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Responsible design and conscious material selection for a reduced environmental impact of the indoor lighting industry

Bachelor thesis within the higher education engineering program Design and Product Development

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Abstract

In response to the pressing climate crisis challenges facing society, there is a critical need for industries to transition towards a circular economy, encompassing entire production chains. Ateljé Lyktan, a company specializing in innovative lighting solutions, aims to reduce its environmental impact through the selecting of sustainable materials. This thesis investigates potential sustainable materials for indoor lighting products through a comprehensive situation and life cycle analysis of an existing product in ateljé Lyktans's range, coupled with extensive literature research to identify current market alternatives. The study identified several material options, focusing primarily on biologically based polymers and polymer composites.

These alternatives were evaluated using a two-step methodology. The initial screening employed both the chart method and a questionnaire method, while the following ranking process utilized a decision matrix to pinpoint the most promising materials according to this study. The findings highlighted two promising candidates: polylactic acid (PLA) and the composite Biodolomer I. However, neither material fully satisfied all requirements, particularly in terms of durability necessary for the long lifecycle of indoor lighting products. Further investigation into fiber reinforcements, which can enhance the mechanical properties and longevity of bioplastics, revealed flax and hemp as suitable options. Additionally, the fibers OnceMore and FibraQ were recommended for further testing. The study underscores the necessity for developing sufficient end-of-life infrastructure, including new technologies for recycling and composting, to facilitate the large-scale adoption of bioplastics and fiber-reinforced materials.

The conclusion calls for ongoing research into sustainable material alternatives and emphasizes the imperative for industries to intensify efforts towards sustainability. This includes the development of robust infrastructure for material recycling and composting, essential for achieving a circular economy.

Keywords: Materials, Sustainability, Design, Manufacturing, Polymers, Composites, Fiber reinforcements, Indoor lighting, Recycling, Circular economy.

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Important Words and Abbreviations

Words	Explanation
Luminarie	A complete lighting unit.
Shade	The material around the light source in a lighting solution, creating the shape of the “lamp”.
Louver	Material designed to regulate airflow or light penetration.
Upper diffuser	Material on top of the shade which directs light in the desired way
Biomagnification	Substances (typically contaminated) increase in concentration in tissues of organisms, successively in higher parts of the food chain.
Bioaccumulation	Gradual accumulation of substances in an organism.
Carcinogenicity	Chemical substances or a mixture of substances inducing cancer or increase its incidence.
Cardiological, hepatological, neurological and renal complications.	Complications connected to the heart, liver, gallbladder, biliary tree, and pancreas, the nervous system and kidneys.
Abbreviations	
SAA	Secondary aluminum alloy.
PP	Poly(propylene-co-ethylene) or Polypropylene.
PA	Polyamide.
PET / PETE	Polyethylene terephthalate.
LDPE	Low-density polyethylene.
HDPE	High-density polyethylene.
PVC	Polyvinyl chloride.
PS	Polystyrene.
PC	Polycarbonate.
DDT	Dichlorodiphenyltrichloroethane is a pesticide, toxic to many living organisms and a possible carcinogen to humans.
PLA	Polylactic acid, a bioplastic..
PHA	Polyhydroxyalkanoates, a type of bioplastic.
PEFC	World’s biggest certification system for sustainable forestry.
FSC	Forest Stewardship Council, a certificate for sustainable forestry.
RSC	The Recycled Claim Standard, a certificate verifying recycled parts and defines “recycled”.

1. Introduction

Today, society faces several challenges, not least connected to sustainable development. In the future, it will be of utmost importance to make conscious material choices across all industries, to reduce the usage of raw materials, and to reuse them. Materials and manufacturing processes are constantly developing and are currently being challenged by the aspiration of society to switch from a linear economy to a more circular one. One of the many companies aspiring to develop their products to fit in a sustainable society is the Swedish lighting solution company ateljé Lyktan. They have the desire to investigate the market to find more sustainable material alternatives to what they use today. The aim of this thesis is to research and find at least one alternative material which is promising for the indoor lighting industry in a future circular economy.

1.1 Background

Understanding the current situation's benefits and challenges is crucial in developing a better alternative for the future in the lighting industry. In the following section the current material and manufacturing process is investigated as a starting point for the following investigation of new materials. The concept of sustainable products and a circular economy as well as tests for knowing if materials are usable was also researched. The information from this research formed the aim and limitations of the thesis.

1.1.1 Indoor Lighting Manufacturing and Material of the Product Today

The lighting industry, like many other branches, is facing challenges with the occurring climate crisis and the adjustment to manufacture fossil-free products that will work properly on the circular market. While analyzing the environmental impact of indoor lighting products, the largest share of CO₂ emissions belongs to the use-stage. It is caused by the energy consumption the luminaire needs to fulfill its function and emit the expected amount of light. There are many solutions, such as intelligent lighting control systems, that help the user to consume as little energy as possible and adjust the light to the environment and specific user needs. However, CO₂ emissions in this stage of the product lifecycle depend mostly on the energy mix in the country where the product will be used, and this factor is not influenced by the designers or manufacturers. Due to these reasons, this study focuses on the material selection, the second largest CO₂ emitter among all the stages of the luminaire lifecycle.

A conscious and responsible material selection is a powerful tool that can be used by producers to reduce the environmental impact of indoor lighting industry and to improve functionality of the luminaires on the circular market. In this study an evaluation of Bumling, a pendant manufactured by ateljé Lyktan is used as a reference in the material selection process in order to show the potential alternatives for the sustainable and fossil-free production of indoor lighting.

Bumling is a piece of classic Swedish design formed by Anders Pehrson and launched at the lightning exhibition in Gothenburg in 1968, now ranging in different sizes and types [\(Home | Ateljé Lyktan, n.d.\)](#). It can be bought as a pendant (hanging from the ceiling, can be seen in figure 1), attachable to a wall, as a table lamp or as a floor lamp. It varies in size, ranging from the biggest with a circumference of 600 mm

to the smallest, miniature version, which is 190 mm.

The shade of the product *Bumling* is currently manufactured through pressure turning. This is a processing method where sheet metal or a metal pipe is mechanically shaped by using a forming tool to apply pressure while the workpiece rotates at high speed (Hermanders, n.d.). Because of the rotation, only shapes with axial symmetry can be created through this process. Atleje Lyktan has cooperated with the Swedish manufacturer Tryckta which offers several production processes of metals including pressure turning, deep drawing, punching, welding, braking and processing with 3D-laser (*Trycksvarvning*, n.d.). The pressure turning can be done both manually and automatically in their machine park. Pressure turning is an optimal method to use when producing a smaller number of products because of its low initial cost and it is primarily used on metals.



Figure 1: *Bumling* as a pendant in brushed aluminum

The shade of *Bumling*'s luminaire is made of aluminum, either varnished or brushed. Although it is called aluminum in everyday speech, rather than using pure aluminum, it's more common to use an alloy where aluminum is combined with copper, manganese, silicone, magnesium, zinc and other minerals. The material used for the lamp shade and ceiling cup of *Bumling* is aluminum 1050A, a "commercially pure" aluminum alloy, containing at least 99 % aluminum. Aluminum in the 1000 series has the lowest mechanical properties and is therefore the most formable. They are not heat treatable and have a high corrosion resistance (Thompson, 2021). Brushed aluminum is aluminum that has been mechanically abraded with an abrasive brush that creates the seemingly scratched texture that can be compared to stainless steel (Yijin Hardware, n.d.). This material can be used for many purposes due to its flexible properties and timeless appearance (Ningbo Yichou, 2023). It has a natural shine and is resistant to wear and corrosion, resulting in the material having a long lifespan and does not need to be replaced often.

GRANTA Edupack was used to get more specific information about Aluminum 1050A, collected in table 1 (*Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024*). Cost, mechanical properties and carbon dioxide footprint, among other specifics, will be useful to know when comparing to other materials later in the process.

Table 1: *Properties about Aluminum 1050A*

	Aluminum
Price per unit volume (SEK/m³)	7,47e ⁴ -1,07e ⁵
Density (kg/m³)	2,67e ³ -2,73e ³
Tensile strength (MPa)	76-84
Young's modulus (GPa)	69-72

Melting point (°C)	
CO₂ footprint (kg/kg)	8,13-9,48
Recyclability (Yes/No)	Yes
CO₂ footprint, recycling (kg/kg)	2,48-2,74
Biodegradable (Yes/No)	No
Origin in EU (Yes/no)	Yes

Even if aluminum is completely recyclable, 75% of the world's aluminum is still in use, making it more difficult to use recycled aluminum than to use raw material that achieves the desired, high quality with lower effort (*Återvinning Av Aluminium | Minimal Miljöpåverkan*, n.d.) Additionally, aluminum production requires a high amount of energy, resulting in it only being economically viable in locations where electricity is profuse and cheap. A great advantage with utilizing recycled aluminum is the reduction of energy usage and the carbon dioxide production to only 5% of primary aluminum production. However, recycled metals often imply many alloys being mixed, resulting in inferior properties compared to the virgin ones. Therefore, one of the main requirements for the recycling process is to keep different grades of aluminum separately (Thompson, 2021).

There are health hazards caused by the production of primary aluminum. It involves chemical hazards especially during alumina refining process, such as bauxite dusts, caustic soda, fluoride and diesel exhaust fumes. There are several disease and death causes reported in relation to the chemical and physical threats appearing in the workplace environment while producing the primary aluminum (Wesdock & Arnold, 2014).

There are also other problematic aspects about aluminum. To prevent downcycling of aluminum it is necessary to isolate it mainly from iron but also other different elements such as copper and zinc or nonmetallic inclusions (Nunes et al., 2023). The overall demand for recycled aluminum will increase significantly due to the automotive sector's development, especially because of the development of electric vehicles. The fact that SAAs¹ used for casting in automobile industry are mixed with wrought alloys containing scraps from automobile shredders gives material with limited usability and low recyclability if no new recycling routes are created. The automotive sector is already the primary recipient of recycled aluminum from all sectors and its dominating position will expand, making it more challenging for other sectors to receive and use recycled aluminum in products where higher ductility and mechanical properties are required.

