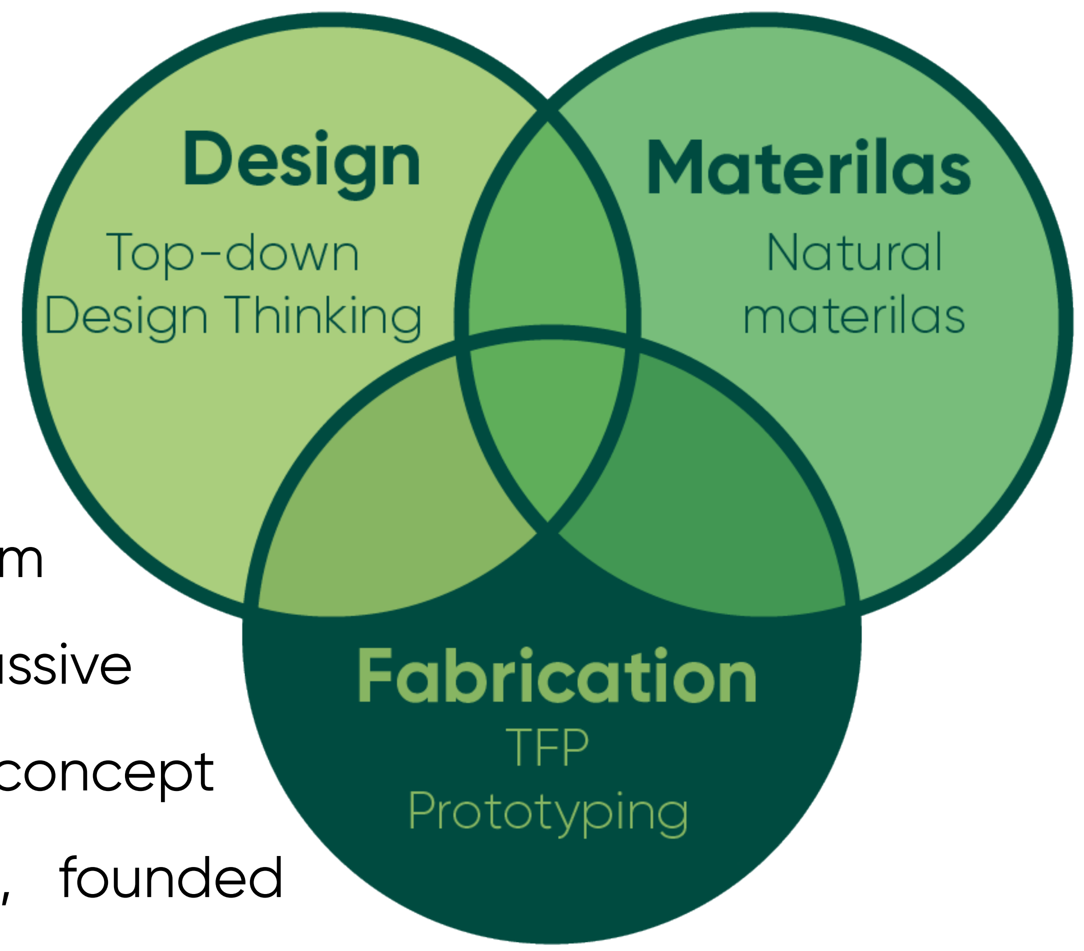
To unfurl its wings and start a flight, the earwig must go through multiple steps of complex movements. First, it uses its legs to lift the elytra layer and expose the hindwings. Then, it flexes and rotates its wings, using its forelegs to push the hindwings out of their folded "Z" position. As the wings unfurl, the earwig pumps resin into the veins of its wings, which causes them to expand and become rigid. Once its branches are fully opened, the earwig takes off with great speed and agility (Haas et al., 2000).

Methodology

This section will present the methodology used to elaborate and ensure a multidisciplinary approach is consistent throughout the project when trying to answer the research question. Merging concepts like three pillars of sustainability with assessing it by LCA, combined with design thinking, biomimicry top-down frameworks, and fabrication of Tailored Fiber Placement (TFP) for prototyping, led to creating the final product that is based on the Materials as a Design Tool philosophy practice.

Materials as a Design Tool

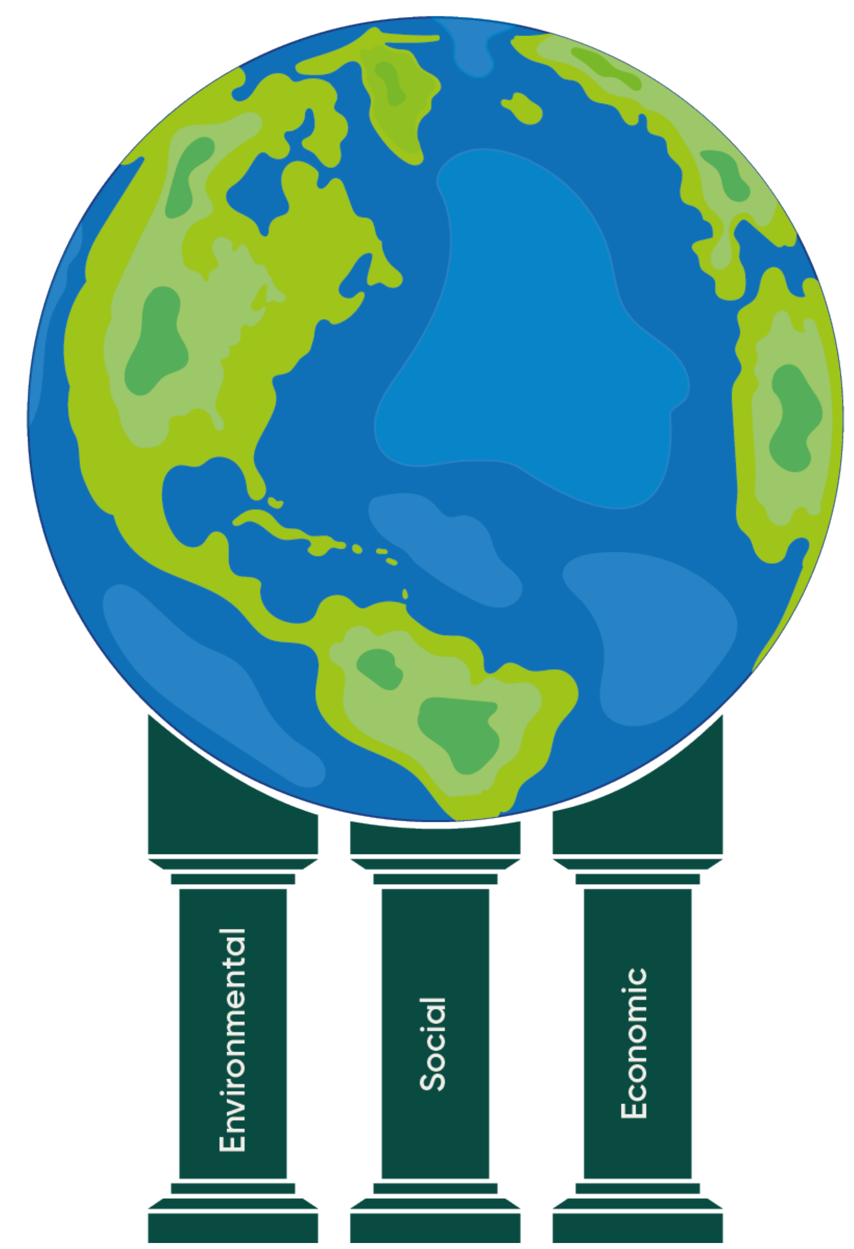
Figure 7: Materilas as a design tool graph



Materials as a design tool is a multidisciplinary philosophy that recognizes the intrinsic value and transformative potential of materials in the creative process and views them as active participants rather than passive elements. It is proved to be a working concept and explored by BioMat Institute, founded by Prof. Dr.-Ing. M. Sc. Eng. Arch. Hanaa Dahy. It represents a paradigm shift in design thinking, emphasizing a holistic approach that combines design, fabrication, and materials seamlessly which can be visualized in the graph below -Figure7 (Dahy, 2019). Due to its multidisciplinarity and holistic approach toward design, it was chosen to be the main backbone of the whole structure of this project. By focusing on sustainability and its three pillars a design framework of biomimetic top-down and design thinking were combined. The materials for this project were chosen to be natural textiles and fibers that are ethically produced. A fabrication method of TFP was chosen because of its innovative approach to design and sustainability. Combining the design, fabrication, and materials created this framework for the master project. This iterative practice allows for a deeper understanding of how materials can shape and inform the design outcome, resulting in a more cohesive and harmonious process where the material becomes an active participant and collaborator in the design journey.

Three Pillars of Sustainability

This concept was decided to be implemented in the project because of its very holistic approach toward sustainability from several angles. It will now be briefly presented the methodological framework behind it, giving a better overview of this method.



The modern concept of sustainability globally did not emerge until the late '20s of 20th century (Meadows et al., 1960). That is why the ideas of sustainability, assessing it, and creating the theories are pretty new. One of them is a three-pillar of a sustainability implementation concept. This framework was first proposed by (Brundtland, 1987) in the United Nations in the late 1980s and has since become a widely accepted way of thinking about sustainability. It was chosen for this project because it is a multidisciplinary implementation and solution-oriented approach built on economic, social, and environmental sustainability. That helps tackle sustainability from multiple angles of three pillars to achieve the best result.

The environmental sustainability pillar involves the management of the environment with things like biodiversity, productivity, and resilience over time. It consists in preserving the natural resources that support life on Earth. It also involves reducing the negative impact of human activities on the environment, such as pollution, deforestation, and climate change. This sustainability can be achieved using renewable energy sources such as wind, solar, and hydropower electricity, which do not contribute to Co2 emissions. Another aspect is using sustainable materials such as the ones used in this project (jute, cotton, paper pulp|) Additionally, recycling and waste reduction can help reduce the amount of trash in landfills, reducing the environmental impact of human activities (Brundtland, 1987)

.

The social pillar focuses on social aspects related to sustainability by promoting peace or better quality of work – that this master thesis focuses mostly about. Unfortunately, this is the least understood and defined pillar of sustainability compared to the other two. However, social factors strongly influence human behavior, which is why it is uncompromisingly linked to sustainability's economic and ecological dimensions. Social sustainability can be achieved in many ways. One way is through the universal healthcare and education systems that ensure equal access to these basic human needs. Another way is through social equality, inclusion, and better quality of work, which reduces social tensions and promotes social cohesion (Brundtland, 1987).

The last pillar is the economic one. It is essential for business existence, strategy, and profitability. Unfortunately, the limited resources on the planet are often not considered here, creating a problem when trying to achieve long-term economic sustainability. Growth cannot be achieved

by depleting natural resources. Still, it can be through developing a diverse and resilient economy that adapts to changing economic conditions or promotes sustainable consumption (Brundtland, 1987).

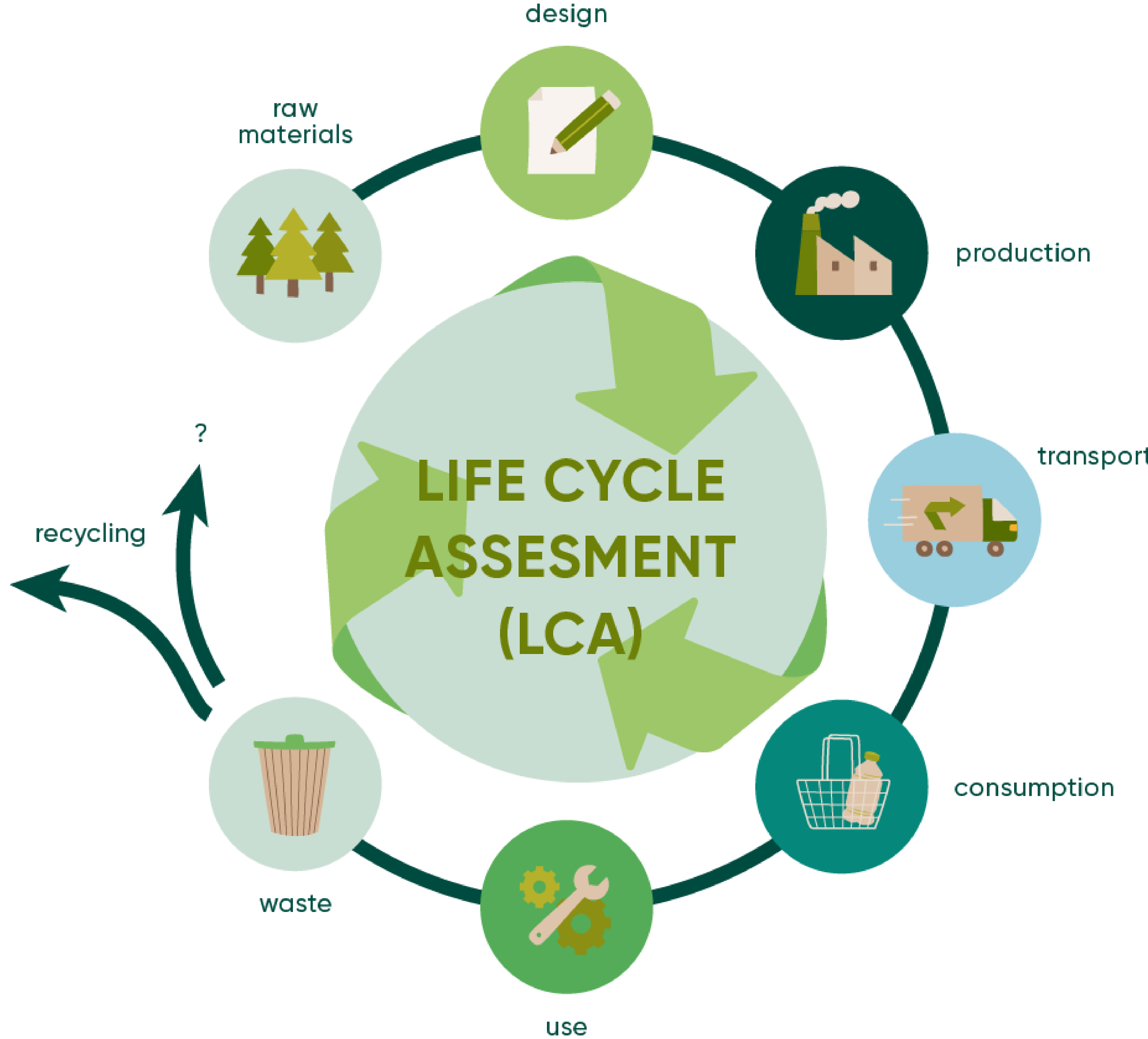
Those three pillars work independently, but each of them needs to be fulfilled in this project in order to contribute towards sustainability and sustainable development.

LCA

Looking at the three pillars of sustainability presented above, a Life Cycle Assessment (LCA) method was chosen as a great way of assessing this master's product sustainability impact and contribution toward sustainable development. Here the theoretical part of it will be presented for a better overview and understanding of this complex method.

LCA is a relatively recent method of evaluating the environmental impact of a product, process, or service throughout its entire life cycle. It is a systematic and comprehensive approach that examines the inputs, outputs, and impacts on all stages of the product's life cycle, from raw material extraction to the final disposal. LCA is an essential tool for decision-makers, policymakers, and companies to understand and assess the environmental impact of their products and services (Muralikrishna & Manickam, 2017). The methodology has been standardized by international organizations such as the International Organization for Standardization (ISO), and it is used in multiple sectors, including energy, agriculture, construction, and transportation. It consists of four main phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (Muralikrishna & Manickam, 2017) Figure 8.

Figure 8: Representation of LCA



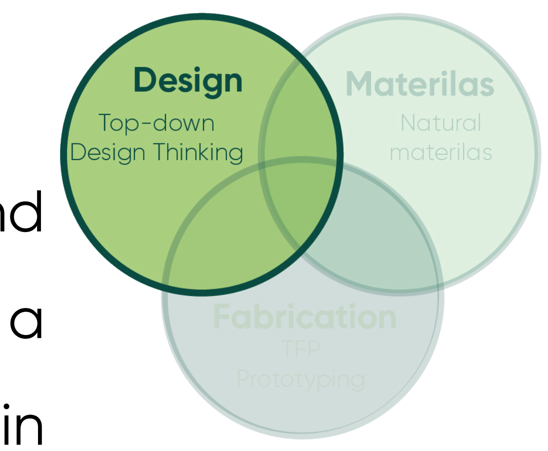
In the goal and scope definition stage, the focus is on defining and determining the scope of the analysis, including the system boundaries, functional unit, and data quality requirements. The available team is the branch of measurement for the product or service being assessed, and it should be carefully chosen to reflect the intended use of the product or service.

In the next stage, the inputs and outputs of the product or service are quantified, and data on the energy and material flow emissions and waste through the whole life of that product is collected. That data is then used to construct an LCI, which provides a comprehensive picture of the environmental impacts of the product or service.

In the impact assessment stage, the LCI is translated into environmental impacts, such as climate change, human toxicity, acidification, and global warming. This is done using environmental impact categories and characterization factors, which are used to calculate the potential environmental impact of the product or service in each category. The results are presented in the form of an impact assessment report.
The most important is the interpretation stage. It involves analyzing and making recommendations for improving the environmental performance of the product or process. This may include identifying opportunities for reducing environmental impacts, optimizing the use of resources, or enhancing end-of-life management options. The results can also be presented to the stakeholders at this stage for critical review. Here the results lead to a conclusion whether the ambitions of the goal and scope can be met.

LCA is a methodology that enables the evaluation of the environmental impact of a product or service throughout its entire life cycle. It provides a systematic and objective approach that can inform decision-making processes related to sustainability and environmental management and has become a widely accepted tool in various sectors. In this project, it is become a very useful tool to assess the sustainability burden and the contribution towards the three pillars of sustainability.

Top-down Biomimicry approach



After presenting the overview of the origin and history of biomimetics, here it will be discussed as a method of designing and its fundamental principles in detail. Following the backbone structure of the whole project that is of Materials as a Design Tool led to using biomimicry for the design part. Having already a design problem researched and later defined, lead on choosing this theoretical framework for biomimetic research and further project development (Aziz & El Sherif, 2016).

The top-down (Design to biology) approach in biomimetics involves a designer's study of a natural phenomenon or animal and then attempting to replicate or mimic it in a synthesized system (Speck et al., 2017). It starts by already having a defined design problem for example lack of privacy and distractions occurring in the office and looking for its solution. This approach is often used in cases where the function and purpose of a natural system are already known to a creator. The challenge is developing a synthetic plan to perform the same functional properties. The structure of this approach can be visualized in an arrow pointing down with steps to follow in Figure 9. From the Design problem, searching for biological analogies, identifying appropriate principles, abstracting from the physical model, and testing to the final design solution (Verbrugghe et al., 2023).

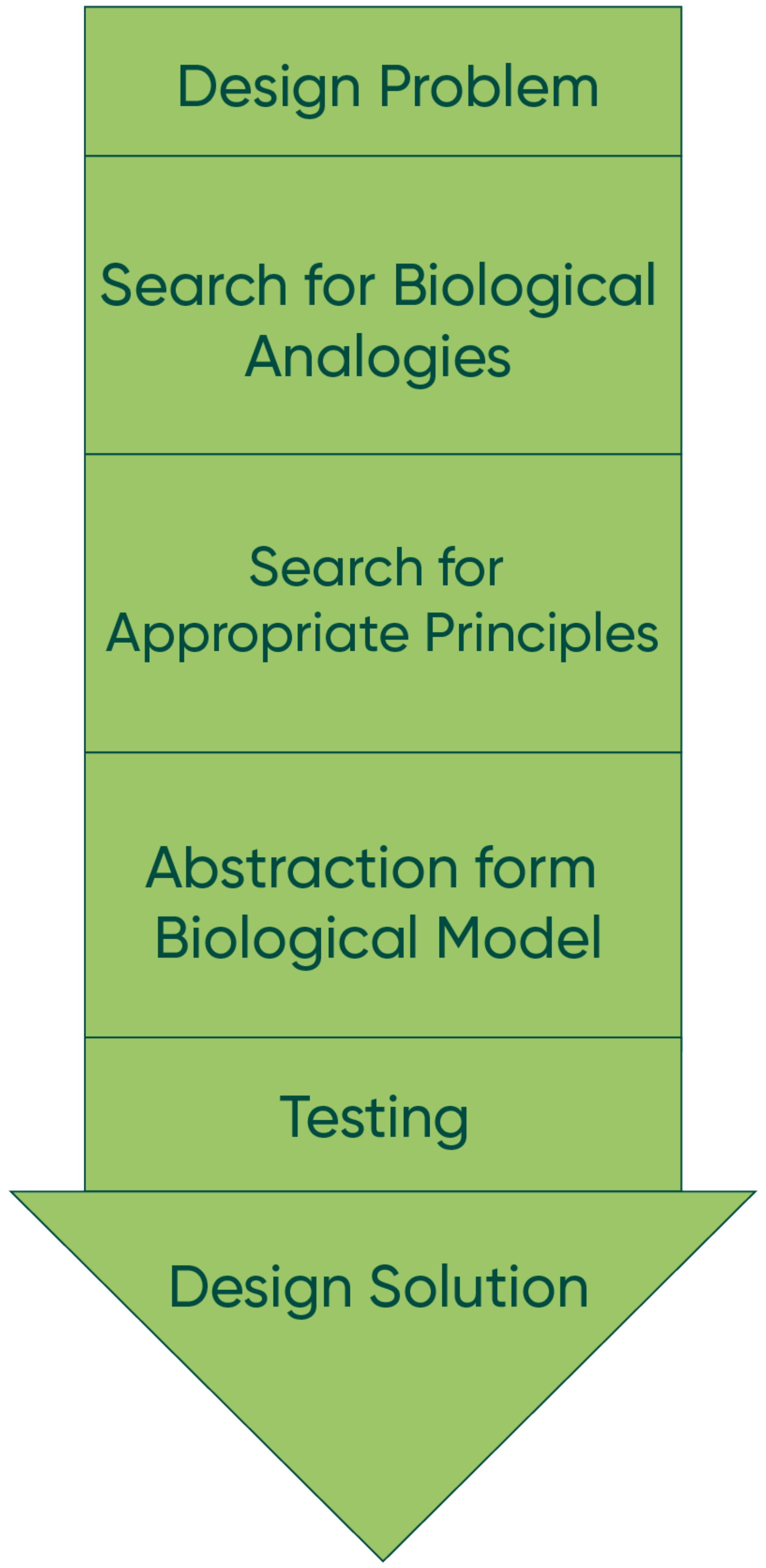
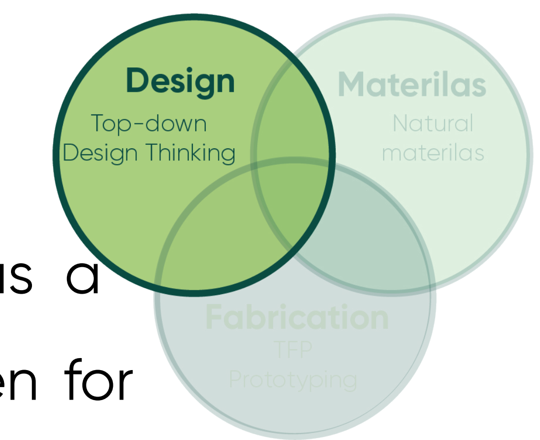


Figure 9: Representation Biomimicry Top-down approach

One of the key advantages of design looking at the biology approach is that it can lead to rapid progress development of new technologies and designs. Starting with a well-understood natural system, researchers can focus on replicating specific features or properties of that system rather than starting from scratch. This can save time and resources and help identify key challenges and areas for improvement. However, the top-down approach also has some limitations. One challenge is that natural systems are often highly complex, and it can be difficult to identify which features or properties are essential for achieving a particular function. Additionally, biological systems are usually optimized for specific environmental conditions, and replicating their role in a synthetic system may require significant modifications to account for different environmental factors (López Forniés & Muro, 2012).

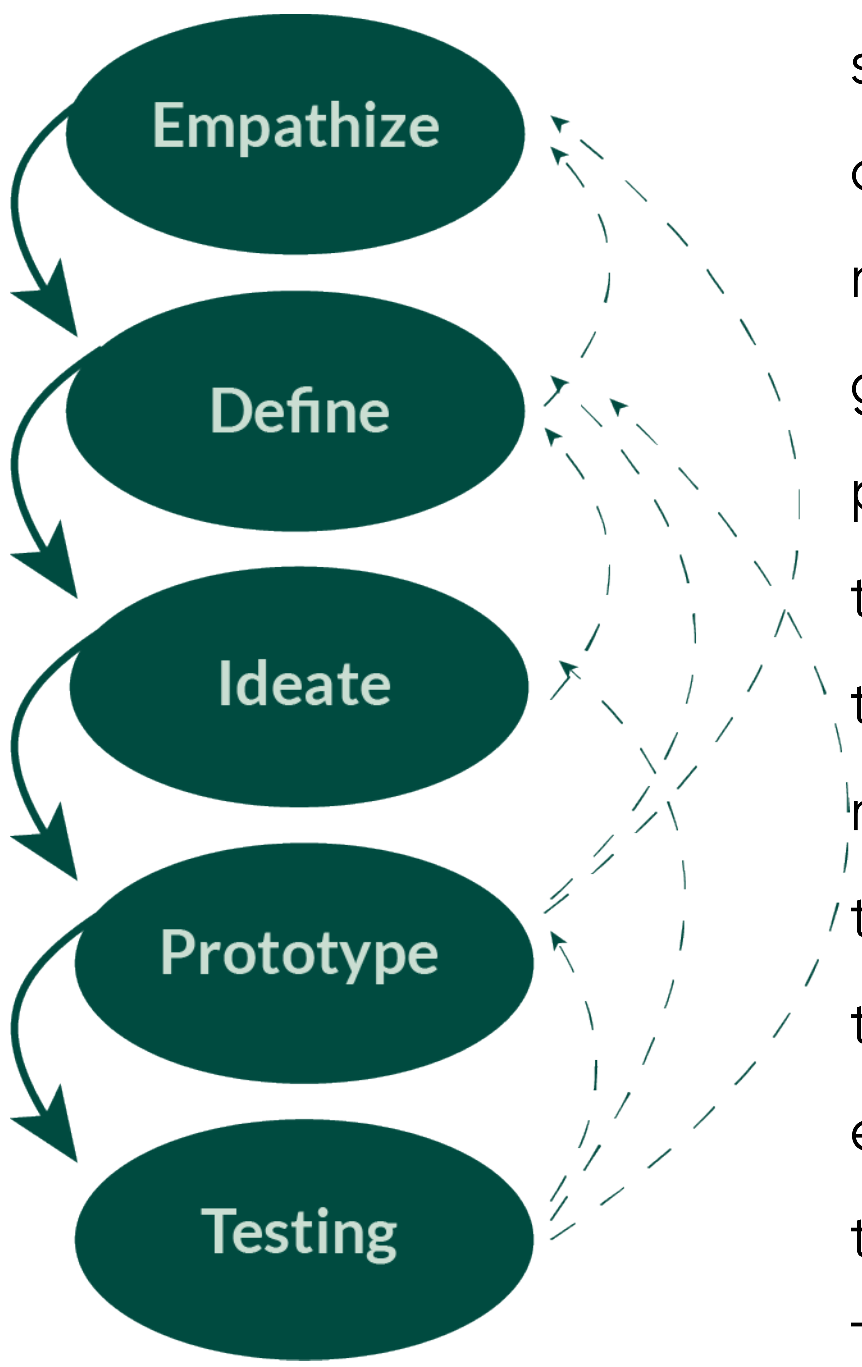
In summary, the top-down approach is essential in biomimetics. It enables replicating specific functions or properties seen by designers in natural systems. In this case, an earwing insect folding pattern. Those approaches help to gain a deeper understanding of natural systems and knowledge to create new products, designs, and technologies.



Design thinking

Another design method used in the Materilas as a Design tool concept is Design thinking. It was chosen for this project due to its creative and iterative approach to problem-

Figure 10: Representation of Design Thinking

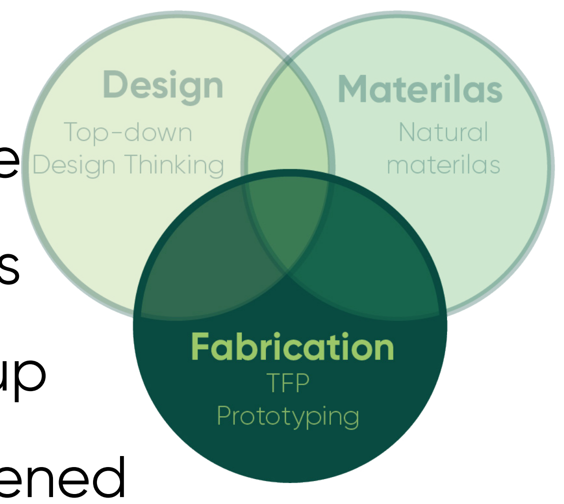


solving. It is focused on human-centered design and involves understanding the needs and motivations of users while generating a wide range of ideas and later prototyping and testing potential solutions to see how they work in practice. Design thinking is an iterative process, which means that the practice is repeated many times until a solution is found and meets the user's needs Figure 10. Designers are encouraged to continually test and refine their ideas and learn from their mistakes. The core principles of design thinking include empathy, ideation, prototyping, and testing. Each stage plays an essential role in the design thinking process, which helps designers create solutions that are effective and user-centered (Carlgren et al., 2016).

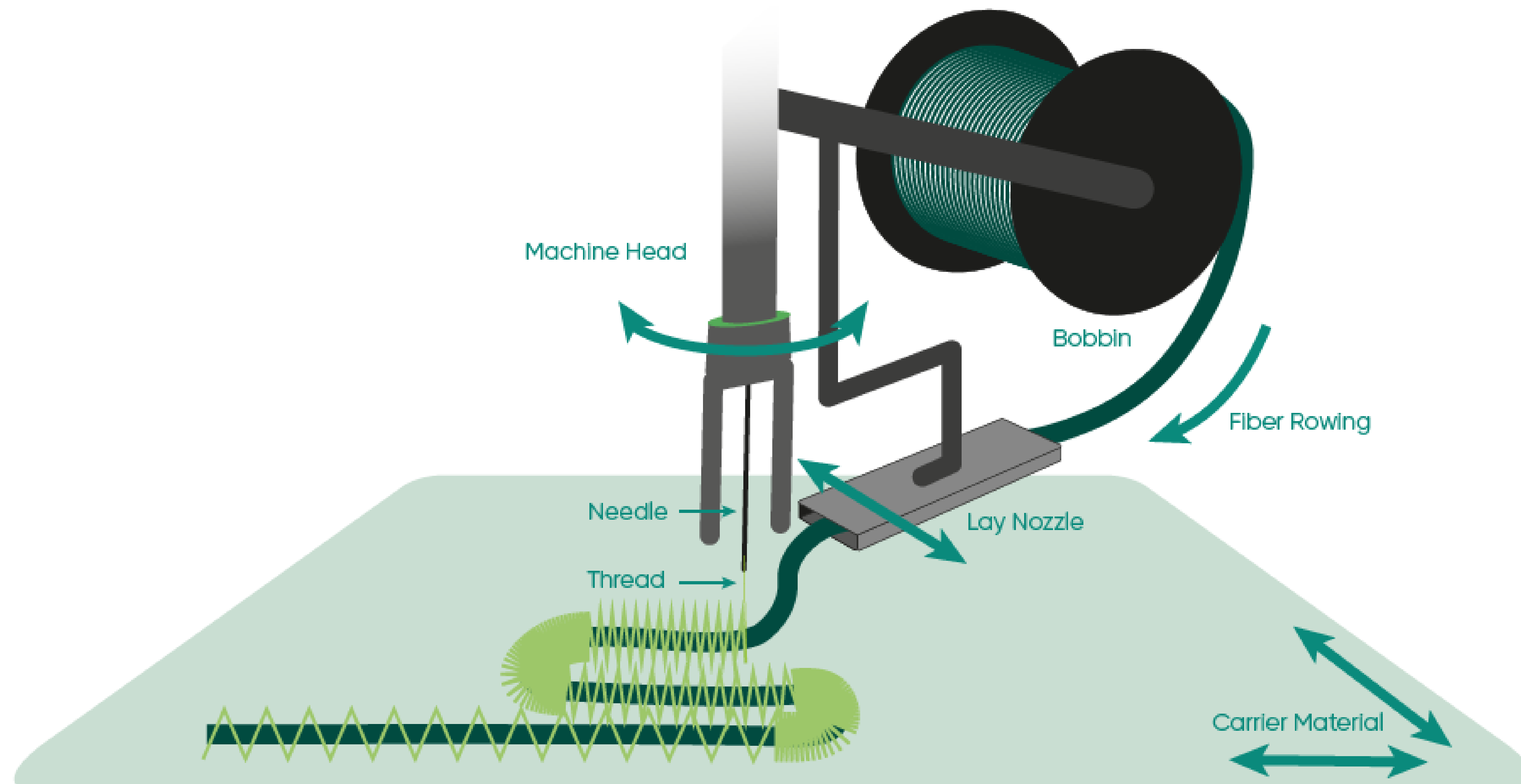
- The first stage of design thinking is empathy. This involves understanding the user's needs, motivations, and pain points through observation, research, or interviews. This helps to develop a deep understanding of the user's perspective to create effective solutions.
- The second stage focuses on defining the problem to be solved based on the insights gathered in the first stage of the process. The problem is being narrowed by analyzing the information collected and synthesizing the data to create a problem statement. It must be specific, actionable, and relevant to the user's needs, essential for creating a successful solution.
- The third stage is ideation. It involves generating various ideas and concepts that understand the needs and goals identified in the first empathy stage. Designers may use brainstorming, stakeholder mapping, or other creative techniques to generate ideas and concepts. This stage focused on creativity and exploration without being limited by practical constraints or assumptions.
- Once plenty of ideas have been generated, the next stage is prototyping. This involves creating a physical or digital representation of the proposed solution. Prototyping aims to test different ideas quickly and usually cheaply and see how they work in practice. Prototyping can involve anything from low-fidelity simple sketches or paper models to a realistic high-fidelity 3D model (Walker et al., 2002). Both prototyping methods have been presented sincerely in the chapter below.
- The final step in the design thinking process is testing. It involves collecting feedback from users and stakeholders on the prototype while using that feedback to redefine and improve the final solution. Testing is an iterative process, with multiple rounds of testing and refinement required for an effective solution.