On the inside of the shade, Bumling has 10 circular louvers which are meant to direct and diffuse the light. The louvers are injection molded, by a cooperation partner to ateljé Lyktan, in a fossil-based polymer

¹ SAA – secondary aluminum alloys

called Polypropylene, or PP². This plastic is one of the most used in production of consumer goods. The recycling process of PP is effective and economical because it floats on water and therefore is easy to separate from other plastic waste. However, breaking down the PP involves heat and UV treatment which limits the amount of recycling processes (Thompson, 2021). The circular louvers measure 20 mm in height and their circumference varies depending on the size of the product as well as the placement of the specific louver

² Poly(propylene-co-ethylene)

1.1.2 What are considered sustainable products?

When developing sustainable products, many aspects need to be considered. There are many strategies for designers to use about how to create sustainable products, including selecting eco-friendly materials, designing products that are easy to recycle and designing for a sustainable consumer behavior (Belletiere et al., 2013). When designing a product its total lifecycle should be considered. This would mean that conscious materials and the design of the product itself can enable easy recycling and re-use from the beginning. When designing, the aim for products should be a long life.

The material selection is crucial in how sustainable a product is. Thoroughness in the amount of material that is used and how that material affects the environment is important (Belletiere et al., 2013). Materials that are toxic or in other ways harmful to the environment or organisms should be avoided as well as materials that deplete the earth's resources. Using recycled materials or waste from other industries can be a good way of doing this but it is not always possible. In case of extraction of new materials, they should come from renewable sources. There are also certifications on some materials ensuring that extraction has been done in a justifiable way.

For a product to be truly sustainable, both ecological and social aspects should be included, meaning that factors like fair working conditions in the factories and within the company are crucial as well.

1.1.3 Circular Economy

Society is facing many challenges in the future, including pollution, biodiversity loss, global warming and resources being insufficient for the population. Stemming from discussions on how to solve these issues, the concept of circular economy, a system where nature is regenerated, and nothing becomes waste has been raised (*What Is a Circular Economy?* | *Ellen MacArthur Foundation*, n.d.). In contrast to society today which is mostly linear, materials and products are used and then thrown out as waste, this is a system where all products and materials should be kept in closed-loop systems through recycling, reuse, maintenance, remanufacturing and composting and other processes. The circular economy system is based on three main principles:

- Eliminate waste and pollution through design,
- Circulate both materials and products at their highest value by keeping them in use,
- Revitalize nature and its systems.

A circular economy promotes economic resilience by disconnecting economic growth from resource consumption which reduces the vulnerability to price fluctuations and resource insufficiencies (*What Is a Circular Economy?* | *Ellen MacArthur Foundation*, n.d.). It creates entrepreneurial opportunities, innovation and can enhance the competitiveness on the market by encouraging reuse, recycling and product-as-a-service business models. The circular economy could be a step towards more equal and inclusive socio-economic systems by extending the life cycle of products and making affordable goods and services more accessible. It fosters sharing and collaborative consumption models, creating social cohesion as well as resilience to socio-economic shocks.

This system is one of the most prominent concepts on how to make society sustainable, where nature, wildlife and humans can coexist for many generations from now. For prioritizing resource efficiency and minimizing waste to become reality, a shift in economic thinking and consumer behavior would be required (*What Is a Circular Economy?* | *Ellen MacArthur Foundation*, n.d.). The circular economy approach aligns with the international sustainability agendas like the United Nations Sustainable

Development Goals.

The fact that resources on the planet are finite is a reason to adopt the circular economy system. It is also one of few concepts which solves how society can continue to prosper without depending on consumption of new products and materials. Therefore, to design truly sustainable products, it should fit well into the circularity where products have a long lifecycle, are repairable and fully recyclable.

1.1.4 UN Sustainable Development Goals

Finding more sustainable material alternatives for the manufacturing of Bumling and adaptation to the reality of the circular market is also motivated by the UN Global Sustainability Goals that ateljé Lyktan decided to implement into their company. The most relevant goal for this thesis work is goal 12 that covers ensuring sustainable consumption and production patterns where phasing out fossil fuels and choosing the right material plays a crucial role (*Goal 12 | Department of Economic and Social Affairs*, n.d.). Target 12.4 describes the importance of eliminating usage and emission of hazardous chemicals to the environment throughout the whole product lifecycle. Recycling, reusing and maintaining the good condition of the products to prolong their lifespan are covered by target 12.5 and is also essential.

1.1.5 Technical Tests and Demands

There are several technical tests and demands that a material with the purpose of being a luminaire should pass. The most crucial tests for the material to pass are an aging test, a filament test and an EMC-test. The main purpose of aging test is to explore materials durability against a range of different physical conditions that are typical for environment where the product will be used such as UV-light, high temperature or ozone (*What Is the Aging Test? -*, n.d.). As a result, an expected life span can be estimated and, furthermore, eventual design challenges can be discovered.

Another important test that needs to be conducted to all electronic devices, including luminaires, is the Electromagnetic Compatibility (EMC) test that controls if the product can function satisfactorily in its electromagnetically environment. (*14.8 EMC Testing - Knovel*, n.d.) There are several European standards such as EN 55015 or the European Parliament Electromagnetic Compatibility (EMC) Directive (2014/30/EU) that describes the allowed parameters and limits electromagnetic emissions from electronical equipment.

It is also of great significance that the selected material meets regulations and demands from the EU regarding chemicals and substances. Because of the limited time frame, there will not be enough time to ensure that the material(s) meet these demands by practical testing, but they should be taken into consideration in the theoretical investigation.

1.2 Purpose and Aim

Together with ateljé Lyktan, the prospects for using recyclable and/or recycled materials at reasonable prices in the lighting industry for a circular society have been investigated. This was carried out by examining one of ateljé Lyktan's existing products, its materials and its production methods to see if any of these can be changed or replaced with more sustainable alternatives. In order to find truly sustainable material alternatives, manufacturing methods and processing methods for both the product and the new material must be thoroughly investigated. This includes, among other things, performing life cycle analyses of both materials and an existing product. The thesis also includes an investigation of available

sources with the goal of finding local suppliers for a long-term, sustainable business strategy that fits into a circular economy.

Sustainability work includes a sustainable situation with societal, ethical and ecological aspects being considered. In the work, the main focus lies on the ecological aspects, how materials and manufacturing processes affect the environment, but these cannot be considered completely sustainable unless ethical and societal requirements are also met.

The aim of the thesis is to expand knowledge on the subject by finding at least one suitable material and investigating its life cycle, as well as to investigate how ateljé Lyktan could manufacture a luminaire in this material into a specific product in the future to make it more durable.

1.3 Limitations

This work is limited to a specific product's shade and circular louver in ateljé Lyktan's range. The product is called Bumling and is one of the company's signature products. This product is an indoor luminaire used in both public spaces, such as school or office environments, or in private spaces. Currently, the company produces high-quality, durable lighting solutions for public spaces in a higher price range. This results in greater flexibility in the material's price range, but it must be within reasonable limits for potential future purchases and production. It is important that the material/s has a high durability and less climate impact than the material already used in the luminaire.

Due to the time frame, the material(s) discovered will not be extensively tested. Those processes would require more time than is available. Therefore, this becomes a natural step in the further development after the end of the thesis.

2. Theory

In this chapter the theoretical findings from the literature research are presented as well as the research connected to design aspects of products, like how coloring affects sustainability and how to design products for a long lifecycle. The purpose of the research was to broaden the knowledge of sustainable materials and evaluate if they are suitable for use in the lighting industry. It is also an opportunity to do an in-depth investigation without the typical restrictions, connected to cost or partnerships for example, that employees and experts in the industry would have.

An essential part of the investigation is to limit the research. There are many hundreds of possibly suitable materials for the indoor lighting application, but the time limit makes it impossible to research them all. Therefore, the investigation mainly covers materials that possess similar properties to aluminum (which the shade and upper diffuser is made from) and plastic (which the louvers are made from).

2.1 Metals

Primarily, research was done to investigate metals with similar mechanical properties to aluminum. The section includes metals like zinc alloys and copper alloys. These could be considered the most probable alternatives or substitutes to the current luminaires; however, they may lack in innovativeness which was partially the purpose of the project. Metals are finite resources and may not be considered entirely circular because of this.

2.1.1 Zinc and Zinc Alloys

Zinc is a brittle metal with a blueish and white tone (*Zinc (Zn) - Properties, Applications*, n.d.). Zinc is a relatively strong, ductile and impact resistant material with low to moderate cost. As a result of zinc reacting with water and carbon dioxide, zinc carbonate, a dark blue-grey tarnish is formed on the surface protecting the metal (Thompson, 2021). This protective tarnish ensures that the metal only loses around 1 micron per year, making even very thin zinc sheets last more than half a century. The material is often used for galvanizing and plating steel and iron to prevent corrosion and is also a significant alloying element commonly used in bronzes, aluminums, brasses and magnesium alloys (Pola et al., 2020).

Zinc alloys are particularly well-suited for manufacturing through die-casting and foundry because of their general low melting temperature and high fluidity, which results in a long die life, low energy consumption and the ability to fill complex mold cavities as well as thin sections (Pola et al., 2020). The performance of zinc-alloys is decreased in temperatures above 80-90°C, or after a long time in room temperature, so called aging (Thompson, 2021). Because of this, zinc alloys are mostly used for components that are smaller and non-structural, like thin-walled precise parts in kitchen equipment or bathroom fixtures for instance. Zinc's mechanical properties and great castability puts it in competition with aluminum and injection molded engineering thermoplastics like polyamide (PA) and polypropylene (PP).

Zinc is mined from its principal ore zinc sulphide in large quantities all over the world. The process of extracting and separating the zinc from other minerals results in air emissions, hazardous by-products and other waste (Thompson, 2021). It has a negative impact on the environment despite efforts to collect and repurpose it. Zinc is widely recycled today and can be 100% recycled without losing its physical or chemical properties (*Zinc Recycling | American Galvanizers Association*, n.d.).

To find a suitable zinc-alloy for this specific application, GRANTA Edupack was used to browse among known alternatives. Here, mechanical properties, sustainability information as well as typical applications for the materials can be found. One of the most suitable alloys is a Zinc-aluminum alloy called “Zinc-aluminum alloy, alloy A, slush casting” (Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024).

Table 2: Properties of "Zinc-Aluminum alloy, Alloy A, Slush casting"

	Zn-Al-alloy
Price per unit volume (SEK/m³)	2,29e ⁵ -3,14e ⁵
Density (kg/m³)	6,45e ³ -6,65e ³
Tensile strength (MPa)	150-235
Young's modulus (GPa)	75-95
Melting point (°C)	380-390
CO₂ footprint (kg/kg)	3,16-3,57
Recyclability (Yes/No)	Yes
CO₂ footprint, recycling (kg/kg)	0,935-1
Biodegradable (Yes/No)	No
Origin in EU (Yes/no)	Yes

2.1.2 Brass, Bronze and Other Copper Alloys

Copper is the third most consumed metal after steel and aluminum, known for its excellent conductivity and corrosion resistance (Thompson, 2021). Brass is an alloy made from copper and zinc with varying proportions that determine the exact properties of the material. The color of brass varies from red/brown to yellow/gold and can be used as an indicator of how much zinc is mixed into the copper. The more copper there is in the alloy, the warmer the brass will be in its color tone. Red brass contains around 10% zinc while yellow brass contains around 30%. Oxidation of all copper alloys can cause gradual changes in its color and produce a surface patina. By lacquering the surface, it can prevent the alloys from oxidation and changing color if this is not desirable.

Copper alloys can be identified by the Unified Numbering System, a system created by the North American copper and brass industry (Thompson, 2021). Every copper alloy is assigned a unique code, starting with the letter C. Following the C is the first number, indicating copper content, followed by an

addition of four numbers indicating other alloying elements. C1 indicates high copper while C2 through C4 are wrought brasses. These brasses have an improved strength compared to high copper, resulting in good castability and machinability. Brasses containing up to one-third zinc maintain a special atomic structure called face-centered crystal (FCC) structure making them very ductile and formable. Reductions of the copper results in a gradually more formable and corrosion resistant material. Brasses with one-third zinc are known to have the optimal balance of strength and ductility while also being corrosion resistant and are characterized by their bright yellow appearance. Brasses with more than one-third zinc can contain both the FCC-structure and body centered cubic (BCC) structure, resulting in a harder and stronger material. These tend to be formed by extrusion, casting and machining. The tensile strength of brass is around 525 MPa, which can be compared to aluminum alloys at around 310 MPa.

Another copper alloy is nickel silver, also known as cupronickel, which is a combination of copper and nickel (Thompson, 2021). These alloys have great mechanical properties. As the proportion of nickel increases, it makes the material more silvery-white and at 40% it can be mistaken for silver, hence the name nickel silver. All types of nickel silver are suitable for machining and casting. Copper alloys, where the main alloying element is neither zinc nor nickel, are called bronzes and can be useful when a greater strength and hardness is required.

Copper is derived from sulphide and oxide ores in small concentrations (Thompson, 2021). To produce one 1 kg of copper it can require more than a ton of ore, creating a large amount of waste. Due to this, processing facilities are often situated close to the mines and can have a large, negative impact on air quality, surface and groundwater quality as well as the land surrounding it. To minimize the pollution and loss of biodiversity, there are strict guidelines that the companies must follow. Copper is infinitely recyclable without any loss of quality and when recycled, the process saves about 85% of the energy used to produce primary copper. However, it is more complicated when copper is alloyed since many applications, electrical wiring for instance, cannot accept impurities. Furthermore, it is seldom economically viable to remove all the alloyed elements which has led to virgin copper often being mixed into the recycled copper. This process can reduce the proportion of impurities to the acceptable levels for applications where high purity is required. In conclusion, the infrastructure for recycling exists but is not used as much as it could.

Primary copper is relatively expensive, it can be 10 times more expensive than steel, nonetheless, it is more efficient to machine. In large quantities, copper alloys can have a lower unit price than steel because of this. Bronze's price heavily depends on its alloy, with tin being much more expensive than aluminum for example. Bronze is not economically viable in most cases despite it often having superior mechanical properties compared to brass. Zinc alloys are a cheaper alternative to brass and bronze, but may lack tensile strength, durability or stiffness depending on its application.

Brass and bronze are both suitable for high-quality items because of their high strengths, durability, corrosion resistance and they can be polished for a good surface finish. They can also be painted or plated for design purposes. These metals reflect light well which can be utilized in creative ways.

When browsed for the most relevant option of brass, "Brass, CuZn39Pb2, C37700, soft (leaded (clock) brass)" was found. Some selected mechanical properties of the brass alloy are presented below in table 3 for an easy overview.

Table 3: Properties of the brass alloy

	Brass
Price per unit volume (SEK/m³)	6,26e ⁵ -6,89e ⁵
Density (kg/m³)	8,18e ³ -8,35e ³
Tensile strength (MPa)	400-420
Young's modulus (GPa)	97 - 103
Melting point (°C)	882-902
CO₂ footprint (kg/kg)	3,64 - 4,18
Recyclability (Yes/No)	Yes
CO₂ footprint, recycling (kg/kg)	1,23-1,36
Biodegradable (Yes/No)	No
Origin in EU (Yes/no)	Yes

Once again, GRANTA Edupack was browsed for different bronzes and nickel silvers. One of the seemingly most suitable is named “Bronze, CuNi10Zn27, C74500, hard (10% nickel silver)” (Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024). It has the more commonly used tradenames Bridgeport, Nickel-silver, Revere, Riverside and Seymour and are typically used for decorative items, pressed and drawn articles, table flatware, musical instruments among others. More specific mechanical properties and sustainability information are presented in table 4.

Table 4: Properties of the Bronze-alloy

	Bronze
Price per unit volume (SEK/m³)	8,3e ⁵ -9,75e ⁵
Density (kg/m³)	8,55e ³ -8,56e ³
Tensile strength (MPa)	470-540
Young's modulus (GPa)	123-128

Melting point (°C)	1,01e ³ -1,03e ³
CO₂ footprint (kg/kg)	4,53-5,21
Recyclability (Yes/No)	Yes
CO₂ footprint, recycling (kg/kg)	1,46-1,61
Biodegradable (Yes/No)	No
Origin in EU (Yes/no)	Yes

2.2 Polymers and Composites

After researching metals, polymers were considered interesting. Polymers are a large group of materials that can be naturally found in nature and biological organisms as cellulose and proteins for instance, but they can also be man-made and is the foundation of materials like concrete, rubbers and plastics (Rial, 2022). Structurally, polymers consist of large molecules called macromolecules which are made up of smaller units known as monomers. Polymers can be divided into three types: natural, semi-synthetic or synthetic polymers. Natural polymers can be either organic or inorganic and are naturally found in plants and animals in forms such as starch and proteins. The semi-synthetic polymers are natural polymers that have been chemically modified while the synthetic polymers are completely man-made. Plastic stands out as the most widespread and frequently used synthetic polymer, finding application across diverse industries. There is a wide variety in different polymer's properties, such as flexibility, hardness, water solubility, softening temperature and biodegradability, making them a versatile material group with applications in most industries. Some of the most common plastics are polyethylene terephthalate (PET or PETE), high-density and low-density polyethylene (HDPE and LDPE), polyvinyl chloride (PVC), polypropylene (PP) and polystyrene (PS) (Plastic Oceans International, 2021).

Plastics are frequently utilized in society today, but there are many issues connected to synthetic plastic use, endangering both the environment and the health of all organisms on earth. Annually, more than 380 million tons of plastic is produced, and this number is increasing (Bin Abu Sofian et al., 2024). It is important to highlight what happens to the plastic waste and it was estimated in 2020 that approximately 28 million metric tons of plastic will enter the oceans annually by 2025 (Cook & Halden, 2020). While some of the plastic waste is visible there is also a large amount of micro- and nanoplastics in a size range of 5 mm or less that are present everywhere, including in nature, in human homes and in the bodies of most organisms.

There are many dangers to the health of humans and animals connected to plastic waste. Wildlife is suffering from mistakenly ingesting plastic litter, causing harm and even death to the animals (Cook & Halden, 2020). Micro and nano plastics, found everywhere, are potentially creating issues like

biomagnification of the plastic particles and bioaccumulation of toxins in the food chain. Some polymers and polymer additives have been shown to have a correlation with carcinogenicity and if subjected to chronic exposure, it may be the cause of cardiological, hepatological, neurological and renal complications in both humans and animals. Additionally, plastics are jeopardizing the environmental health by spreading contaminants, such as the pesticide DDT that can be found at concentrations of a million times the typical concentration in nature (Cook & Halden, 2020).

Not only are there ecological and health issues connected to the usage of synthetic plastics, but there could also be an economic reason to step away from them. Due to geo-economic factors in the export of petroleum, the prices of plastics are constantly increasing, and this trend will most likely continue (Kim & Pal, 2011). In comparison, plant-based alternatives may be more cost efficient in the future.

These issues prove why it would be beneficial to decrease synthetic plastic production and use, as well as making efforts in cleaning up and recovering the environment from plastic litter. However, there are types of plastic that are based off biological materials, so called bioplastics or bio-based plastics. These are not necessarily biodegradable, but many of them are and can be removed from the environment at their end-of-life (Havstad, 2020). There are fossil-based plastics that are biodegradable but since fossil fuels are finite materials there are still reasons to focus more on biologically based plastics.

2.2.1 Additives and Fillers in Plastics

Not only do plastics consist of polymers, but they often contain fillers and additives. Most of the commercial plastics are compounded with other monomeric additives which improve their properties for processing and performance at end-use (Deanin, 1975). There are both conventional and bio-based fillers, and for a plastic to be considered 100% bio-based all its material, both polymer and additives/fillers, need to be from natural or renewable origin (Tolinski & Carlin, 2021).

Additives

Additives are being added to polymers in small percentages to improve their properties (Tolinski & Carlin, 2021). Additives can be used to protect the polymer from oxidation caused by UV-light or heat, encourage crystallization, improve the materials flexibility or melt flow, make it tougher against impacts, lubricate its surface, reduce electrical static build-up in the material or to color it. Some of the main types of additives are:

- Antioxidants and heat stabilizers. Antioxidants are utilized as protection from oxidation of polymers and stabilizers are essential in PVC-processing. In the past these were based on toxic heavy metals like lead or cadmium but are now being substituted by more friendly metal carboxylates based on elements like calcium and magnesium for instance. Both antioxidants and stabilizers are often based of petroleum or natural gas, but recently antioxidants based on the naturally occurring vitamin E and plant extracts has been developed. They are not yet used in commercial scale.
- Plasticizers, used in flexible PVC, can greatly influence whether a material is considered environmentally friendly or not. Plasticizers based on phthalates have raised health concerns for being hormone disruptors, however, there are alternatives with some of them made from renewable sources. “Greener” options to phthalate-based materials are isoboride-based plasticizers and bio-plasticizers made from citrates and vegetable oils.