In summary, design thinking is a human-centered, iterative, collaborative problem-solving approach. By putting the needs and goals of the user at the center of the design, authors can create truly effective and innovative solutions. Design thinking is a flexible and adaptable approach that can be applied to a wide range of fields to create better products, services, and experiences for their users and that is why it was chosen as a second framework for the project (Carlgren et al., 2016).

TFP (Tailored Fiber Placement)



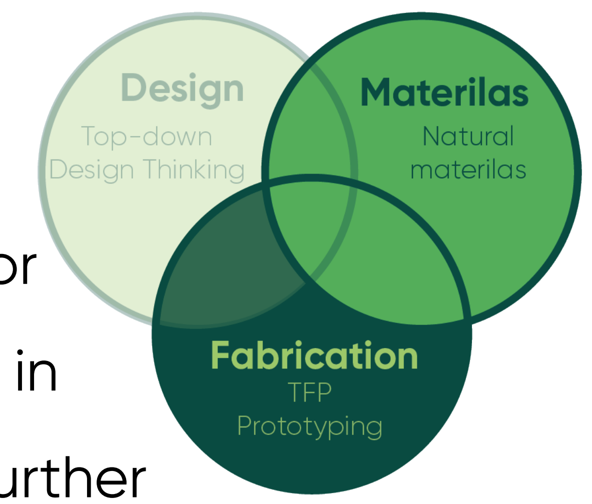
Embroidery is a well-known, conventional technique for decorating or waving on textiles. Embroidery is found in almost every culture, and its roots growing up in ancient civilizations. Mass production scale happened within the industrial revolution and technology (Selm et al.,2 0 0 1). Due to constantly innovating and more research through the years, the embroidery technique has made new functional applications thanks to the unique ability to create 3D and lightweight structures on the fabrics (Spickenheuer et al., 2018). Due to those inventions, embroidery is now widely used in various industries, particularly in the aerospace and automotive sectors, where composite parts for aircraft, such as wings, fuselage sections, and engine components, are produced (Carosella et al., 2020). TFP fabrication allows for producing complex, high-performance, substantial, and lightweight parts (Marsh, 2011). Although widely used in those industries, this technique has yet to be explored in the product design sector, making it a young method and approach toward design (Baszyński et al., 2020). All those presented benefits make the choice of this additive manufacturing method are very beneficial for the biomimicry-inspired partitioner. This technique will be further explored in the synthesis chapter, where it will implement as a design practice for the prototype and future final product.



The additive manufacturing technology of TFP was invented at the Leibniz-Institut for Polymerforschung at Dresden (Uhlig et al., 2016). It offers high-quality performance at the manufacturing level (Spickenheuer et al., 2018). It is an advanced manufacturing technique that involves laying down individual fibers in a precise and controlled manner to create high-performance structures. This method ensures the orientation of the thread on the ground fabric or material in multiple directions. It lets create three-dimensional designs allowing other forms or shapes to be completed. One of the critical advantages of TFP is its ability to produce parts with minimal material waste and produce complex shapes and structures with a high degree of accuracy. The precise placement of fibers enables the production of components with optimized fiber orientation and thickness, reducing the need for excess material. This can lead to significant cost savings and a more sustainable manufacturing process (Tailored Fiber Placement - LayStitchTM Automated Fiber Placement Machines, n.d.) Those presented benefits contribute towards the three pillars of the sustainability concept, making the technique desired for manufacturing and sustainability in this project.

Moreover, pattern creation with different CAD software ensures rapid prototyping and development of the final product. The CAD software is used to design the path, and the TFP machine then follows the design to place the fibers in the correct orientation and order. CAD software in TFP enables the creation of complex geometries and intricate patterns, producing highly customized parts tailored to specific requirements (Mecnika et al., 2015).

In conclusion, TFP is a manufacturing process that offers many advantages in producing multiple materials, including complex shapes, with high accuracy while considering environmental benefits. Furthermore, it is a technique that has yet to be fully established in the product design sector and will be given a further approach to design in this paper.



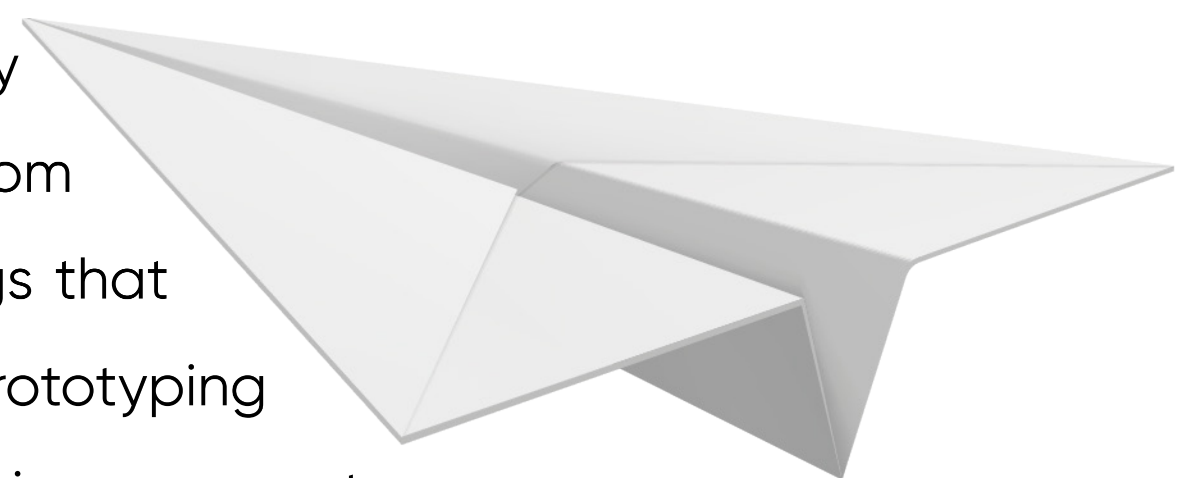
Prototyping

The prototyping fabrication was chosen for the design of the partitioner because it is crucial in developing an object and later validating it for further alterations. It is a crucial step in the top-down approach and design thinking framework. It is an experimental process where ideas are turned into tangible objects. Those which are done in low fidelity are about to capture and test the design concept in order to validate the picture. Design Prototyping is one of the phases of design thinking and usually comes after the ideation phase (Elverum et al., 2016). Prototyping serves the purpose of creating a physical or digital representation of possible solutions that have been discussed and defined during the initial stages of designing, rather than committing to a single solution and going through the whole design process, prototypes enable designers to test and verify their concepts by presenting an early iteration of the solution to actual users and obtaining quick feedback (Ramírez, 2018).

The advantage of prototyping is helping designers understand their idea and present them as boundary objects (Trompette & Vinck, 2009) at stakeholder meetings to lower the risks and costs associated with the upscale models. It also allows the stakeholders to give feedback on the model and their opinions. Another advantage is seeing the flaws and adapting to the changes early in the process.

Prototyping can be done in two ways of fidelity:

Low fidelity is often paper-based and usually needs to focus on user interaction. They vary from hand-drawn objects to prints and small things that can be done quickly and cost little money. This prototyping type helps visualize the design solution and its improvement ideas. It is better than just having sketches because the user can better understand the product and its properties (Rudd et al., 1996).

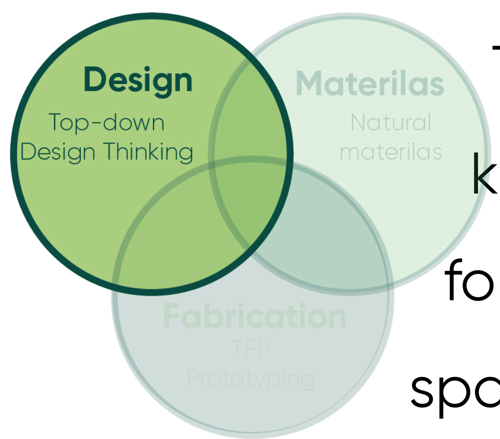


High-fidelity allows user interactions while designed to be as close to the original idea as possible. Those types of prototypes are done to collect more human performance data, demonstrate the actual process to the stakeholders, and identify minor issues in the workflow (Rudd et al., 1996).

Synthesis

This section will present the results from the used earlier-mentioned methodology. Different analyses have revealed and explained multiple aspects surrounding the partitioner. The multidisciplinary characteristics include exploring the biomimicry segment, prototyping, design methods, three pillars of sustainability, and the environmental burden associated with the product. The combined results will create the foundation of knowledge and define the future design potential.

Biomimetics Top-down approach



The idea for the partitioner as a solution started with knowing about the current office problem: the need for more adjustable privacy in the open office concept space. This led to choosing the top-down approach as one of the structures to follow when designing a solution for the problem. The advance towards this process is showcased in Figure 11.

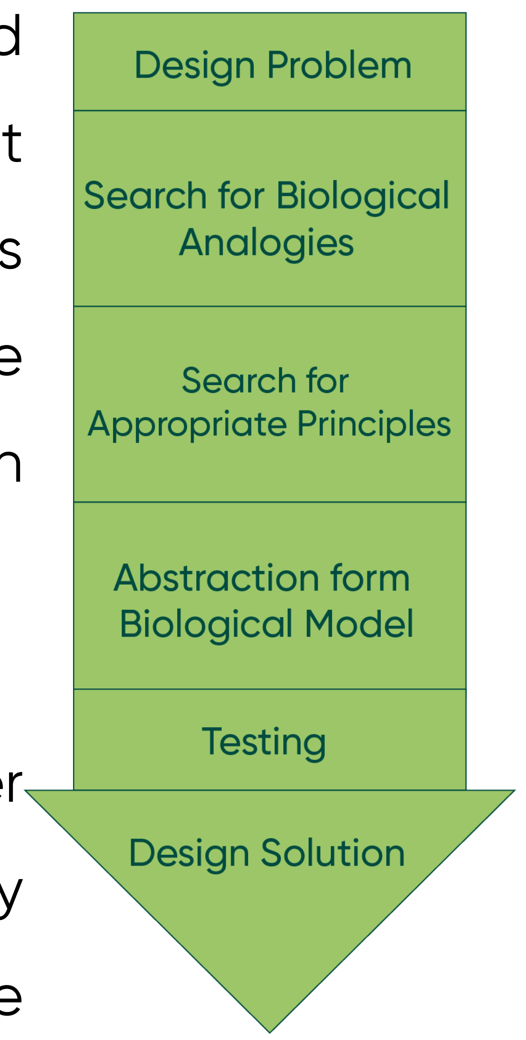
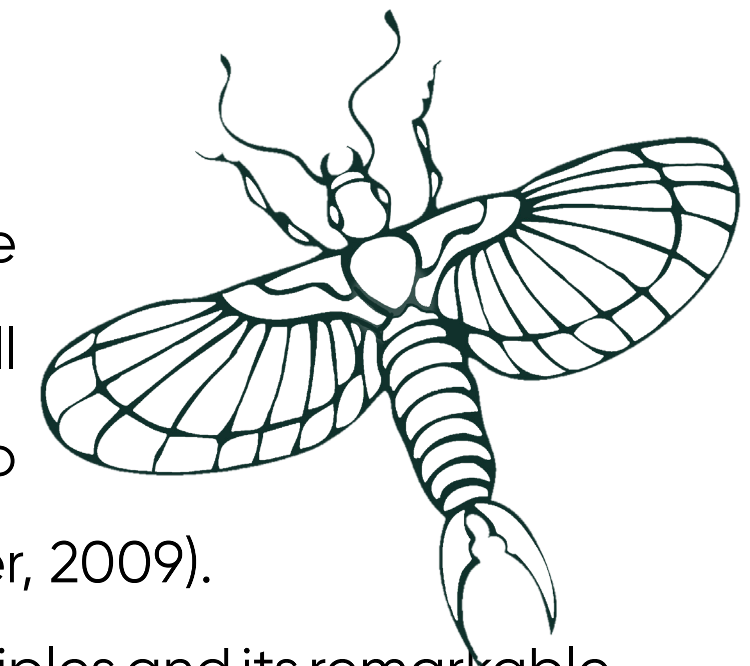


Figure 9: Representation Biomimicry Top-down approach

Following the top-down approach, the next step after having already defined the problem was to look for currently existing solutions in the biological analogies of foldable patterns in nature. Here multiple organisms have been researched and discovered on their overall foldability proficiency, from beetles and wasps to the earwing (order Dermaptera) (Rankin & Palmer, 2009).

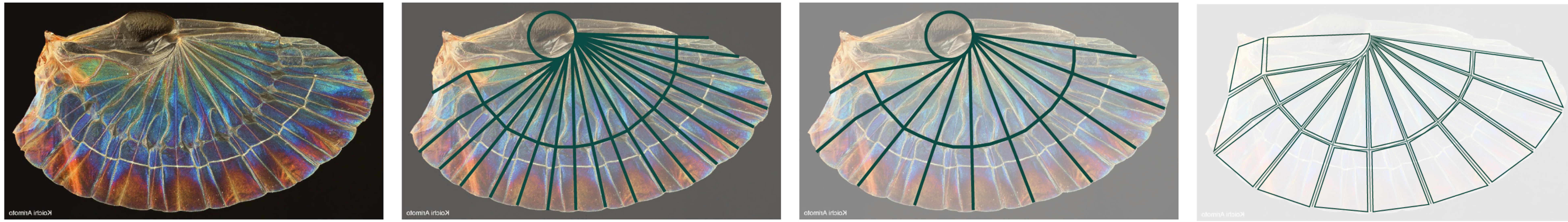


This led to identifying the earwig insect's principles and its remarkable capability of folding the wing in a 1:10 ratio, one of the biggestin the world (Haas et al., 2000). These properties are best for the inspiration of the partitioner design due to having a sizeable deployable wing area during the flight and compacted form when not in use (Doroftei & Doroftei, 2014). This space divider lets employees decide when to be divided/separated from other coworkers for focusing purposes.

The next step is an abstraction from the biological model towards the manufacturing and design capabilities. In this step, the wing of an Earwig was analyzed and later simplified. The illustration below presents the process and focuses on finding and understanding the principles of the foldability pattern in the wing lines and later simplifying that model in Figure 12.

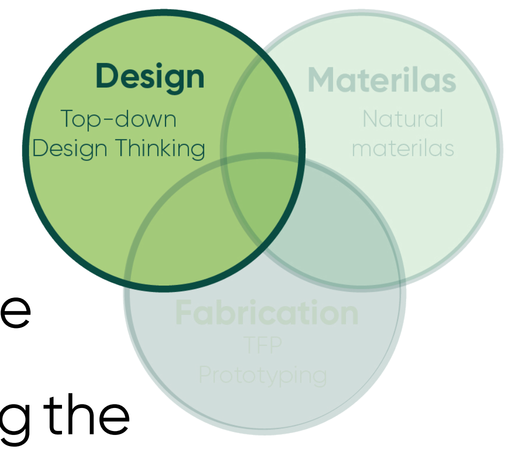
After that came testing the compliant mechanism (Larry et al., 2031). A low-fidelity model was made out of paper to test the principle and decide if the direction in the way of thinking is correct and should be further developed in the design and prototyping phase with different materials (Prototyping | Usability.Gov, n.d.).

Figure 12: Simplified process from earwig wing to the technical model



The last stage in the Top-down approach is a final design solution. This will be presented and more deeply discussed in a concept development chapter.

Design Thinking



While following the Top-down approach mentioned above, the project was based additionally on an iterative and non-linear design thinking process, especially during the prototyping phase (Carlgren et al., 2016). The iterative process is presented in Figure 13.

The empathy stage started with truly understanding the problems occurring in the open office concept. It was conducted through research on a literature review of employees' work behavior and the Importance of privacy in a workspace. It aimed at understanding the user's perspective and, for further assurance, meeting the needs of the employees.