- Impact modifiers are additives which are particularly significant for the brittle plastic PLA. PLA are mostly used in food-use products and is biodegradable which impact modifier does not interfere with.
- Lubricants, anti-blocking agents and slip agents. These are used to allow higher processability of the plastic melt or as prevention for surface-sticking in thin-film plastic. Lubricants are often made from simple hydrocarbon waxes but can be more chemically complicated as well. Anti-blocking agents are small filler particles which can prevent layers of plastic film from bonding and mixing. Slip agents are usually based on animal or plant fatty acid amides and are used in processing to allow plastic film to slide against itself or metal machinery without sticking.
- Flame retardants. The cheapest and most effective flame retardants are halogen-based, elements which are known for being damaging to the ozone layer. Consequently, more environmentally friendly mineral-based flame retardants are increasingly being used. These affect the mechanical properties of the plastic when incorporated in their effective proportions. Flame retardants based on phosphorous are also increasingly popular but are problematic for the environment.
- Antistatic agents, often fatty acid amines or esters, prevent static build-up at the surface of the plastic by dispelling electrical charge.
- Colorants. These are rarely bio-based although some manufacturers claim that some meet the standards for bio-content and composting by using non-petrochemical-based carrier material for the pigments. These can be dispersed into the polymer (Tolinski & Carlin, 2021).

Fillers and fiber reinforcements

Fillers are used in plastics to displace polymer in the composition of products which significantly reduces the amount of plastic resin used in them, and in turn the cost of the plastic in case of high resin prices (Tolinski & Carlin, 2021). One of the most common fillers for affordable plastics is calcium carbonate (CaCO_3) which, when loaded at 10-60%, can increase stiffness, hardness and dimensional stability of the plastic. Calcium carbonate is chemically simple, naturally occurring in nature and does not degrade as much from being reprocessed as polymers do. It can even lower the processing energy of the conversion process of some polymers, almost reducing the environmental footprint by being added into it.

Many types of fibers, including glass fibers, carbon fibers and different kinds of plant fibers, can be used as reinforcement in plastics (Tolinski & Carlin, 2021). Glass fiber-reinforced plastics have become a valuable material in lightweight engineering applications common in the automotive industry. Carbon-fiber plastic composites are important in the process of making airplanes lighter. Glass fibers are a cheap alternative to other materials with similar properties. Carbon-fibers are quite expensive but have similar mechanical properties to steel. Environmentally wise, these reinforced plastics are contradictory considering they make vehicles lighter, saving fuel when the vehicle is used, but can be difficult or impossible to recycle with current technology.

Reinforcements of plant-based fibers are increasingly important in the plastic industry (Tolinski & Carlin, 2021). They can add to the bio-based content while also enhancing desirable engineering properties to the material. Fibers from numerous plants can be used, and are spread around the world, allowing developing countries to participate in the global industrial material market. Although there are many positive aspects with plant fibers there are also some limitations to using them, like their sensitivity to water and environmental exposure because of the biodegradability. The degradation often starts at 170°C , resulting in plant fibers not being able to be processed methods where high-temperature or high pressure is used.

Many polymers are hydrophobic, creating an issue for the hydrophilic plants as they do not bond well naturally. Compared to glass fibers, the cost of high-quality plant fibers is the same or lower, but glass fibers achieve higher mechanical properties per unit cost. Some fibers that can be used as reinforcements in plastic are jute, hemp, flax, bamboo, cotton and wood.

Although there are some limitations, bio-based additives and plant-based fiber reinforcements can be used to increase the eco-friendly content of plastic compounds. The development is still in a relatively early stage but these methods of reinforcing plastics and reducing their environmental footprint are likely to continue advancing.

2.2.2 Bio-based Plastics

There are many types of biologically based plastics currently being developed. The most dominating ones are biobased thermoplastics that can be recycled and remolded several times in high temperatures (Nordisk Bioplastförening, n.d.). Bioplastics are made from organic material called biomass in order to replace crude oil partially or completely to decrease their carbon footprint. There are three generations of raw materials used for bioplastic production: the first generation includes carbohydrate-rich plants that rapidly bind significant amounts of carbon such as sugar cane or maize. Second generation raw materials cover cellulose and inedible byproducts from the food industry. The third-generation raw material is mostly in the experimental phase and includes materials such as algae or carbon dioxide and methane that are two main contributors to the greenhouse effect.

Bio-based plastics can be divided into categories according to their biodegradability and share of fossil fuels used in production. Some of the biodegradable bioplastics can be classified as compostable. This is indicated by appropriate certificates that test if the degradation of plastic fulfills a timeframe defined in European standard EN 13432 and if all features of a product such as paint or label are industrially also compostable (Nordisk Bioplastförening, n.d.). Another crucial aspect that needs to be taken into consideration when analyzing the environmental impact of products made of bioplastics is additives that help a polymer to achieve the expected properties or lower the price. Some of them might be harmful to the environment or based on non-renewable materials.

Bioplastics are widely used in many industries and their global production capacity is expected to grow from 2,18 million tons in 2023 to 7,43 million tons in 2028. The most common bioplastics used in production for consumer goods market are the non-biodegradable polyamide (PA) and biodegradable polylactic acid (PLA). Both polymers were responsible for almost 50% of the global production capacities of bioplastics in the year of 2023 (European Bioplastics, n.d.). Other relevant bioplastics for this project are those that are also biodegradable, and the dominant types are:

- starch-based plastics (thermoplastic starch polymers [TPS]),
- cellulose-based plastics (cellophane),
- PHA-based plastics (PHB, poly(hydroxybutyrate-co-hydroxyvalerate) [PHBV]),
- protein-based plastics (Havstad, 2020).

In this section, several biologically based plastics are investigated.

PLA-plastics

Polylactic acid (PLA) is a biobased thermoplastic derived from natural lactic acid that has its origin in plants such as potatoes, maize or rice. Along with the development in production of PLA it is expected

that biomass will be sourced in a wider selection of agricultural by-products. By replacing PS and PET with PLA it can reduce carbon dioxide emission by 75%. It is important to keep in mind that the production process of PLA is more energy consuming and power from non-renewable resources should be avoided. Moreover, biobased feedstock production that is necessary to derivate PLA uses pesticides and fertilizer containing phosphor and nitrogen as well as high consumption of both land and water leads to a worse environmental performance than fossil-based alternatives.(Thompson, 2021)

PLA, like many other thermoplastics, is recyclable without significant quality deterioration, but there is a challenge to separate it from other plastic waste. The presence of different kinds of additives and colors as well as the complexity of the product can significantly reduce the quality of mechanical recycling output. Another disadvantage of mechanical recycling is the risk of hydrolysis occurring that causes deterioration of mechanical properties. Additionally, PLA fulfills EU standard EN 13432 which means that the material is industrially compostable, but it can lead to decreased usage of peat which is not environmentally profitable (Schwarz et al., 2023).

Development and improvement of end-of-life alternatives for PLA are demanded since it is the only way to increase drastically the environmental impact of bioplastics (Schwarz et al., 2023). One of the most promising ways to recycle PLA is to use the new depolymerization technology that can be performed in two ways: recycling to oligomers used in an existing PLA production plant or recycling to lactide which can be used to product PLA or in other applications.

A wide range of properties from stiff and rigid to flexible makes PLA applicable in many areas such as toys, packaging, textiles or stationery. It is possible thanks to combability with thermoplastic processing equipment that makes PLA suitable for injection molding, extrusion, additive manufacturing or fiber drawing. PLA grades that have been developed for packaging industry indicate high stiffness and transparency and can be considered as competitive to polyethylene (PE), polystyrene (PS), polypropylene (PP) and polyethylene terephthalate (PET). Products made of PLA textile fiber such as home textiles or nonwovens are easy to maintain due to their wicking properties and moisture management. In additive manufacturing methods, like fused deposition modelling (FDM) or fused filament modelling (FFF), PLA filament performs as good or even better than acrylonitrile butadiene styrene (ABS) and at the same time does not emit any harmful fumes when melted like ABS does. PLA has a strong ability to visual and physical adjustments thanks to a range of different additives and fillers. For example, if copper powder is added, the produced part acquires higher density and can be additionally polished (Ashby et al., 2014).

However, challenges with biomass production, relatively high price and low melting point can be considered as disadvantageous (Abdelshafy et al., 2023). Nowadays biomass for commercial use is derived from first-generation feedstock (like corn, wheat or sugar beet) which can bring obstacles in the future, particularly in regions where limitations in available land creates competition between food production and first-generation feedstock cultivation. Moreover, the lack of infrastructure for biorefineries in comparison with the well-developed and easy to use infrastructure of petrol industry in Europe makes fossil-based plastics even more attractive.

The general mechanical properties as well as sustainability information of PLA is presented in table 5 and is based on information in GRANTA Edupack (*Ansys GRANTA EDUPACK Software, 2024; Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024*).

Table 5: General properties of PLA-plastic

	PLA
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Price per unit volume (SEK/m³)	3,64e ⁴ - 4,97 e ⁴
Density (kg/m³)	1,2e ³ - 1,29e ³
Tensile strength (MPa)	45 - 72
Young's modulus (GPa)	2,4 - 3,6
Melting point (°C)	135 - 181
CO₂ footprint (kg/kg)	2,15 - 2,4
Recyclability (Yes/No)	Yes
CO₂ footprint, recycling (kg/kg)	0,738 - 0,816
Biodegradable (Yes/No)	Yes
Origin in EU (Yes/no)	Yes

There are many manufacturers of PLA today. A European company producing PLA-plastics is FKUR Kunststoff GmbH. They support a circular economy and have several trademarked bioplastics in their range, containing either 100% or high biologically based content. These can be used for many different applications.

PHA-plastics

One of the main groups of biodegradable, biologically based plastics are polyhydroxyalkanoates, commonly called PHA-plastics. These are biodegradable polyesters that can be synthesized using microorganisms in an environment where there is a scarcity of nutrients but an abundance of carbon sources (Bin Abu Sofian et al., 2024). It is a microbial fermentation process where sugars or oils are utilized by the microorganisms, resulting in polyesters being deposited and later PHA granules can be recovered by disruption of the microbial cells (Jacquel et al., 2008). These materials have similar mechanical and thermal properties to petroleum-based plastics and are therefore a promising and biodegradable alternative to them (Bin Abu Sofian et al., 2024). They are already in use in industries like in the medical sector, due to their biocompatibility. Furthermore, they are used in the agricultural field as biodegradable films and in the fishing industry to make biodegradable fishing nets to reduce plastic pollution in the oceans.