The next stage focused on defining the main problem after the empathy phase while looking back at it and all the other findings. The literature review helped determine the topic for creating a solution: the need for more desired privacy in open office workstations, where the employees spend a significant portion of their work time concentrating on individual tasks. The lack of privacy causes multiple distractions for the employees through work time, not letting them focus on their duties to fulfill. It must be remembered that complete separation from people is not a solution. Employees value the possibility of connecting with other people as well. Privacy is not always based only on withdrawal from the connections with people but on self-controlling the amount and the intensity

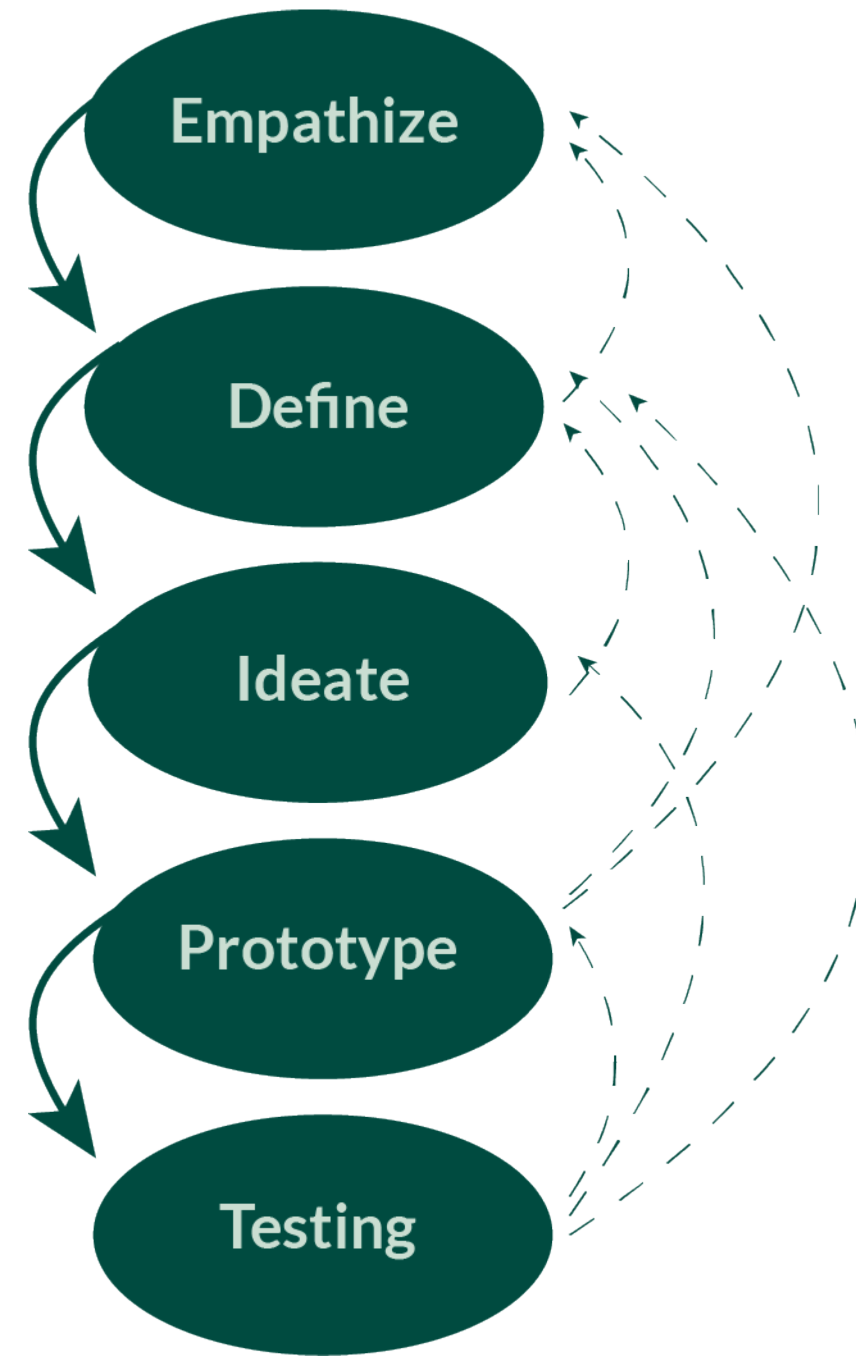


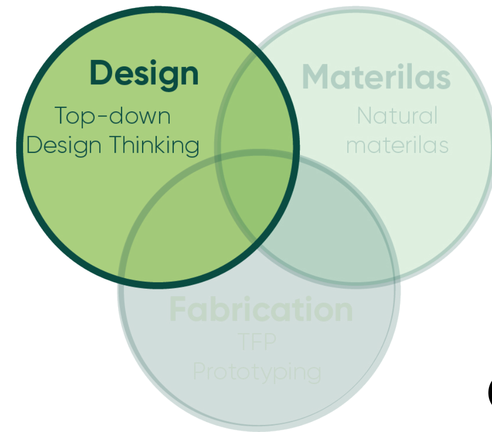
Figure 13: Representation of Design Thinking

of human relations and interactions(Pedersen, 1999).

This possibility needs to be improved in current designs, which creates a niche for a new product design of a retractable partitioner that lets the workers decide if they want to be separated at the exact moment in work time. All this happens in the ideation stage of design thinking. Looking back and understanding the needs and goals identified in the empathy stage, the concept of a retractable partitioner appeared after brainstorming and using other creative techniques. This section also focuses on exploration and creativity, borrowed from the biomimicry and top-down approach to design.

After deciding on using the simplified wing abstraction of an Earwig, the prototyping phase came. Different tools and techniques were required to produce prototypes of the final product. Looking back at all stages of the design thinking method, multiple changes were applied to the original prototype. More of the prototyping and the technique of TFP used will be discussed in further parts of the report.

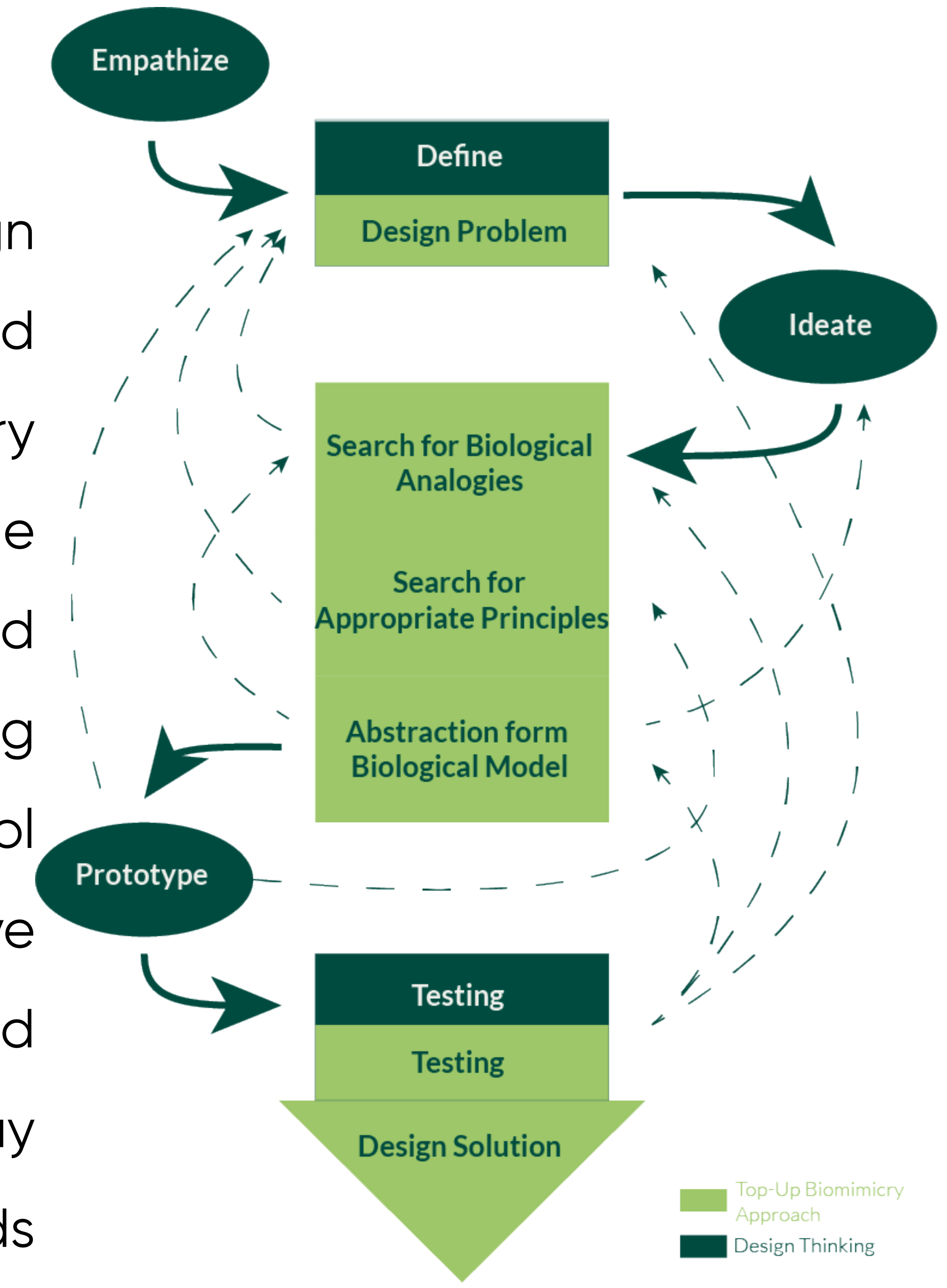
Due to the decision being made of not including the stakeholders and users in the design process a testing step was not conducted in this process.



Design Process

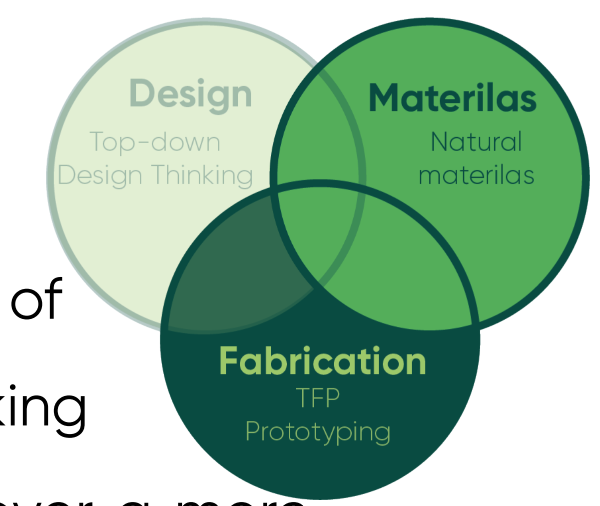
Combining those two design techniques of biomimetics top-down and design thinking gives a multidisciplinary approach to better understanding the design process used in this paper and helps design a better outcome. Using both methods in Materilas as a design tool concept provided more steps to follow, gave room for iterations, and in that case, helped create a more defined and structured way of designing from empathizing towards the final design solution. Both methods are intertwined in several steps, forming a cohesive design process, and filling up alternately gaps that the other method could have. The representation of this design process can be seen in Figure 14.

Figure 14: Representation of Design Thinking and Top-down approach



Prototyping

The prototyping fabrication phase is a critical stage of Materials as a Design Tool , that incorporates design thinking and the Top-down approach. This one was sprawled over a more



extended period and focused on multiple prototypes, from low-fidelity to more complex high-fidelity ones. It encompassed the multidisciplinary approach toward design and prototype facilitation.

The process began with synthesizing an already chosen (while searching for biological analogies and later principles of the top-down biomimicry approach and ideate phase of design thinking) insect called an earwig. Here the simplifying of the wing towards line model happened. It focused on identifying the patterns and lines in the wing and translating it into a technical and geometric design. The process of simplifying the anatomy of the wing can be seen in figure 15 below. It was a crucial step in defining the partitioner's geometry and functionality while translating a biological model into a technical one.

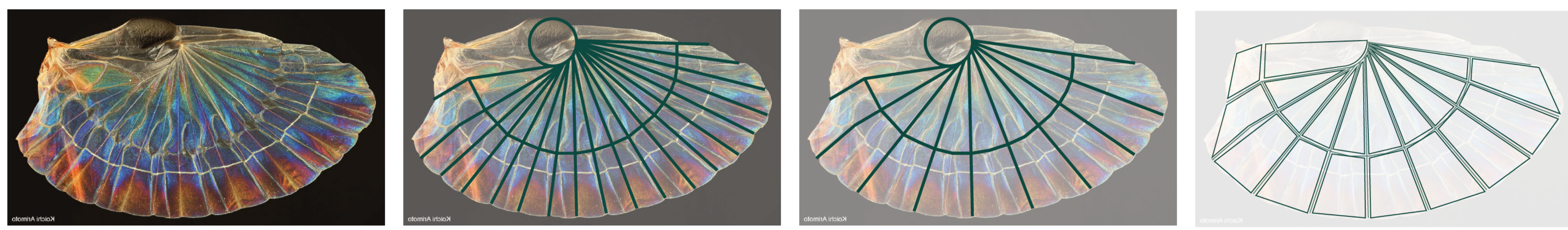
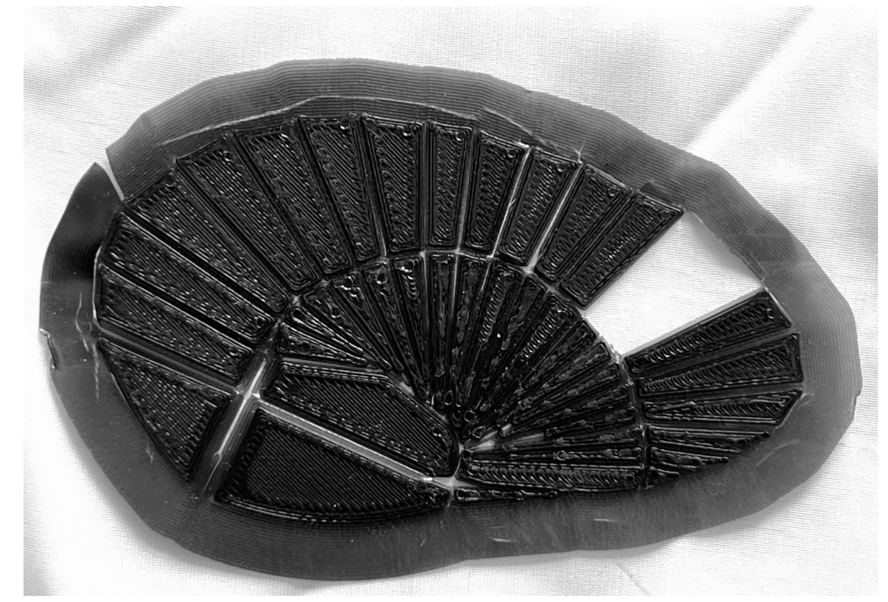


Figure 15 Simplified process from earwig wing to the technical model

Figure 16: prototyping model done in VR-Lab



After that phase, the prototype (figure 16) of low fidelity was designed. The previously synthesized wing design was translated into Adobe Illustrator software. The lines occurring in the wing created a pattern altered for prototyping. A method of additive manufacturing- 3D printing was selected because it allows for the quick and easy production of complex shapes with high accuracy and precision (Pedersen, 1999). Following the Design Thinking methodology (Carlgren et al., 2016), 3D printing enables iterative design changes to be made quickly and easily, allowing for rapid prototyping and the development of new products (Berman, 2012). The following prototype was created on a 3D Ultimaker printer using Autodesk Fusion360 software to create the 3D model first. Later, Ultimaker Cura was used to translate this design into the 3D printable mock-up. This prototype was completed using a filament of Polylactic Acid (PLA). The filament is recyclable and made from natural thermoplastic polyester derived from renewable resources such as corn starch or sugar cane. It is biodegradable under certain conditions with high heat capacity and mechanical strength (JuggerBot 3D, 2022).

3D structural lines and a simple hinge mechanism created Model- figure 17. Unfortunately, this method of printing small flexure joints revealed the limitation of 3D printing methodology and proved to be a different direction of moving forward.

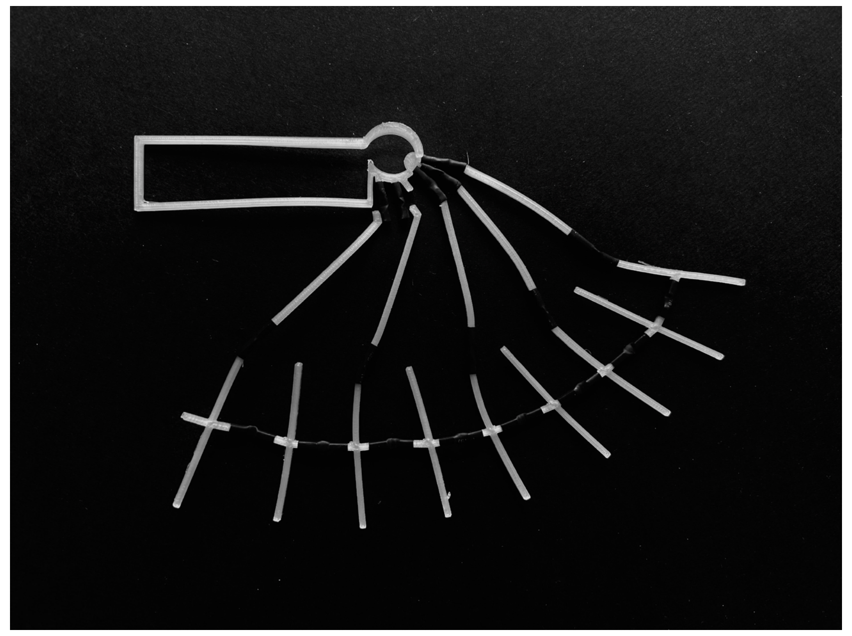


Figure 17: prototyping model done in VR-Lab

It pushed a new idea of creating a mock-up encompassed 3D-printed structural lines/sticks with shrink wrap between them used as a folding joint mechanism -figure 18. It proved to be a functional foldable design. Unfortunately, it also revealed some issues regarding the project: multiple lines stacked together created a very bulk product when folded, and lines/sticks were not easily folded in the correct directions.