PHA-plastics are made into resins and mainly processed through injection molding and extrusion (Mullins & Mullins, 2023). Pure PHA may not be useful as material in commercial products but when combined with other biodegradable polyesters, like polylactic acid (PLA), or processing aides it can result in better manufacturability for current conversion processes. The proportions of PHA and PLA in the resin depend

on factors like performance, cost, end-of-life desires and other considerations but generally the compounded resin consists of more than 50% PHA. Naturally, biodegradability creates some limitations to the material. Heat above 200°C, or longer exposure to a temperature of 175°C, may result in rapid degradation of biodegradable plastics.

Mullins and Mullins (2023) state several recommendations for PHA-processing as well as for the blends with PHA aimed for reducing resistance times and avoiding degradation in the manufacturing stage. Firstly, it is required to dry PHA to reach a moisture content of 0,04% or less. This is to prevent viscosity degradation during the coming processing. Secondly, it is recommended to purge the equipment with Low-Density Polyethylene (LDPE) to remove any previous materials followed by purging out the LDPE with the PHA. If PHA is left for too long in a heated barrel it can result in degradation and purging is important in order to remove any residual, degraded material for this reason. It is also critical to use a process where the mold is heated to ensure the performance of PHA. By monitoring on the temperature and the residence times in these temperatures as well as maintaining the proper dryness of the material and using a warm tool, the process is not overly complicated.

Production of PHAs can be derived from several biological sources, including algae. Algae is a range of primarily water-dwelling organisms capable of photosynthesis (Ma et al., 2022). They are generally considered to be more efficient photosynthesizers than other plants due to their range of antenna pigtails, enabling them to harvest more solar energy, and also their variation of carbon dioxide-concentrating systems. Algae are accountable for more than 50% of the occurring photosynthesis on earth. There are many different species of algae that can be utilized to make bioplastics and compared to petroleum-based polymers, the algae-based bioplastics have superior strength, durability and pliability (Bin Abu Sofian et al., 2024).

PHA-plastics can be degraded into water and carbon dioxide in only 20 to 45 days in the right conditions (Acharjee et al., 2023). In comparison to traditional plastics, with a life expectancy of 100 to 1000 years, this is a great contrast. To be degraded adequate humidity, oxygen and microbes like bacteria or fungi needs to be present. These conditions can be found in most natural ecosystems.

The dominant limiting factor in the progress of bioplastics like PHAs is the cost of feedstock, which can account for up to 50% of the production cost (Vu et al., 2020). While the fermentation process has been optimized and advancements in metabolic and genetic engineering has made bacterial strains more efficient in their utilization process, the high price of carbon sources that are needed is the main constraint (Surendran et al., 2020). As a result, carbon substrates that are renewable as well as cheap are being investigated further around the world. Examples of cheap carbon sources that have been proven excellent to use in this field is animal- and plant oils. One example of this is volatile fatty acids (VFAs), which can be derived from acidogenic fermented organic waste, which is being investigated as an economically feasible carbon feedstock. By using previously used oils or oils that come from oil mill waste streams the price can be decreased even more. Furthermore, it significantly reduces the environmental pollution caused by these oils.

A locally sourced PHA-based material is Proganic, produced by the German company Präpper GmbH (Carus, 2010). This material is made from PHA, which in turn is produced by starch or sugar bacteria, together with carnauba wax and natural mineral filler. The material has its applications in plant pots, toys, eggcups and spoons among others. Proganic won first place as “Bio-based Material of the Year” at the HANNOVER MESSE 2010 because of its biological nature and its ability to be used in consumer goods.

Proganic is biodegradable, heat stable in temperatures up to 100 °C, resilient to water and CO₂ neutral (Proganic® - Proganic, n.d.).

The general mechanical properties as well as sustainability information of PHA is presented in table 6 (Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024).

Table 6: General properties of PHA-plastics

	PHA
Price per unit volume (SEK/m³)	4,71e ⁴ - 6,25e ⁴
Density (kg/m³)	1,23e ³ - 1,25e ³
Tensile strength (MPa)	35-40
Young's modulus (GPa)	3,5-4
Melting point (°C)	171- 182
CO₂ footprint (kg/kg)	0,86 - 0,94
Recyclability (Yes/No)	Yes
CO₂ footprint, recycling (kg/kg)	0,292 - 0,32
Biodegradable (Yes/No)	Yes
Origin in EU (Yes/no)	Yes

One example of a company that creates algae-based plastics, however it is unclear if this is PLA, PHA or another type of plastic, and is trying to upscale its production, is Dansk algeplast. This company uses Danish types of algae and its carbon capture potential to create water dissolvable and compostable plastics (Dansk Alge Plast – Laver Co2 Negativ Alge Plastic, Imens vi Renser Havet, n.d.). The company mainly produces hard plastic, offering plastics with up to twice the strength of synthetic alternatives like PE and PVC, but also have textile materials and thin plastic film that can be used for plastic bags. Since this would be a local alternative, the company, along with others, should be evaluated further to see if the materials are well-suited for the indoor lighting industry.

Bio-based PVC

Polyvinyl chloride (PVC) is naturally transparent, stiff, rigid and amorphous plastic that can be combined with plasticizers to increase its flexibility and expands material's area of application. Rigid PVC is

commonly used in packaging industry while the flexible version appears in chemical resistant gloves for instance. The main manufacturing methods for PVC are dip molding, rotation molding, welding or inflating. These methods allow production of flexible and versatile parts that are colorable due to PVC's characteristics, while keeping the production cost relatively low. PVC itself is recyclable but vinyl chloride (VC) – the main ingredient or a range of other ingredients that it can be mixed with such as stabilizers or plasticizers may produce dioxins, phthalates and cadmium that are harmful to people. In addition, PVC waste may be hard to distinguish from other plastics which is the reason why it may be inefficient to recycle (Rob Thompson, 2021).

Luckily, there are more sustainable alternatives to traditional PVC where chlorine and ethene are sourced from bio-based or renewable sources instead of fossil fuels. World's first commercially used bio-PVC is Biovyn manufactured in Germany by INOVYN where ethylene is derived from wood-based residue from the forestry industry (*BIO-SOURCING | BIOVYN*, n.d.). The supply chain is fully certified by The Roundtable on Sustainable Biomaterials (RSB) and guarantees biomass coming from sustainable forests that do not compete with the food chain (*Inovyn Launches Biovyn-World's First Bio-Attributed PVC.: EBSCOhost*, n.d.). Replacing PVC with its bio-based alternative can also reduce carbon footprint by more than 90% while keeping the exact same properties as the conventional PVC.

GRANTA Edupack provided more detailed information on PVC (*Ansys GRANTA EDUPACK Software, ANSYS, Inc.*, 2024). This is presented below in table 7.

Table 7: Properties of Bio-PVC

	Bio-PVC
Price per unit volume (SEK/m³)	?
Density (kg/m³)	1,08e ³ - 1,12e ³
Tensile strength (MPa)	7,43 - 9,25
Young's modulus (GPa)	6,01e ⁴ - 9,38e ⁴
Melting point (°C)	158 - 169
CO₂ footprint (kg/kg)	?
Recyclability (Yes/No)	Yes
CO₂ footprint, recycling (kg/kg)	?
Biodegradable (Yes/No)	?
Origin in EU (Yes/no)	Yes

Bio-based ABS

One of the most used polymers in design and interior industry is Acrylonitrile Butadiene Styrene (ABS) mainly thanks to its wide colour range and superior aesthetics. ABS is also known for its durability and toughness that have been proven in many iconic products such as Lego bricks or Stelton vacuum jug. Relatively low cost allows to replace polycarbonate (PC) or polyamide (PA) with ABS and to make the material cost around one-third lower. Moreover, transparent grades of ABS are easy to color in a wide range from tinted to solid colours that resist ultra-violet light and tough weather conditions. The visual effect can be uplifted while metal-effect pigments, dye systems or even conventional pigments are added in different proportions and saturations.

ABS parts are usually manufactured by injection moulding and extruding and can be reinforced with the addition of glass fibre or mineral fill or mixed with PA and PC to improve durability and aesthetics (Thompson, 2021). When blended with PA the received product improves its strength at high and low temperatures as well as shrinkage may be reduced in comparison to the traditional PA. Mixing with PC offers a cheaper alternative for producing parts that require high stiffness and high-temperature resistance.

There are several sustainability issues connected to ABS even if this plastic itself considers to be fully recyclable. Very common and wide use of this polymer has led to huge number of varying levels, colours and classes that should not be mixed in recycling process if the high quality is expected to maintain. An additional issue with ABS recycling is the same as with the other polymers: it is hardly separated from mixed waste streams. The most effective and common way to reuse ABS is to collect and reprocess industrial scrap along with virgin material. Another reason why ABS should not be considered as environment friendly is that it is manufactured from non-renewable and fossil fuels and may contain poisonous and polluting acrylonitrile.

Unfortunately, finding a bio-based alternative for ABS is challenging. One of those resins that are available on the market have succeed replacing fossil ingredients with their bio-based equivalents in up to 80% and reduced ABS carbon footprint in up to 57% (Trinseo | MAGNUMTM CO2NETTM BIO ABS Resins, n.d.). There is also a solution for reducing carbon footprint drastically while keeping all the advantages of ingredients coming from non-renewable resources. Terluran R ECO “MR” produced by Ineos contains respectively 50% and 70% post-consumer mechanically recycled content and it is available only in black. The most successful attempt to produce bio-ABS yet is Terluran ECO GP-22 BC100 launched in March 2024 which is said to be fully plant-based, complies with ISCC certification and is recommended for wide range of applications such as construction, household or electronics (*Terluran® ECO - Styrolution® ECO*, n.d.). After being in contact with the company, this seems to be an exaggerated claim, where the material is not entirely plant-based and only considered to be bio-attributed, thus not entirely bio-based.

Details about the mechanical properties of bio-ABS are based on regular ABS in GRANTA Edupack (*Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024*). This is because the consensus is that the bio-based ABS generally has the same mechanical properties as regular ABS. The general information is presented in table 8.