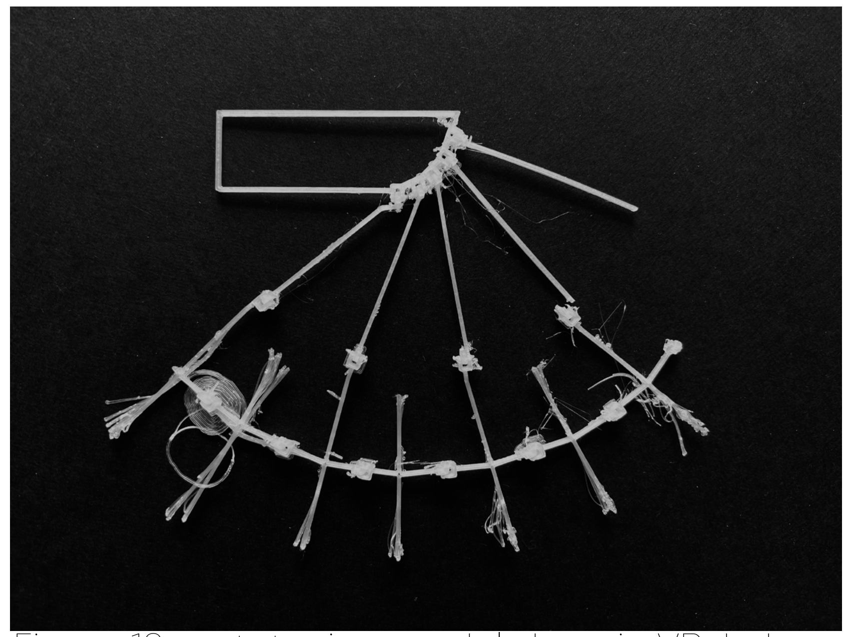


Figure 18 prototyping model done in VR-Lab

Following the design thinking methodology and looking back to the previous phase of it, a new idea emerged to create the foldable pattern using a compliant mechanism (Larry et al., 2031). The reasoning behind this is that this type of mechanism achieves its function through flexible or elastic materials rather than traditional rigid parts or hinges. In a compliant mechanism, the movement and force transmission is achieved through the deformation of the flexible material. This allows for the creation of mechanisms that are simpler, lighter, and have fewer parts prone to breaking compared to traditional, inflexible mechanisms (Larry et al., 2031)

After that phase first mock-up of low fidelity was designed in figure 19; the previously synthesized wing design was translated into Adobe Illustrator software and later printed on paper. The model was created to check the foldability possibilities and if the way of thinking is correct to be discovered further in the process.

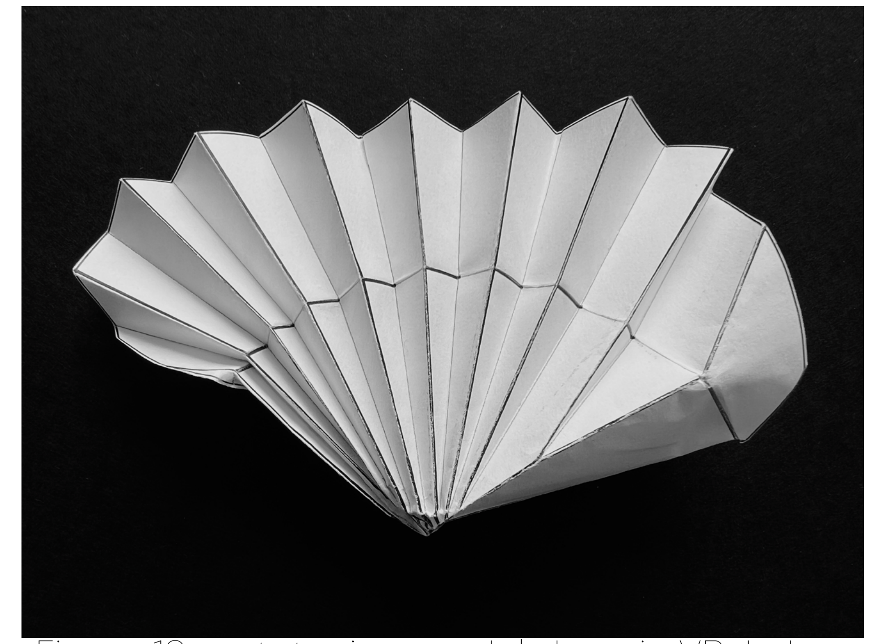


Figure 19 prototyping model done in VR-Lab

The second model presented in figure 20 was done to check the test model's size and if the print assumptions were correct. The time needed for the print was 20 minutes. The second model was created to check the compliant mechanism possibilities of the design. For this, a polyester fabric was stretched on

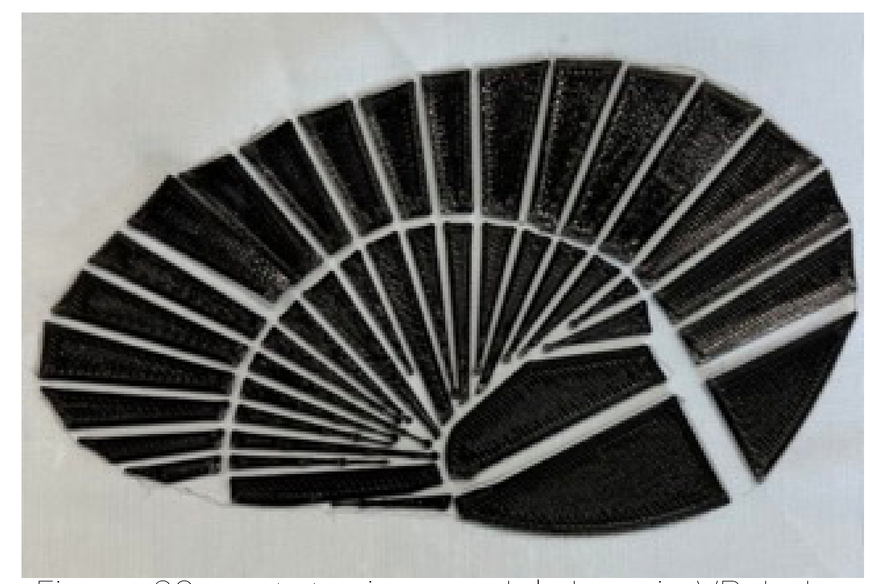


Figure 20: prototyping model done in VR-Lab

which the PLA filament was placed. Unfortunately, this method proved unstable after the print finished; most printed parts from the synthesized wing started to fall and detach themselves from the polyester fabric. This led to creating some iterations to the existing design and finding a solution for this problem.

Figure 21 shows that a third preliminary version emerged from this iterative process. It was based on the previous design, but the fabric was changed from woven polyester to tulle. Fine-knitted mesh fabric with hexagonal openings helped attach the printed parts to it. The first layers of the print were extruded typically, but after two layers, a tulle material was placed. Thanks to the hexagonal openings, further layers of printed PLA could attach themselves to the first two printed layers and accommodate the fabric in between. Unfortunately, this mock-up also was not fulfilling the expectations. Due to the tulle being ridged fabric and the print pieces laying too close to each other, the foldability aspect needed to be fully capable of happening.

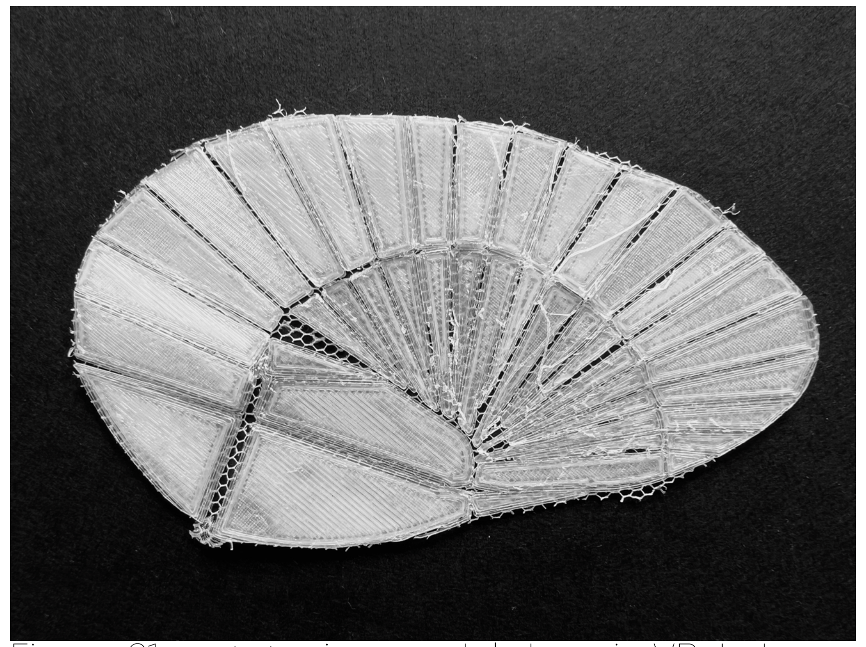


Figure 21 prototyping model done in VR-Lab

Looking back at the fourth stage of the top-down approach and a third of design thinking led to approaching the sampling from a different angle and focusing on using the TFP method. Thanks to this technique, a new tactic to the problem emerged focused on sewing the partitioner, not 3D printing it, while maintaining the compliant mechanism properties. Most of the textiles and fibers used at the beginning of this prototyping stage were made out of synthetic materials due to the low fidelity of those prototypes and financing restrictions.

This prototyping stage led to the creation of several models with various fiber placement designs. The first model seen in figure 22, was created on a thin vlieseline (interfacing textile) with polyester fiber placement only on the edge of the 'wing' sections without filling inside. This model was created to test the strength of the sewing and the foldability possibilities. It paved the way for future exploration of this method.

Figure 22 prototyping model done in VR-Lab

The second test model focused on placing only one layer of a polyester thread of the 'wing' sections onto a 100% polyester textile, as seen infigure 23. This version presented that one layer of thread with ample spacing between each row is not stiffened the fabric as intended. More layers with the possibly tighter placement of rows are needed to achieve the optimal rigidness of desired parts within, easily foldable other ones to create the compliant mechanism system.

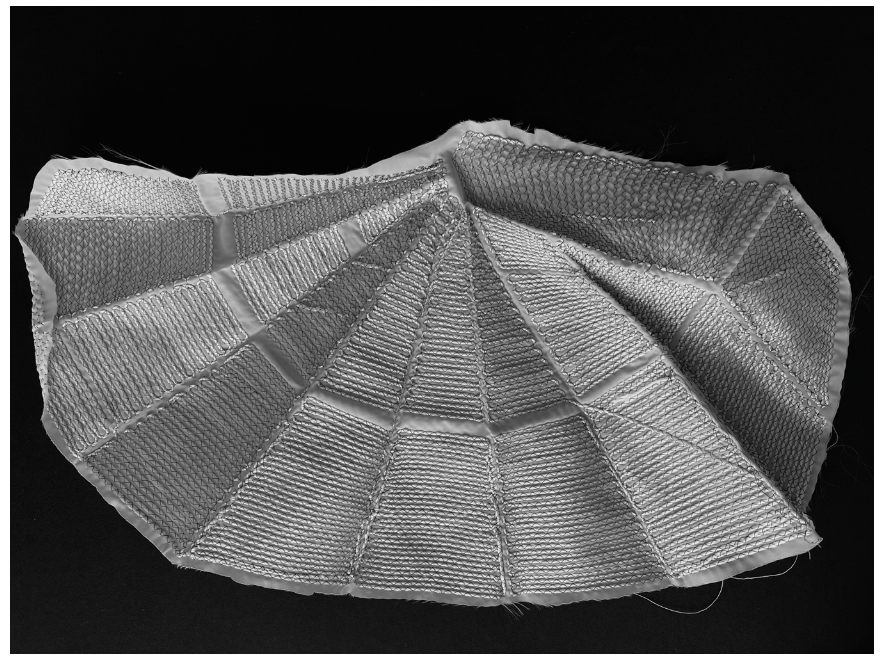


Figure 23 prototyping model done in VR-Lab

As seen in figure 24, the third sample using TFP was created on thick black 100% cotton fabric using polyester and jute twine. Here it was tested how two fiber layers intertwine themselves, providing stiffness, and how placing the rows closer to each other influences the overall fabric behavior. The much denser fabric was also used to check whether the TFP machine could sew on those textiles without any obstacles. This model clearly stated that adding more layers and thickening the number of rows is the correct path to success while sewing on denser fabric.

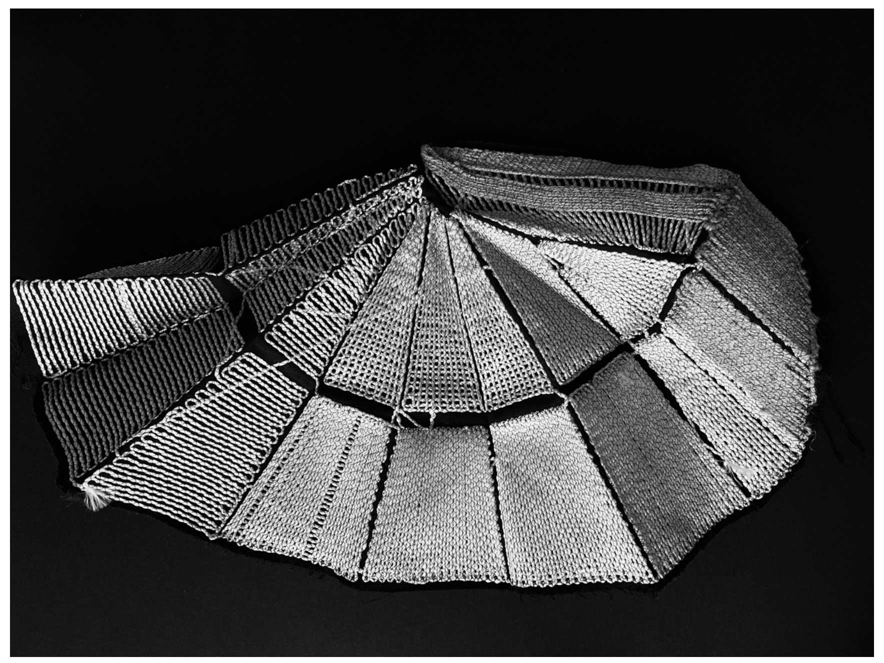


Figure 24 prototyping model done in VR-Lab

The last of the prototypes were done on a larger piece of fabric to include different methods, making it easy to visualize and test the textile-figure 25. Here sewing on washable paper trials happened, proofing that with current technical knowledge of the TFP machine, it is unfeasible to conduct fiber placement on this textile. The number of layers was also tested to achieve a stiff enough object. The fiber path layout was chosen based on the findings that fibers oriented at -45°, 0°, 90°, and 45° (figure 26), create a quasi-isotropic layup sequence, resulting in constant stiffness of the material despite the force direction, offering surface stiffness. The mock-up also presents how stiff the fabric will be after applying 1,2,3, and 4 layers of fiber placement, which is desired.


Figure 25 prototyping model done in VR-Lab

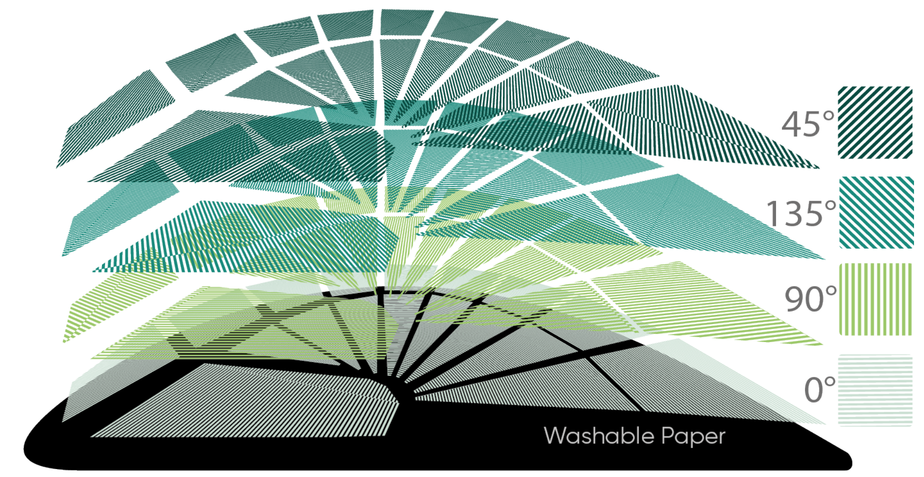
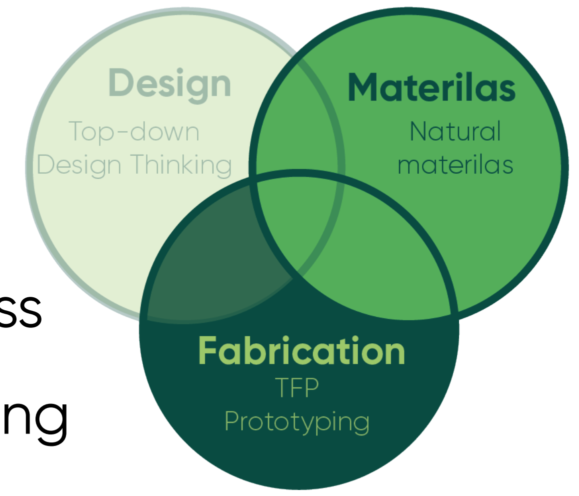


Figure 26 dour layers of -45°, 0°, 90°, and 45°

Each prototype played a crucial role in achieving the final concept prototype design by showing some malfunctions, places for improvement and giving the idea of how the overall structure should look and function. Prototyping is a crucial aspect of the design stage of design thinking and the Top-down approach. This iterative process of reviewing, looking back, and acknowledging the issues occurring throughout the prototype phase lead to the final design solution.



TFP

Tailored Fiber Placement (TFP) is a fabrication process that involves continuously laying filament material by laying a nozzle onto a thin, stretched carrier textile mounted on a 2D movable frame using an industrial-grade embroidery machine (Baszyński et al., 2020) figure 27. This machine allows an infinite set of customizable patterns on a 2D surface. This technique for prototyping and the final product was chosen due to its ability to construct complex and optimized fiber placements that maximize the performance-to-weight ratio while having a deficient level of manufacturing waste in the production process, which is a significant environmental benefit and also approaches the problem from the multidisciplinary perspective of not only focusing on one aspect of the production method but also the remunerations for the environment

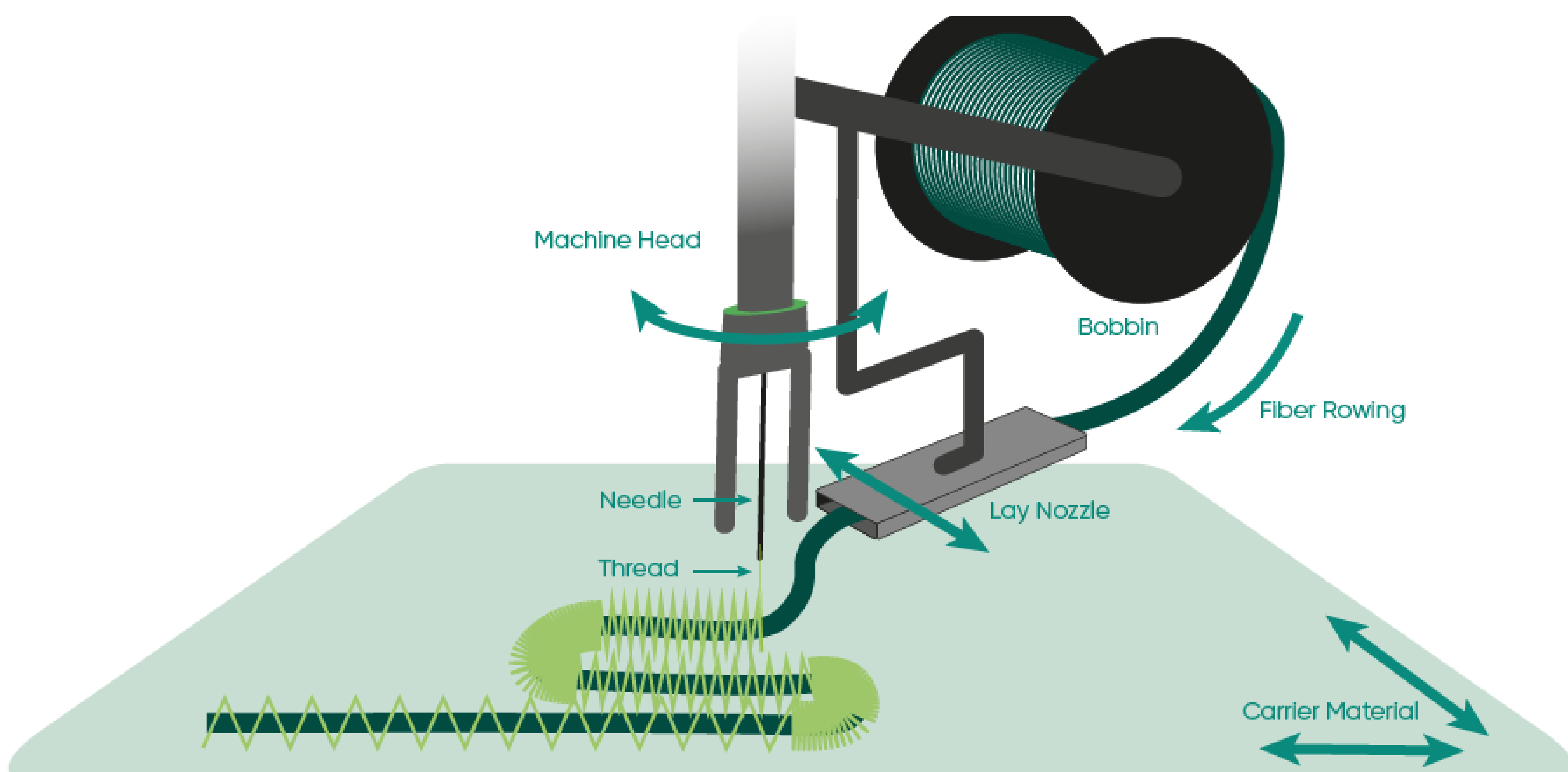


Figure 27: TFP machine components

(Digel Sticktech GmbH & Co, 2023).

At the first prototyping stage, a polyline file with four layers was generated using Adobe Illustrator and later transcribed into the CAD software of Rhinoceros (Appendix 1). At this moment, the fabrication parameters of the process were set in the EDOpass program, including the stitch length and width of the thread, amount of layers, or the number of stitches before the turning point (Appendix 2). Exact values for these parameters were adjusted multiple times during the prototyping stage and rearranged in the results section. Thanks to being structured as an iterative process, the ability to look back at each prototype helped choose the outcomes and decide the final parameters for the print. The automated frame grasping the textile was digitally programmed to follow an arranged polyline path.

The process used a Tajima Fiber Laying Machine TCWM-101 type 1-2A 1037 an industrial-grade embroidery machine that continuously laid filament material upon thin and stretched textiles fixed on a motorized frame (Herakovich, 2012). In those prototypes, dry, non-impregnated polyester and (later in the process) a jute fiber roving was laid using a single-head embroidery machine of the brand Tajima at Aalborg University VR-Lab in Copenhagen. Filament material was organized by being spun over a spool affixed to the head of the device. As fiber was laid down onto the textile, a sewing needle and bobbin held the fibers in place by a second threaded spool- figure 28.

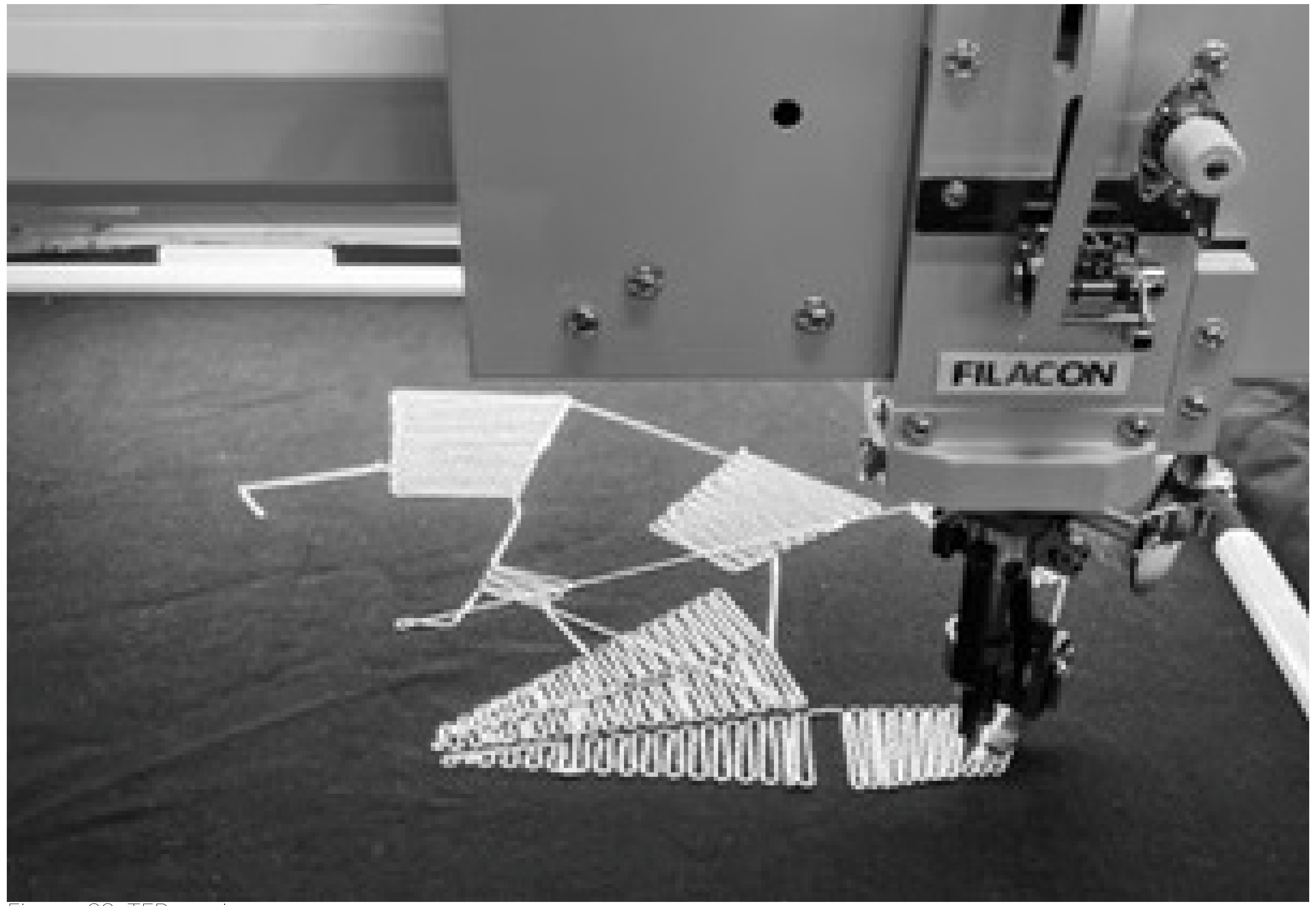


Figure 28: TFP sewing process

After completing several layers of placing the filament material, the machine was stopped, and tiny excess filament material was cut. This leads to using almost all the material needed without having almost any excess waste. The textile was set free from the grasping motorized frame. At this stage, the excess textile was cut to achieve the product's final look.

Using the TFP machine for the partitioner prototype has demonstrated a promising multidisciplinary approach toward sustainability and efficiency in production and prototyping. By leveraging the benefits of automation, precision, and high levels of customization, this advanced manufacturing has the potential to reduce waste and increase material optimization significantly. Moreover, this approach allows for greater flexibility and an iterative approach to multiple factors in the design stage, creating more functional, environmentally friendly products with supporting design thinking methodology. As such, using TFP machines is a valuable step toward achieving a multidisciplinary process of sustainable and efficient production.

Three Pillars of Sustainability

The three pillars of the sustainability framework by (Brundtland, 1987) were chosen for this project due to its holistic approach toward sustainability and not focusing only on one aspect of it. The partitioner design and idea behind it is to fulfill all three categories of that implementation concept.

First, an environmental category in this design is trying to be fulfilled by focusing on preserving resource consumption using the TFP method and its ability to use only the exact amount of material needed for each part without any waste or leftover materials. This is achieved through precise

programming and controlling the fiber placement machine, which can be optimized to match each part's geometry and shape. By minimizing waste, TFP reduces the number of raw materials used, lowers energy consumption, and minimizes the environmental impact of production, transportation, and future disposal. TFP contributes to the environmental pillar of this framework by reducing waste and promoting the efficient use of resources, which helps to conserve natural resources and protect the environment for future generations (Carosella et al., 2020)

The social aspect of sustainability is about creating an equal and justice society, better quality of work environment – that meets the needs of all people while respecting cultural diversity and promoting social cohesion (Rinalducci, 2022). A foldable partitioner is a product that can help fulfill the social pillar of sustainability by providing a flexible and adaptable solution to create better working conditions for employees. This can help improve employee satisfaction and productivity, reduce stress, and improve mental health. Moreover, the partitioner can provide a sense of control and autonomy to the employee, as they can decide when they want to be separated and create their workspace, which is an essential aspect as stated in the Importance of privacy in a Workspace part and by Pedersen (1999) that the privacy is not the full withdraw, that is important mostly, but the ability to control the intensity of all interactions. In addition, by creating separate spaces for different teams or individuals, the partitioner can help to create a more diverse and inclusive workplace where employees feel valued and respected.

The last is the economic pillar of the framework. Here the TFP enables the production of parts with minimal material waste. This reduces the cost of materials and improves the overall efficiency of the manufacturing process. Additionally, it increases the productivity of the manufacturing, by producing complex parts in a single operation, reducing the number of manufacturing steps required and thereby reducing the overall production time and cost, contributing towards the economy and sustainability. Moreover, giving the possibility of privacy to the employees is predicted to boost their productivity. This means a more productive employee would contribute to the company's success, and the overall cost of acquiring the partitioner would surpass the cost of an inefficient employee in the long run (Kim & de Dear, 2013). Additionally, being a foldable product and collapsed at its primary stage, it requires much less space for transportation when packaged. This means this product's transportation cost is also lowered, contributing to the economic pillar of sustainability. Using only the exact amount of materials needed for production, without producing any waste by-product, is not only environmentally sustainable (discussed above) but also fulfills the economic aspect of the three pillars of sustainability by not having to buy more raw material than needed and contributing to the long-term financial viability of a business or industry for creating a more sustainable future (Miguel Mendes Carvalho Monteiro Cravidão, 2021).

Life Cycle Assesment (LCA)

LCA has been carried out based on the product's cradle-to-grave life cycle to validate and provide an overview of the climate emissions of the baseline scenario for the partitioner. This LCA is conducted within three stages: raw material extraction, production, and end-of-life (EoL). It is prepared according to the principles and framework of ISO 14040:2006 (ISO 14040:2006 - Environmental Management — Life Cycle Assessment — Principles and Framework, 2006).

Goal and Scope

The first phase of creating an LCA was to define the goals and limitations of the study (ISO 14040:2006 - Environmental Management — Life Cycle Assessment — Principles and Framework, 2006). The primary purpose of this preliminary LCA was to focus on modeling the base scenario that would present a very estimated climate impact of the partitioner, measured in CO2e. Furthermore, the intention is also to identify phases and select those which have the highest climate impact for further development and space for improvement in the future. The function of the partitioner is to provide seclusion space for an employee when desired.

Functional Unit and Reference Flow

As a starting point for the rest of the study, a function unit and reference flow are determined in this section. All the mentioned above are presented in figure 29 below. The functional unit creates a reference unit for the data assessment and influences the data collection. In this study, the importance lies in providing 0.5m2 of screening for one person for an estimated 5 years of usage in Denmark. As a reference flow, it was chosen as one piece of the partitioner.

Function	Functional Unit	Reference Flow
Providing seclusion space for an employee when desired.	Providing $0.5m^2$ of screening for one person for an estimated 5 years of usage in Denmark	One piece of the partitioner

Figure 29: Functional unit and reference flow

System Boundaries

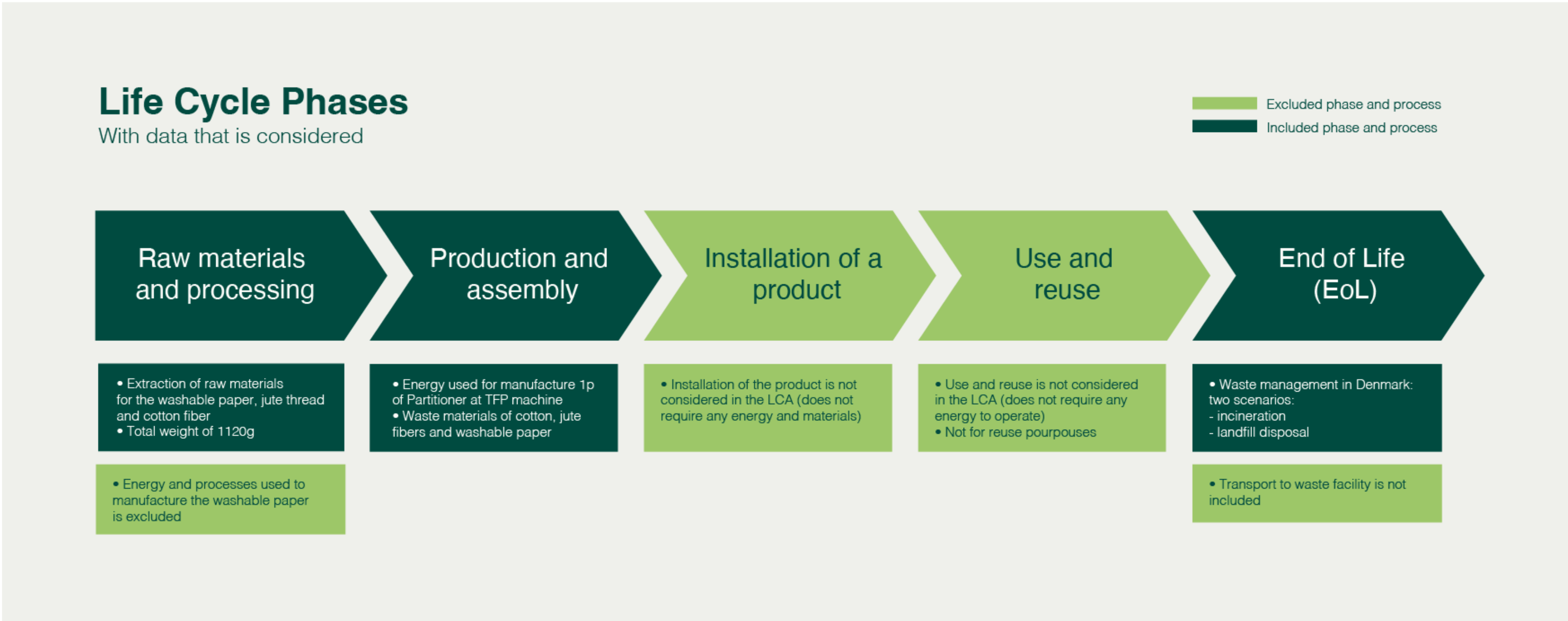


Figure 30: System boundaries

Figure 30, presents the cradle-to-grave approach, the following stages of of the life cycle were included in the modeling:

- Extraction of raw materials and their processes included the fabrication of paper pulp, polylactide granulation, softened water, cotton, and jute fibers.
- Production and assembly of the partitioner using the TFP sewing technique and the waste created during that process.
- End of Life scenarios. This stage includes emissions from the waste of the partitioner by consumers into two scenarios: landfill disposal and incineration.