Table 8: Properties of bio-ABS

	Bio-ABS
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Price per unit volume (SEK/m³)	?
Density (kg/m³)	1,03e ³ - 1,06e ³
Tensile strength (MPa)	37,9 - 51,7
Young's modulus (GPa)	2,07 - 2,76
Melting point (°C)	159 - 274
CO₂ footprint (kg/kg)	?
Recyclability (Yes/No)	Yes
CO₂ footprint, recycling (kg/kg)	?
Biodegradable (Yes/No)	?
Origin in EU (Yes/no)	Yes

Biodolomer® I 900236

Biodolomer® I is a completely new polymer based on PBAT, PLA, talc and calcium carbonate developed by Gaia Biomaterials in Helsingborg, Sweden and can be injection molded or processed through additive manufacturing processes (*Biodolomer I Product Information*, 2024). This material can be used in a wide range of application from food packaging and shopping bags through healthcare products to toys and diapers due to its excellent properties such as optimum balance of rigidity and toughness as well as increased flowability.

A colossal advantage of Biodolomer® I is its high sustainability, decreasing the carbon emission of a produced part by up to 80% compared to traditional plastics. It also possesses certified industrial compostability according to the European standard EN 13442. Extraction and production of PLA and PBAT are the main factors of the materials' environmental impact in the material production phase. If the functional requirement of a product allows an increase in the share of PLA over PBAT or the biogenic share of PBAT, it can reduce the environmental impact additionally. Moreover, applying the Biodolomer® I offer a number of various end-of-life disposal options, for example energy recovery, material recycling or biological treatment (*Comparative LCA of Various Meat Tray Alternatives*, n.d.).

However, since Biodolomer is a compostable material, it is a remaining question how long the product is expected to be functional. The producer of the material offers help with adjusting the durability, but it is important to consider that the environmental aspects such as air humidity or exposition for sun light can

influence the degradation process, and therefore also the lifecycle length. The known information about Biodolomer I is presented below in table 9.

Table 9: Properties of Biodolomer

	Biodolomer I
Price per unit volume (SEK/m³)	?
Density (kg/m³)	1,3e3
Tensile strength (MPa)	400
Young's modulus (GPa)	2,022
Melting point (°C)	170 - 210
CO₂ footprint (kg/kg)	?
Recyclability (Yes/No)	No
CO₂ footprint, recycling (kg/kg)	0
Biodegradable (Yes/No)	Yes (+ compostable)
Origin in EU (Yes/no)	Yes

2.2.3 Recycled and Ocean-bound Plastics

Historically, synthetic plastics have not been used for a long period of time, however, the industry is only expanding. This has created issues connected to plastic litter, and there are many reasons why an effort should be made to recycle our current plastics as well as reclaim the litter. There are environmental benefits since synthetic plastic production relies on fossil fuels and emits harmful greenhouse gases. By recycling, its energy consumption is reduced, and the pollution of land and sea is decreased, even more so if reclaimed plastics from the nature can be included. It can also alleviate pressure on ecosystems and natural resources. Additionally, there are economic advantages to utilize recycled plastic by reducing reliance on unpredictable fossil fuel markets. It also fosters a circular economy where waste is an important resource and reflects a commitment to social responsibility. Due to these reasons, the ability to use recycled and/or reclaimed plastics was a natural step in the process of investigating more sustainable materials.

Recycled low-density polyethylene

Low-density polyethylene (LDPE) is one of the most used polymers characterized by its low cost and lightweight which makes it perfect for usage in packaging industry. The main resources of the recycled (rLDPE) are mostly material recovery facilities that provides usually material in a form of flexible film that can be shredded and densified to feed into an extruder for pelletizing (Gao et al., 2023).

However, rLDPE has its disadvantages when it comes to application in injection molding processes. High viscosity leads to higher energy consumption because high pressure and temperature are required which increases maintenance costs due to wear damage of the cavity surface. Both size and complexity of the produced part can additionally increase energy consumption and limit the already poor potential of rLDPE upcycling applications. (Gao et al., 2023)

A solution for that problem might be decreasing complex viscosity by ultrahigh speed extrusion of film-grade rLDPE (at least 2000 rpm) and making it relevant for injection moulding even into thin-walled parts. Lower viscosity and lower melting temperature leads also to lower energy consumption in comparison to both virgin LDPE and rLDPE. Usage of modified, recycled low-density polyethylene can reduce total embodied energy with 54% and save 6 kg of CO₂ for each kg of injection moulded product. (Gao et al., 2023)

The properties of recycled LDPE are presented in table 10 and are based on information from GRANTA Edupack (*Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024*).

Table 10: Properties of recycled LDPE

	RC LDPE
Price per unit volume (SEK/m³)	18,3 - 20,3
Density (kg/m³)	917 - 932
Tensile strength (MPa)	13,3 - 26,4
Young's modulus (GPa)	0,172-0,283
Melting point (°C)	98-115
CO₂ footprint (kg/kg)	1,94-2,15
Recyclability (Yes/No)	Yes
CO₂ footprint, recycling (kg/kg)	0,673 - 0,745
Biodegradable (Yes/No)	No
Origin in EU (Yes/no)	?

Using reclaimed or ocean-bound plastics from the oceans

Another alternative is to use ocean-bound plastics. These are waste that is thought to be bound to end up in the ocean if not collected or has already ended up in oceans/water streams and can be reintroduced into the industry and be a part of a more circular society in the future. There are several companies selling these kinds of ocean-bound plastics. One example is the Canadian company Oceanworks which offers help for companies to measure their plastic footprint and identify how to take action and reduce their waste (*Oceanworks | Recycled Plastic Solutions | Ocean Plastic Marketplace*, n.d.). They also offer a network of traceable, reclaimed plastic suppliers and manufacturers which can be used to buy material, meaning that although the company itself was founded in Canada, their network includes suppliers all around the world including USA, Europe and parts of Asia. This provides an opportunity to use locally sourced plastic, reintroduce used plastic into a circular society where plastic must be better taken care of than before while also reducing plastic pollution in the environment.

Oceanworks offers PCR-resins in several types of plastics, including examples like PET, high-density and low-density polyethylene, polypropylene and polyamide (*Oceanworks | Recycled Plastic Solutions | Ocean Plastic Marketplace*, n.d.). They can also provide customized solutions if customers have special requirements for the material. Most of the resins can be processed with injection molding and are designed to mimic virgin resins by going through granular feedstock sorting, strict quality controls to ensure repeatable quality. The resins are high in purity, scalable, cost competitive and have reliable technical properties that are processable. The resins are available in several colors, making more specific design choices possible. It is also possible to get samples rapidly and in quite small quantities, as small as 10kg increments. In conclusion, Oceanworks and reclaimed plastics can be an opportunity to help clean up the environment simultaneously as making high-quality products.

There is limited information about each specific type of plastic resins they offer at Oceanworks. One of the plastics offered is a polycarbonate (PC) named OR.212871. This plastic should be able to be both injection molded and extruded. It is offered in a blue color. More detailed mechanical properties on this specific material is presented below in table 11, with information from the datasheet Oceanworks provides on their webpage (Oceanworks, 2024) as well as the GRANTA Edupack page on PC (*Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024*). There are several variants on PC on GRANTA Edupack, and the one closest to the known information of Oceanworks plastic was chosen for the most accurate information.

Table 11: Properties of ocean-bound PC

	Ocean-bound plastic (PC)
Price per unit volume (SEK/m ³)	?
Density (kg/m ³)	1,2e ³
Tensile strength (MPa)	50
Young's modulus (GPa)	2,32 - 2,44

Melting point (°C)	205-298
CO₂ footprint (kg/kg)	5,6-6,18
Recyclability (Yes/No)	Yes
CO₂ footprint, recycling (kg/kg)	1,91-2,11
Biodegradable (Yes/No)	No
Origin in EU (Yes/no)	?

2.2.4 Fiber-Based Plastic Composites

A composite material is where two or more materials are combined to acquire a new combination of properties (Kim & Pal, 2011). In contrast to regular composites where the different elements are inseparable, the elements in fiber-reinforced composites are distinguishable at a molecular level and can be mechanically separated. They work conjointly in the composite and improve the properties in comparison to the constituents alone. Fiber-based composites can be found in nature, as plants and wood for example, or they can be made artificially.

There are different kind of fibres that may be chosen to create a composite with depending on the application, strength and environment where the product will be used (Beckman et al., 2021). For example, if the design requires higher stiffness while remaining flexible then reinforcement with glass fibres and basalt fibres are suitable. If the printed part will be used in humid environments, it is recommended to avoid hydrophilic fibers such as natural cellulose and keratin.

Today, composites are usually made of fossil-based plastics that should be phased out in the nearest future and replaced with bio-based alternatives. High stiffness and strength and low weight of composites makes this type of material applicable even in very demanding conditions such as wind turbines, aircraft industry or protective equipment (*Materialutveckling För Fiberkompositier | RISE*, n.d.). However, complexity and combination with other materials create mixed waste streams which makes it challenging to recycle composites and leads to the situation where the first generation of composite products ends up as a landfill (Van Oudheusden, n.d.).

Textile-based composites

Textile industry is responsible for 20% of the global pollution having a destructive impact on the environment during the whole lifecycle of a textile product (Patti et al., 2020). Fabrics are all around us finding its application from fashion industry, through transport and interior design industries to the constructions fields where they are used as reinforcement elements. Significant amounts of toxic and harmful chemicals being released into nature as well as growing amounts of disposals are the reasons why

decreasing textile waste and upcycling the already existing material is essential.

The most common fibres in the textile industry nowadays are polyester and cotton. Polyester fibres are produced by a chemical reaction involving fossils such as coal or petroleum making this material highly unsustainable for environment (Beckman et al., 2021). However, polyester is easy to recycle by being a thermoplastic polymer that melts in temperature between 245 and 260 C. Cotton is a plant-based fibre made in 95% to 99% of cellulose, long-chained carbohydrate molecules. Main disadvantages of this material are connected to the fact that the industrial produced cotton requires pesticides, fertilizer and water that stand for almost 10% of global agrochemical consumption (Rob Thompson, 2021).

The possible ways of reusing the textile waste are to use various fibres as an ingredient in production of reinforced composites such as thermoplastics, concrete or thermosetting or to transform post-consumer textile nylon into a useful feedstock for extrusion additive manufacturing. Unfortunately, recycling of post-consumer textile clothing is very limited while the polymer has not been designed for upcycling or even recycling (Strano et al., 2023).