Some stages of the life cycle have not been taken into consideration, as follows:

- Installation of the product has been excluded due to the low level of possible emissions regarding that stage. The product does not require any additional resources like electricity to be able to set up.
- Usage of the product has also been excluded from the same reasoning as the installation of the product phase. The product does not require any additional resources like electricity to be able to operate.

Data Gaps

Because the product is in the phase of prototyping, there have been located multiple data gaps, such as:

- The exact production mechanisms, machinery, dye compound, latex, paper pulp, water, and electricity- used to produce a washable paper as a final product.
- Transport of partitioner after its usage stage towards the waste treatment facility from each consumer.
- Transport of the product from the factory to the customer
- Packaging processes, transport, materials, energy usage

Key Assumptions

This section lists the key assumptions for the modeling of the partitioner:

- The production and handling of the product is in Denmark.
- Materials used in the production of the partitioner are manufactured

in Europe.

- Data for the manufacturing process and percentage of materials used in the washable paper was collected from (Papier Do Szycia i Prania - Washpapa, n.d.)
- Waste of 1% of jute fiber during the production phase due to cutting the excess fiber at the TFP manufacturing beginning and end process.
- Waste of 1% of cotton fiber during the production phase due to cutting the excess fiber at the TFP manufacturing beginning and end process.
- Waste of 19% of washable paper during the production phase due to cutting the excess textile at the end of the process.
- Due to the location of the final customers in Denmark, a landfill and incineration of EoL scenarios have been chosen.
- The cutting process is not included in the modeling because it is a human task at this stage of product development. If, in the future, the production phase will be done on a larger scale, a machine cutter would be needed, and therefore, another process would be added to the calculation.

Life Cycle Inventory

The next phase of the study is presenting all inventory relevant to the process while mapping the inputs and outputs of the system (Hauschild et al., 2017).

To clarify and present in a cohesive form all current materials, production processes, sources, and EoL processes related to the production of the partitioner, a table has been prepared.

<table>
<tr><th></th><th>Materials/
Production related processess</th><th>EoL related
processess</th></tr>
<tr><td>Washable Paper</td><td>• Sulfate Pulp, unbleached {RER}| market for sulfate pulp, unbleached| Cut-off, U
•Polylactide, granulate {GLO}| market for polylactide, granulate| Cut-off, U
•Water, completley sofened {RER}|market for water, completley sofened | Cut-off, U</td><td>•Inert waste, for final disposal{RoW}| treatment for inert waste, iner material landfill | Cut-off, U</td></tr>
<tr><td>Cotton thread</td><td>•Fibre, cotton {GLO}| market for fibre, cotton | Cut-off, U</td><td>•Inert waste, for final disposal{RoW}| treatment for inert waste, iner material landfill | Cut-off, U</td></tr>
<tr><td>Jute thread</td><td>•Fibre, jute {GLO}| market for fibre, jute | Cut-off, U</td><td>•Inert waste, for final disposal{RoW}| treatment for inert waste, iner material landfill | Cut-off, U</td></tr>
<tr><td>Sewing</td><td>•Electricity, high voltage {DK}|market for electricity, high voltage| Cut-off, U</td><td>N/A</td></tr>
</table>

Figure 31: Life Cyccle Inventory table

Interpretation

The most established LCA software was utilized for facilitating the Life Cycle Impact (LCI) Assessment- SimaPro (Goedkoop et al., 2016). The Ecoinvent 3 - allocation database was used to model the baseline scenarios using the ReCiPe 2016 Midpoint (H) method and hierarchy's perspective as a 'default model'. This method has frequent updates; thanks to that, it includes the latest data needed for the calculation.

Modeling the baseline scenario showed that the partitioner's total emissions are 5,36 kg Co2eq (Appendix 3). Out of the total emissions, it is presented in the process tree (Appendix 4), that the sewing phase that has the highest impact. This outcome is predictable due to the TFP machine using high-voltage electricity from Denmark throughout the whole manufacturing time. This shows sore room for improvement in future use. The fabrication could use a 100% green high-voltage energy from i.e. windmills for lower impact. The EoL phase was calculated only for the incineration process as consequence of it being the biggest probability of end-of-life scenario, due to more than 80% of Danish waste being treated in that way (Joan, 2014).

to the long-term financial viability of a business or industry for creating a more sustainable future (Miguel Mendes Carvalho Monteiro Cravidão, 2021).

Concept Development

This section of the report will present the concept development of the open office partitioner. Following the design process of Materilas as a Design Too, while gaining knowledge throughout the literature review and prototyping led to the creation of the final concept development.

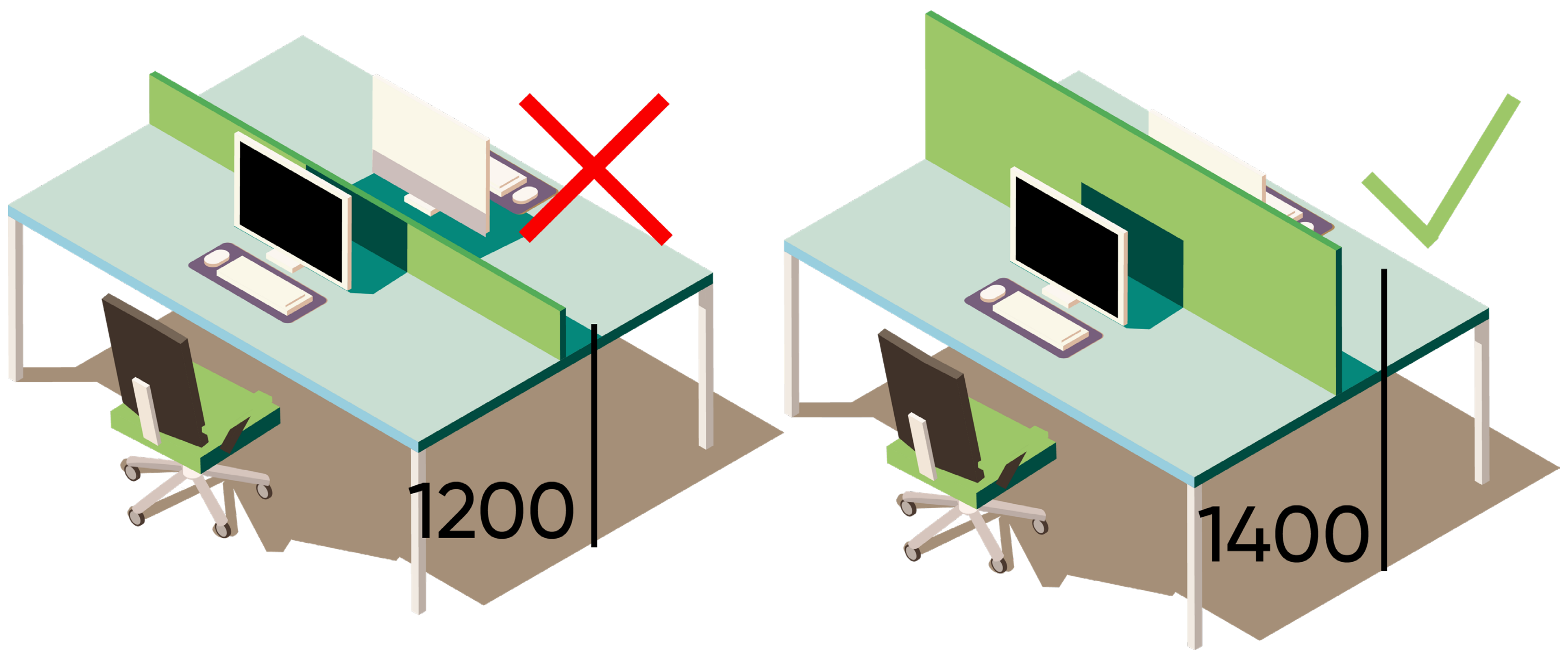


Figure 32: workstation parameters

One of the stages was determining the optimal dimensions of the partitioner to look at the optimal desk sizing and what height of the partitioner can be beneficial for the employees. The article of (Yildirim et al., 2007). Presented that those employees, coupled with a workstation with a high partitioner of 1400cm (measured from the ground), got more satisfaction than being separated by a lower partitioner (1200cm). Presumably, they were happy to have partitions giving them a higher level of visual and acoustical privacy while minimizing interruptions and distractions in the workspace. Also, the standard desk measures are based on human anthropometrical data (Ivelić et al., 2002) and are determined to be 900cm X 1800cm X 760cm as the most standard and optimal for the workplace.

Gaining knowledge from both of those research, the possible frame dimensions of a future partitioner become determined by the 1400cm overall height of an optimal partitioner, subtracting the 760cm of the desk height. The result shows that the partitioner's height should be around 640cm. The object's length should be at most 1800cm looking at the desk's optimal length, but it also should be manageable to provide privacy and seclusion. That is why a length of 1400mm was set to be optimal for creating the final prototype.

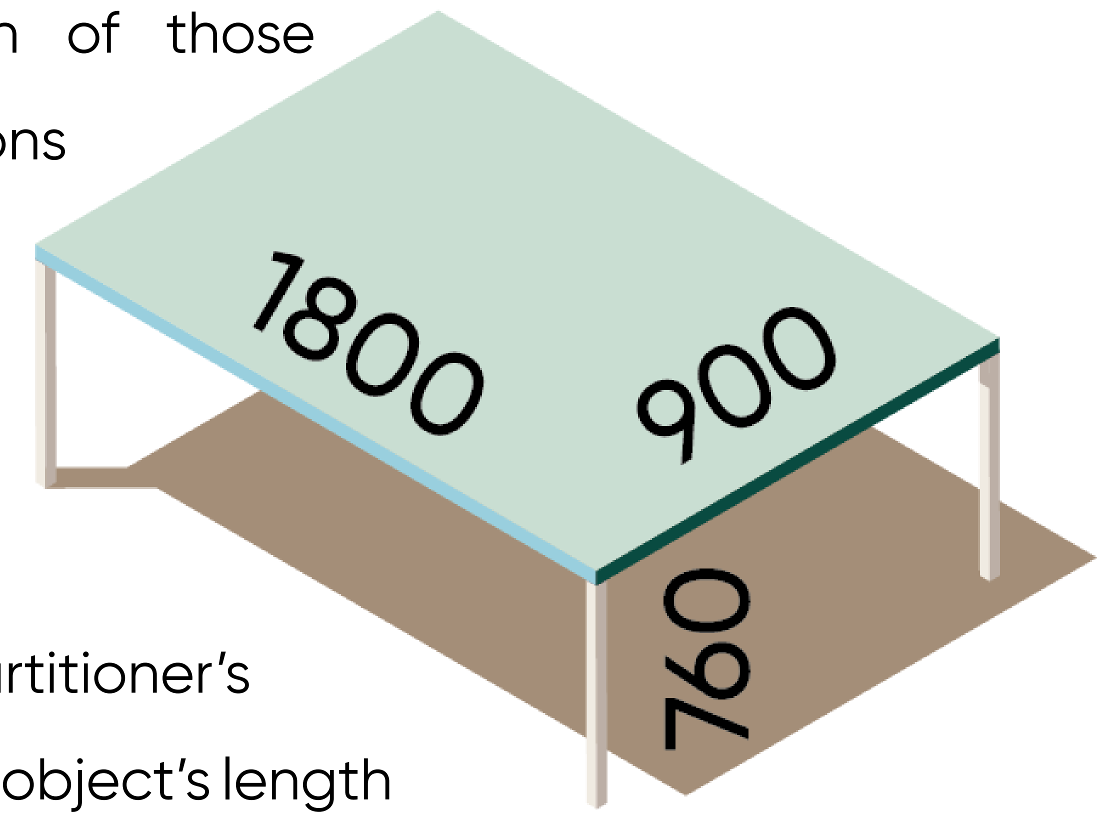


Figure 33: Standard desk dimentions

For creating the concept development, a Tajima Fiber Laying Machine TCWM-101 type 1-2A 1037 with a single head was chosen. Thanks to the possibilities of TFP technology described in the previous chapter, a design of fiber placement could be created precisely. Based on the work (Baszyński et al., 2020), and several prototypes, the angle of the filament thread was decided. Placing the filament at four different layers of 0°, 45°, -45° and 90° -figure 34 consecutively placed, one on top of the other, aims at creating a quasi-isotropic layout sequence, resulting in constant rigidity of the material regardless of the force direction applied, yet offering minimal elasticity of the surface for not letting the piece bend easily.

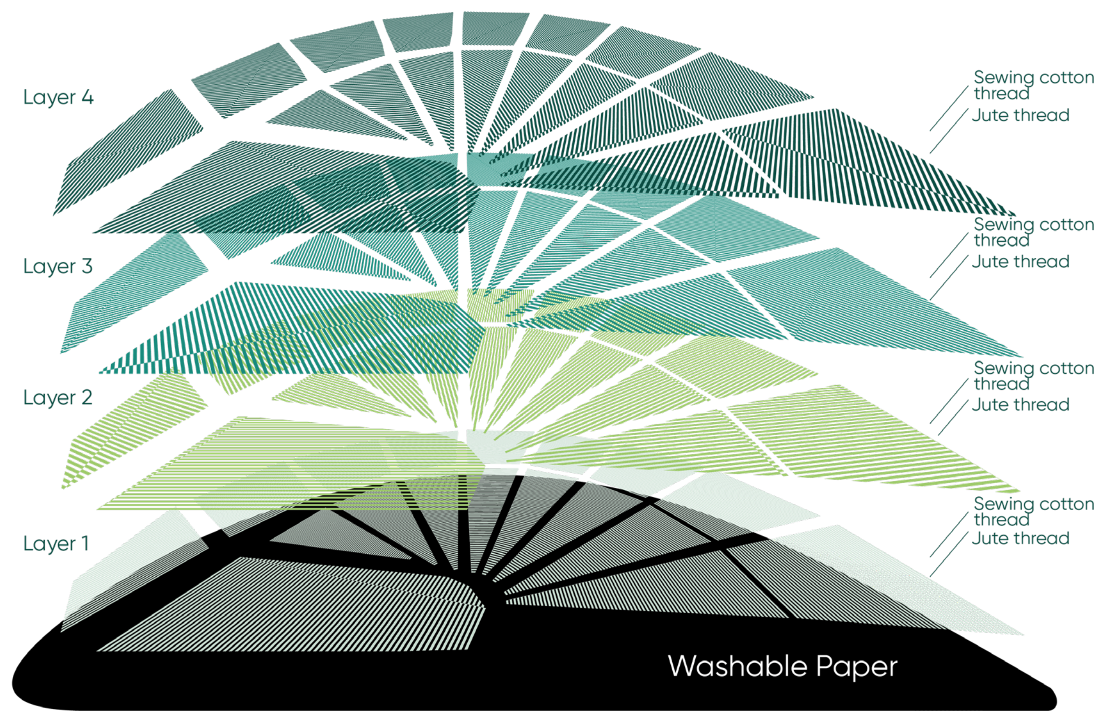


Figure 34: Layers of filament

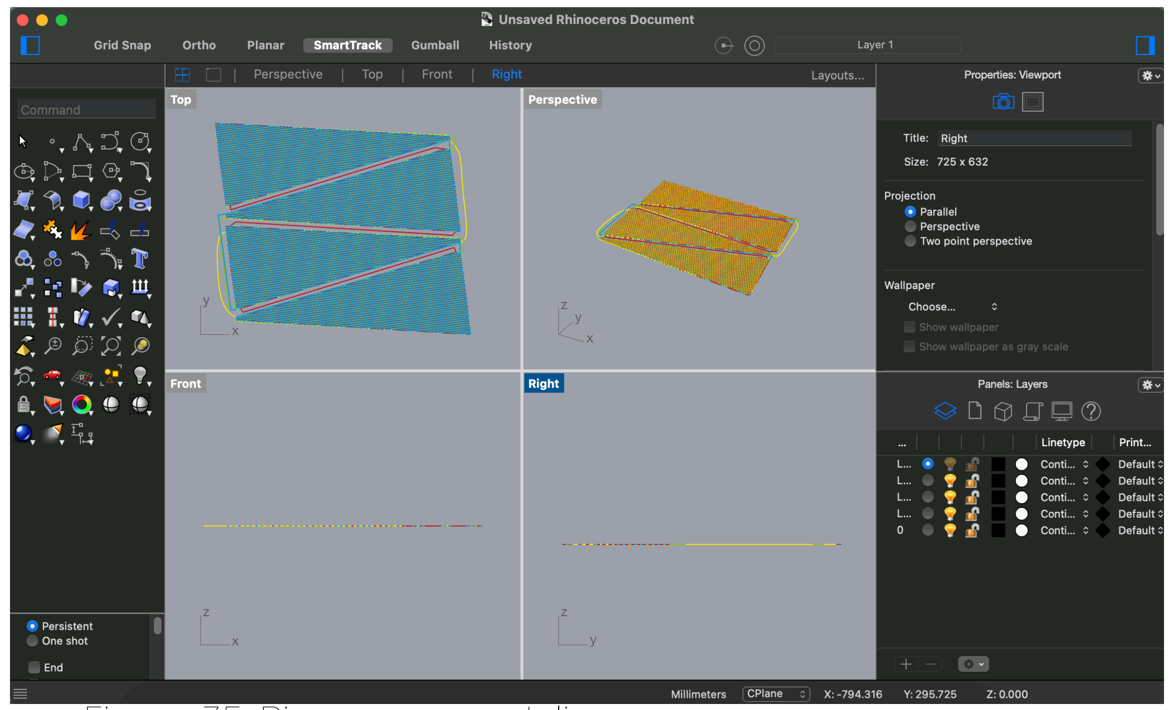


Figure 35: Rinocreos modeling

Those layers for the manufacturing process were designed in Adobe Illustrator software, placed in Rhinoceros 3D software- figure 35 and then exported as a .dxf file to the EDOpass program for creating the sewing specifications. Figure 36 presents the EDOpass program with the settings applied to the manufacturing process. For adding the rigidness to the filament fiber, a minimum (d min) and maximum (d max) stitch length was set to 2,2mm/ 3,3mm the zig-zag sewing dimensions were also determined to be 2,2mm.

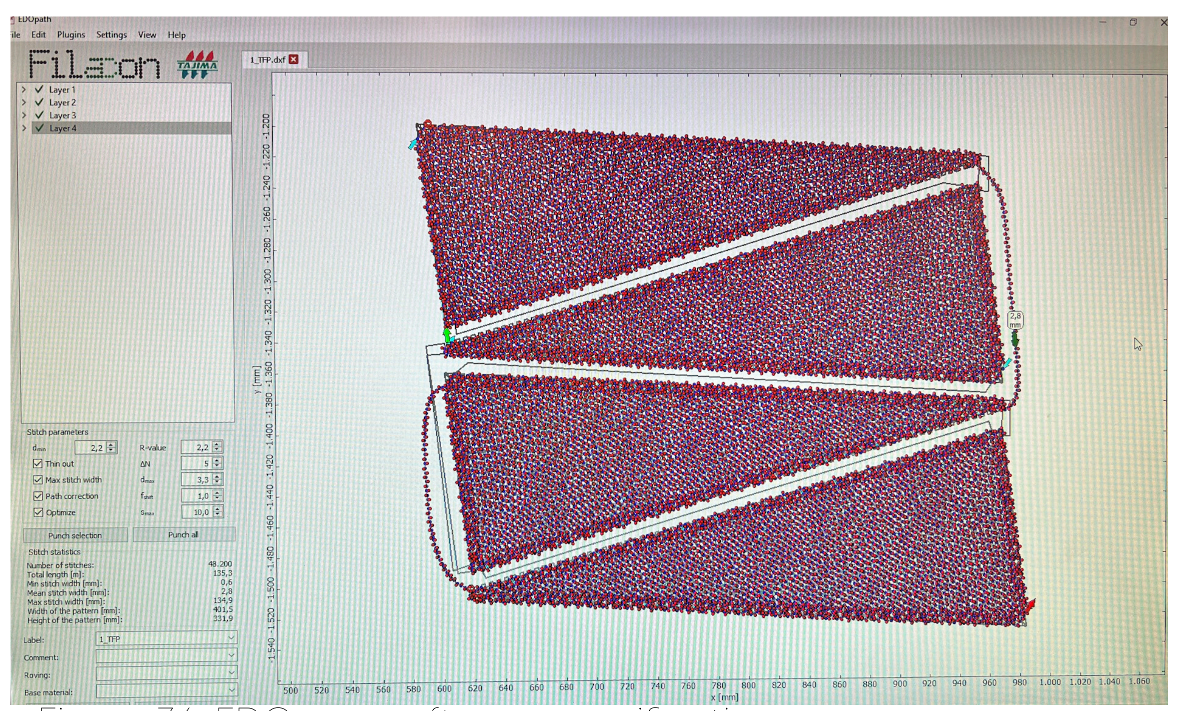
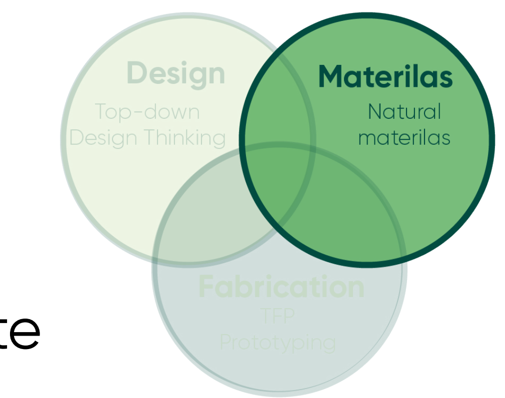
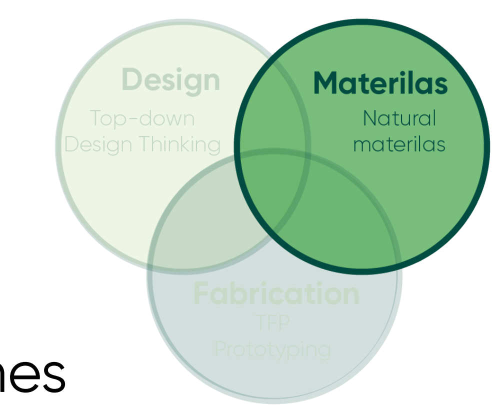


Figure 36: EDOpass software specifications



The filament thread was decided to be a biodegradable jute twine because of its strength, sustainability, and low cost of production aspects. Jute cultivation requires minimal use of pesticides and fertilizers, making it an eco-friendly crop falling into three pillars of sustainability thinking. Additionally, jute plants act as carbon sinks, absorbing, on average, 7302,38 thousand tons of CO2 from the atmosphere during their growth period and emitting 5309,91 tones of O2 annually (Mohammad Shahidul & Kamal, 2012). This fiber, composed of many lignin and cellulose, is sturdy and durable, making it best for use in an open office workspace. Moreover, the fabrication method used natural cotton fibers of TEX 24 for the bobbin and TEX 24 for the upper thread, as suggested by the machine service person as optimal for sewing purposes.



The washable paper was chosen to be the base layer of the product due to its many advantages. It is a very flexible and durable product, especially when it comes to bending and folding it multiple times without damaging the structure of the textile. Additionally, it is manufactured in Europe concerning human rights and with certification of OEKO-TEX® Standard 100 and Forest Stewardship Council (SCS) (Washable Sewing Paper - Washpapa, n.d.). Washable paper is primarily made of cellulose, latex, and water, making it easy to produce and not needing multiple manufacturing resources (Alternative Textiles, n.d.).

Figure 37: TFP fabrication process

Acknowledging the machine limitations and conducting prototyping before placing the jute filament, the washable paper presented some challenges. Due to them occurring, it was decided not to place it on the washable paper directly but first sew it on a cotton base layer. Later cut the pieces stitched on the cotton textile and placed them on the final textile - washable paper. This alteration was made due to some difficulties occurring in the prototyping phase by not properly stitching the jute thread into the textile. It is worth mentioning that the prototyping was made by a trained person, but not someone with in-depth knowledge of the machine's potential and its nuances. That said, it is assumed that if the partitioner is scaled up in production, this issue would be easily solved by specialists knowing much more about the machine and its manufacturing potential.

Stitching the final prototype started by separating the partitioner parts into sections that fit the machine frame. In the ultimate production phase, an adjusted TFP machine should be chosen to sew all partitioner parts in one process without separating them into sections. This will shorten the process of overall production and also will lower the human labor needed for overseeing the process.

When this task was completed, 7 sections were stitched using 1000m of jute twine in the span of a week in the VR-lab facility at Aalborg University Copenhagen The rotations of the needle were set up for 400 per minute (Appendix 5). The next step was to cut out all the pieces by hand from the base textile and place them on the final one – washable paper. This process was conducted using glue. The last step was to fold the partitioner correctly to give a 'memory' to the fabric and prepare it for more accessible transport and storage.

Final Concept Prototype Photo:

Figure 38: Final concept

This process led to the final concept prototype. It needs to be mentioned that the machine in the VR-Lab at Aalborg University has limitations, leading to a more protracted process and requiring much more human labor to maintain the manufacturing than the ultimate product. Using sustainable materials, less energy consumption, and providing seclusion for the employees go hand in hand with the three pillars of the sustainability approach and care for the environment, making the partitioner an excellent object for the workspace.

Figure 39: Final concept visualization

Next Steps

A final partitioner prototype has been created. Nevertheless, there is always room for improvement and further development. This section will deal with this subject, presenting the next steps to be considered.

The design of the partitioner was created with an understanding of employees' wishes found in research that provided a comprehensive understanding of the problems and needs in the open office. Employees have their requirements and desires but do not possess the full knowledge of novel manufacturing methods and design techniques. Therefore, the design process was decided that it did not require employee participation in the process. It is better when an employee is already presented with a finished product and then can say what improvements should be applied for a better product result.

That is why it would be valuable to present the finished prototype to the employees and gain their opinion to develop further product improvements. Thanks to the product already being a tangible model, it would be much easier for the employees to use it and provide comments on desired improvements.

Additionally, after the final concept phase, it was discovered room for improvement. The partitioner was supposed to support itself freely when being open. Conducting the final concept process, presented that additional support (preferably from the back of the object) is needed when the partitioner is being deployed in order to be standing freely. This design iteration should be conducted on the product in order to be fully working in the future.

In addition, it would be a significant step to test the acoustic parameters of the object and how it contributes towards noise reduction. This aspect currently is not explored in the project, but it is assumed that due to the object design and materials chosen, it might contribute towards sound wave reduction. This design aspect would also deal with the noise problem found in open office workspaces, making the design even more beneficial for the employees.

Discussion

The final prototype aims to present a partitioner that can give the important possibility of seclusion to the employees while contributing towards sustainability by implementing materials as a design tool philosophy, biomimicry design practice, and Tailored Fiber Placement (TFP) manufacturing processes. In this section, it will be elaborated on how the decisions made through the project have affected the outcome.

Validating the concept

Not having collaboration with an organization allowed the project to be structured more loosely and gave more time for research, prototyping, and finding the foldability principle in nature. Not having to deliver and live up to expectations from a collaboration partner allowed on conceptualize and shape the project freely. On the other hand, having a collaboration partner would have helped validate the work; hence, the final concept and project would be better anchored in reality. Not having a collaboration partner proved to be more complex to decide, especially at the beginning of the project, which direction to take. Due to this, finding the problem in the current world phase took longer than expected. Since the project did not have a corporate partner, it was unnecessary to fulfill specific requirements when designing the product; hence the scope of creating the solution was much broader to fit into multiple different offices or indoor spaces.

Narrowing the scope

Not having a collaborator led to a lengthy study on the current world problems. The idea of looking at the open office came from listening to friends complaining about their current jobs and how distracted they feel when working in an open office workspace. Those complaints lead to long research on indoor spaces that require human privacy. Here several places were indicated - airports, hospitals, waiting rooms, and open offices- that the project decided to focus on. The research found that the open office workspace concept was designed as a new solution for the workspace in the 1980s. It was supposed to bring creativity, teamwork, and communication to the office. Unfortunately, as time passed, it started to present some downsides of this design. Some of them are loss of visual privacy, constant distractions, and noise. In many cases, it leads to a lowering in the productivity of an employee. Looking at those findings, an idea for the space divider emerged. Research states that one of the most critical privacy factors is the possibility of deciding when to separate yourself from people. This finding was crucial for the later project development. Foldability was chosen as a great feature that can foster the possibility of separating co-workers when desired.

Biomimicry

The best folding patterns already exist in nature, which is why biomimicry was chosen to foster the creation of the prototype. Having it in the projects contributes toward moving from the only philosophical understanding of nature towards creating tangible products that can be employed in the real world. Biomimicry is the perfect method for grasping and understanding nature principles and translating them into design principles. By merging technology, sustainability, design, and other innovative fields of study to foster a multidisciplinary approach, it creates a better end goal for future implementation and improvement of everyday human lives. This method was also chosen due to its already proven working process when creating design solutions and sustainability (Dahy et al., 2022).

Structure of the project

To support facilitating the project, it was decided to use materials as a design tool philosophy (Dahy, 2019). This concept helped structured the project within three categories of design, fabrication, and materials.

For the design section, it was decided to use two frameworks simultaneously of biomimicry top-down and design thinking. They helped structure the project and gave more concrete steps to follow in the design process. It must be noted that design thinking also focuses on the collaboration between the designers and users. In this scenario, design thinking was chosen only due to its iterative structure. The focus on collaborating with users had no impact when choosing this framework because, from the beginning, it was understood that users were not required in this process due to their lack of knowledge of the methods and techniques. The top-down biomimicry approach was chosen because it helped structure the work of translating the found principle in nature toward the technical design and gave a good path to follow in order to achieve the desired goal.

Materials were chosen to be sustainable with the least resources used and with the proper conditions of human rights in mind. Jute fiber was chosen because of its benefits for sustainability, like collecting CO2 from the atmosphere and using no, to minimal amount of fertilizers in the growing process (Mohammad Shahidul & Kamal, 2012). The washable paper was chosen also due to its sustainable production practice and using mostly natural components and being made mostly out of the paper pulp, which can also come from already recycled paper. Cotton threads were chosen for the TFP machine because they are biodegradable versus polyester ones (Nikolay, 2021).

The fabrication section was decided on using the TFP manufacturing which will be elaborated below.

Tailored Fiber Placement

Since working within the sustainability field and being very curious about novel fabrication techniques, a TFP machine was chosen as the perfect fit. Being freshly installed in the spring semester of 2023 in the VR lab at Aalborg University in Copenhagen gave me an excellent opportunity to try new manufacturing methods. Receiving training and prototyping proved to be very challenging due to needing a specialist of TFP on site. That is why also the prototyping phase took much longer time than expected.

Not having complete knowledge about the machine and learning it on the go led to continuously changing the parameters of sewing, like the height of the lay nozzle, the speed of sewing, or learning how to add layers. The fear of breaking the machine, by not having complete knowledge and full responsibility when using it, leads to being more cautious. That is why the full potential of rotations per minute was not explored further to additionally increase the speed or more than four layers of the filament twine. Not only the machine proved to be a challenge, but the EDOpass software also had multiple variables that needed to be considered when prototyping and learning the program on the go. Reflecting on this, probably if the machine was at the university campus and had been used by multiple students before, it would have helped with the overall knowledge and knowing the limitations of the manufacturing process. Being a new device and putting full responsibility on the student when making prototypes lead to being more precocious when using it and not exploring its full potential.

Sustainability

Three pillars of sustainability concept was used to ensure that the creation of the partitioner goes hand in hand with sustainability in mind. It is a broad holistic concept that is applied in multiple sectors and approaches sustainability from a social, environmental, and economic position, making it more holistic and focused on achieving long-term sustainability (Brundtland, 1987) Additionally to assess the sustainability burden for the product an LCA was carried out to gain an inside of what parts or processes are having the biggest sustainability impact by CO2e and what could be changed in the future.

Sustainable Design Engineering

Hence, this project was conducted in Sustainable Design Engineering education, it focused on bringing multiple disciplines when entering the creation of a final outcome of the project. This paper brings a particular focus on biomimetics and its design application of it in the design world but still gathers knowledge and information from multiple disciplines to achieve the final outcome of the project. By working multidisciplinary there is a big potential to ensure that all relevant steps for the project will be met and acknowledged when defining the problem, creating a concept, and final solution by bridging the gaps between different disciplines to develop an innovative sustainable solution.

This project could serve as an inspiration for organizations wanting to change their work environment for their employees. Presenting the statistics of how employees behave and creating a product that tackles all pillars of sustainability, lets the employees decide on their own the level of seclusion, makes it a great product for future use in open office workspace.

Conclusions

Through the project, the world of office design was explored. Multiple findings from the literature review and the design of a final concept lead to answering the research question.

• How can biomimetics foster creating a sustainable, compliant mechanism partitioner, using a TFP method, that provides the possibility of seclusion for the open space office?

In the context of this thesis, biomimetics was used as the main design tool when fostering the process. Understanding and later translating the folding principle from an earwig insect toward the design world helped create a partitioner that also uses a compliant mechanism system. Incorporating it into the partitioner, eliminate the need for complex and potentially failed mechanical components. All those choices are going simultaneously with the sustainability vision. It is achieved by focusing on all three pillars simultaneously of it when designing the object.

1. Fulfilling social sustainability aspect by providing the possibility of seclusion to improve the working conditions, reduce stress and improve mental health.
2. The economic pillar is aiming to be fulfilled by lowering distractions, hence improving the employee's productivity, resulting in an economic gain for the company in the long run. Additionally, usage only of the materials needed without producing vast waste, means that the resources are not being wasted and money is not being thrown away.
3. Moreover, using the only number of materials needed for the manufacturing process also contributes to fulfilling the third pillar of environmental sustainability, by not needing to consume more resources than needed in the manufacturing process.

The TFP method is also taking a big part in fostering sustainability by letting the production process be efficient and also placing the filament thread only where needed, without producing almost any waste. Using a foldable compliant mechanism partitioner gives the employees a possibility of separating themselves from other co-workers. As the literature review showed the word possibility is the key to privacy because it lets humans decide when they want to engage with other people and when not. It gives them a sense of control, but also provides the seclusion to work undisturbed when desired. Using all above mentioned methods, theories, and techniques leads to answering the research question and creating the final concept prototype.

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