Fiber-reinforced polymer composites (FRPC) perform excellent properties such as high stiffness and strength making them attractive for various applications in industry (Wong et al., 2023). There are several additive manufacturing (AM) methods such as material extrusion, vat photopolymerization or Automated Fiber Placement (APM) where the FRPC can be used depending on the complexity and physical properties of the manufactured part. Moreover, in comparison with traditional manufacturing methods, additive manufacturing brings a plenty of benefits: it does not require that much toxic chemicals and reduces time-to-market which makes it easier to do modifications in design (Beckman et al., 2021).

Wood-plastic composites (WPC)

Composites made of wood and plastic, or WPC as they are commonly abbreviated as, are composites made from either virgin, recycled or waste plastic and wood (Kim & Pal, 2011). They can be used in a range of industries, like in outdoor deck floors, park benches and indoor furniture and are claimed to be more environmentally friendly as well as require less maintenance than solid wood (with preservatives).

The Swedish company Biofiber Tech Sweden AB has developed FibraQ, modified wood fibers that, depending on requirements from customers, can be mixed with either virgin or recycled plastic as well as other bioplastics to form a sustainable and functional compound (*Sustainable Plastic | Fibra Q | Sweden*, n.d.). The innovation is the technology itself making wood fibers more compatible with plastics. The company uses wood from Swedish, sustainably managed forests and can be considered carbon negative due to tree's ability to store carbon dioxide throughout its lifetime.

The compound can be used in several processing methods including 3D-printing, extrusion, injection molding and thermoforming (*Sustainable Plastic | Fibra Q | Sweden*, n.d.). The production is highly scalable due to the ability to use infrastructure of existing producers of wood fiber and paper. Biofiber Tech offers FibraQ combined with plastics like PP/PE, ABS, TPE, 100% bio-compounds or they can be further customized to meet special requirements and sustainability goals. During processing, masterbatches can be added to give the product different colors, and some of them can be coated, printed or painted. A common challenge with composites is how to recycle them and separate the different

elements. FibraQ compounds can be mechanically recycled and are claimed to be separable through several processes, including density-based and NIR-based methods.

2.3 Impacting Factors in a Product's Sustainability

Many factors play a part in evaluating a product's sustainability and environmental impact and many have already been mentioned in this thesis. In production, the energy mix of the country the production is located in impacts the overall sustainability. The choice of process as well as additives and fillers also impact the sustainability of materials, which was stated in the chapter about polymers and fiber reinforcements.

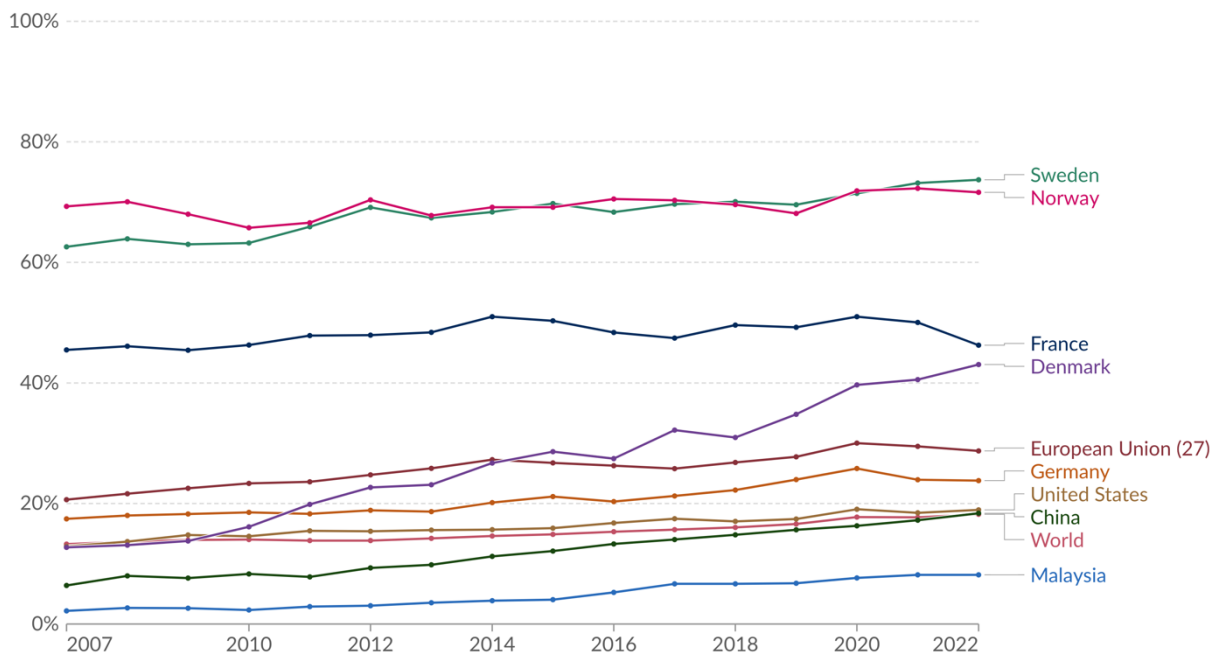
2.3.1 Energy Mix

One of the key aspects that can influence the ecological sustainability of a product (or material) is where its production is located. This is due to the differences in the energy mix of different countries. Whether it is mining or extracting of raw materials, production or usage of an electrical product electricity is required. Electricity and heat can be produced from fossil fuels like oil, coal and gas, nuclear energy or renewables such as hydropower, wind, solar, bioenergy to name a few (Ritchie et al., 2024). The energy production does not only account for about three-quarters of the world's greenhouse gas emissions, being the largest contributor to climate change but is also harmful to human and animal health by polluting the air. To decrease the negative impact from energy consumption the world should shift away from high-carbon sources (fossil fuels) to low-carbon sources like nuclear energy and renewables.

Every country is responsible for their own energy and what sources they use. It can be produced by the country itself or be bought from other countries, most commonly both, in varying proportions. Because of this, the mix can be vastly different from country to country, with some having a "cleaner" energy (meaning that the energy is produced from a higher proportion of low-carbon sources) than others. The energy mix in the specific country where production or use is, is crucial when determining a product's impact on the environment. Below, the share of primary energy consumption from low-carbon sources is presented in a chart by country or region in figure 2. These countries/regions were selected based on relevancy for the thesis and for comparison purposes. The chart was made based on information from the Energy institute – Statistical Review of World Energy from 2023 and collected on the website Our World in Data (Ritchie et al., 2024).

Share of primary energy consumption from low-carbon sources

Measured as a percentage of primary energy¹ using the substitution method². Low-carbon energy is defined as the sum of nuclear and renewable sources.



Data source: Energy Institute - Statistical Review of World Energy (2023)

OurWorldInData.org/energy | CC BY

Note: Renewables include hydropower, solar, wind, geothermal, wave, tidal, and bioenergy, but not traditional biofuels.

1. Primary energy: Primary energy is the energy available as resources – such as the fuels burnt in power plants – before it has been transformed. This relates to the coal before it has been burned, the uranium, or the barrels of oil. Primary energy includes energy that the end user needs, in the form of electricity, transport and heating, plus inefficiencies and energy that is lost when raw resources are transformed into a usable form. You can read more on the different ways of measuring energy in our article.

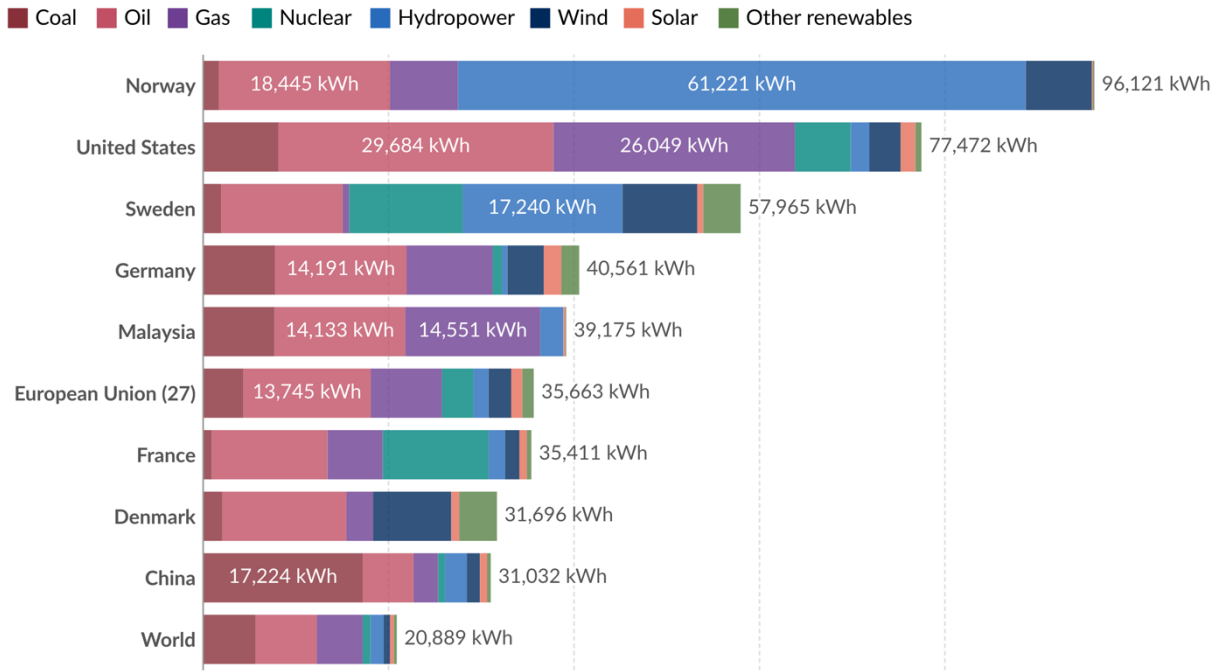
2. Substitution method: The 'substitution method' is used by researchers to correct primary energy consumption for efficiency losses experienced by fossil fuels. It tries to adjust non-fossil energy sources to the inputs that would be needed if it was generated from fossil fuels. It assumes that wind and solar electricity is as inefficient as coal or gas. To do this, energy generation from non-fossil sources are divided by a standard 'thermal efficiency factor' – typically around 0.4. Nuclear power is also adjusted despite it also experiencing thermal losses in a power plant. Since it's reported in terms of electricity output, we need to do this adjustment to calculate its equivalent input value. You can read more about this adjustment in our article.

Figure 2: Chart on share of primary energy consumption from low-carbon sources in several countries or regions.

Below (in figure 3), per capita primary energy consumption by source is presented for the same countries and regions, also based on information from the Energy institute – Statistical Review of World Energy from 2023 (Ritchie et al., 2024).

Per capita primary energy consumption by source, 2022

Primary energy¹ is measured in kilowatt-hours² per person, using the substitution method³.



Data source: Energy Institute - Statistical Review of World Energy (2023); Population based on various sources (2023) OurWorldInData.org/energy-mix | CC BY

- 1. Primary energy:** Primary energy is the energy available as resources – such as the fuels burnt in power plants – before it has been transformed. This relates to the coal before it has been burned, the uranium, or the barrels of oil. Primary energy includes energy that the end user needs, in the form of electricity, transport and heating, plus inefficiencies and energy that is lost when raw resources are transformed into a usable form. You can read more on the different ways of measuring energy in our article.
- 2. Watt-hour:** A watt-hour is the energy delivered by one watt of power for one hour. Since one watt is equivalent to one Joule per second, a watt-hour is equivalent to 3600 Joules of energy. Metric prefixes are used for multiples of the unit, usually: - kilowatt-hours (kWh), or a thousand watt-hours. - Megawatt-hours (MWh), or a million watt-hours. - Gigawatt-hours (GWh), or a billion watt-hours. - Terawatt-hours (TWh), or a trillion watt-hours.
- 3. Substitution method:** The 'substitution method' is used by researchers to correct primary energy consumption for efficiency losses experienced by fossil fuels. It tries to adjust non-fossil energy sources to the inputs that would be needed if it was generated from fossil fuels. It assumes that wind and solar electricity is as inefficient as coal or gas. To do this, energy generation from non-fossil sources are divided by a standard 'thermal efficiency factor' – typically around 0.4 Nuclear power is also adjusted despite it also experiencing thermal losses in a power plant. Since it's reported in terms of electricity output, we need to do this adjustment to calculate its equivalent input value. You can read more about this adjustment in our article.

Figure 3: Per capita energy consumption by source as of 2022 of selected countries and regions.

2.4 Design for Sustainability

When designing and developing products it should be formed for a circular economy. That includes designing for a long lifecycle, designing for life extension, designing for product care and other adaptations. Products with a long lifecycle are better for the environment since they save energy consumption by limiting manufacturing of new products in addition to saving resources.

2.4.1 Adaptive Design and Managing Future Uncertainties

A circular business model will not work if products need to be switched out while still functioning because of updates or trends. Therefore, design which enables products to extend their life and adapt to changes in society is essential. This poses many challenges, one of them being how products can retain their perceived economic value over their lifetime, something they often fail to do when the user stops perceiving it as meaningful or useful (Nyström et al., 2021). This is often referred to as premature obsolescence and can be avoided to an extent by the company investing in design or manufacturing to make more durable products.

To face the challenge of creating long-lasting products, the designs in the development stage should be easily adjustable to increase the production efficiency (Nyström et al., 2021). The final product should be adaptable which can be done through considering following aspects:

- The product's flexibility: Does the product have more than one function without significant alterations having to be made?
- The modularity: Does the product possess a segregated architecture, allowing components and parts to easily detach and be replaced?
- The upgradability: Is the product changeable to achieve upgraded properties like better performance or to meet new needs?

It is argued that by creating products with an adaptive design it can be economically beneficial for both customers and the company (Nyström et al., 2021). Money can be saved by the customer by avoiding buying new products while the company saves production costs by not producing as many new products. The company may also meet the customer's initial needs in a better way, perhaps even more or different needs than before, through the product's customization ability. It is also environmentally beneficial to be able to repair products by replacing modules or components rather than producing a whole new product. However, this type of investment is a risk for the company as well. Additional costs may be required if more sustainable, and often more expensive, materials are used or if production processes are added or changed. There is a risk of not recovering these additional costs if hard-to-predict changes happen in the future. This can be societal trends or legal conditions changing as well as developments in technology emerging making the product obsolete. It is also necessary to assess the product design and production processes, which adds to the costs.

Studies show that product durability rarely is the reason for the discarding of products, rather it is new legalizations, changes in user behavior or preference, and product aesthetic that are the main causes (Nyström et al., 2021). Although the product may still fulfill its purpose, or can with minor repairs, it is still perceived by the user as undesirable. Two main approaches to future uncertainties can be distinguished: preventative and curative actions. Preventative actions, aiming to prevent premature product obsolescence, are made in the design stage by constructing the product to allow expansion or modification beyond the original specifications. Curative actions are taken in the use phase by continuing to support the product during its lifecycle with promotions of processes and technology.

2.4.2 Product Care

While adaptable design can make a great difference for the product's sustainability and in prolonging its lifecycle, some responsibility lies on the consumer to take good care of the product in its use stage. Sustainable consumer behavior can, however, be facilitated by its design.

Product care are the activities the consumer carries out with the aim to extend a product's lifecycle (Ackermann et al., 2021). Examples of this can be maintenance, repairs and preventative measures. It can also include a generally careful handling of products. Product care is an essential part of addressing environmental issues and supports the circular economy concept where the "power of the inner circle" is a key aspect, arguing that the greatest portion of savings can be gained by the inner loops. The inner loops refer to lengthening the first lifecycle of a product and because of its great impact, these are preferred over the outer loops, like refurbishing and recycling. When studied, the amount of product care that consumers perform has been found to be dependent on product attributes (such as its price, material and how easy it is to repair), consumer characteristics (like skills and repair knowledge) as well as the extent of emotional bond between the user and the product.

The product attribute playing the most important role in the likeliness of product care being performed is its initial pricing (Ackermann et al., 2021). A low initial price results in people not taking care of the product, while an expensive product, like a car which often is a large investment, promotes product care. The same behavior can be seen when the perceived value, either emotional, functional or aesthetic, is low. Efforts in making high-value products should be made to lengthen the product's lifecycle and postpone replacement. Designers can accomplish this by using materials that age gracefully or by promoting product care, ensuring that a high aesthetic and functional value can be maintained. The accessibility of parts that need care also increases the likelihood of product care. This can be done through incorporating easy maintenance and repairs in the design by, for example, avoiding narrow holes or slits and using parts that have easily available spares. Fostering for product care can result in higher customer loyalty for the brand, which in turn increases the probability of future purchases. Furthermore, there is a growing environmental awareness among consumers, leading to a high demand for sustainable manufacturers and products.

There are many positive aspects with the luminaire Bumling when its design is evaluated according to sustainability. Pricing is high, encouraging product care and long use of the product. The design is robust and timeless, minimizing the risk of consumers becoming tired of the product and wanting to replace it because of this. The current luminaire material aluminum is a metal which has a long lifecycle and ages well without any major visual changes for many years, especially not for a product like a pendant luminaire which is not made for being "physically used". This product will most likely hang from the ceiling with users only physically interacting with the on and off button or once the LED lamp is replaced. In the search for alternative materials, it is crucial to take aspects like visual aging and easy product care into account in order to maximize its lifecycle. Atelié Lyktan rarely sells single products to private customers, and more often to companies in larger batches. They are often placed in more public environments like offices, schools and hotels. Therefore, the emotional bonds to the products may not be relevant in most cases, however, easy product care and a long lifecycle is, and should be considered. The product Bumling is one of the products that are sold to private customers, and in this specific case it may be relevant to consider as well.

3. Methodology and Implementation

This thesis follows a typical material selection process including numerous methods, such as creation of a requirement specification, an eco-audit, extensive research in different literary sources, screening and ranking among others. In the following chapter the methods, their purpose as well as their implementations are described. The results and takeaways are presented in the chapters “Result” and “Evaluation Results”.

3.1 Material Selection Process

A material selection process can be implemented through a strategy consisting of four steps: translation, screening, ranking and implementation. In the first step, translation, the task is to convert the design requirements into a list constraints, objectives and free variables the potential material must fulfill. In the screening stage those materials that cannot meet the constraints can be eliminated and the remaining materials are then ranked according to how good they meet the requirements during the next stage. Finally, additional research of top-ranked candidates can be proceeded at the documentation step to choose the best material and analyze how to adjust the production method and design to exploit its potential.

3.2 Stating the Requirements

When a product is created it is essential to understand what functions it should have in order to solve the main problem it was created for. A specification of requirements was made for Bumling to understand and structure the requirements for a product in the indoor lighting industry. The requirement specification was based on the research of the product Bumling (presented in 1.1 Background) as well as the aim of the thesis. This step is a part of the initial product analysis to accurately search for suitable materials for the future.

The requirements were also presented as lists of objectives and constraints which subsequently were a significant part of the evaluation process, where screening and ranking was performed. In that process several material alternatives were narrowed down into only the most suitable options for indoor lighting. It is important that the final material/-s meet the requirements.

3.3 Creating a Bill of Materials (BOM)

To analyze the product Bumling further, a bill of materials what created. The functionality of these is to structure the known information, like materials, processes and masses, that describes the different components of the product.

The bill was created, stating material, mass, processing methods (primary and secondary), length and end of life. The information about the components has been provided by ateljé Lyktan. Only the most relevant components for the thesis were included in the bill, resulting in three components: the shade, the circular louvers and the upper diffuser. This information was significant in the next phase of the product analysis.

3.4 Lifecycle Analysis in GRANTA Edupack – Eco-Audit Tool

GRANTA Edupack is a software with several helpful functionalities and tools for engineers and designers. It contains, among other things, material databases, different ways of comparing materials based on selected parameters including making charts, and a tool for performing an analysis of products' environmental impact (*Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024*). The environmental impact tool is called eco-audit and was used in the thesis to analyze the current impact of Bumling.

The eco-audit tool is a very practical tool for environmental analyses because of the many aspects it considers, and by executing the calculations, saving time compared to if this was to be done manually. In the eco-audit a large amount of information is required. Firstly, the components are listed combined with the exact material as well as the mass and primary (and secondary if there is one) manufacturing processes of these. Here, it is also listed how much of the materials are currently being recycled, downcycled or ending up in landfills. Secondly, the transport is calculated by entering the estimated distances the materials and components are being transported, from raw material to the ateljé Lyktan's head office where it is bought. It is also entered with what kind of vehicle it is transported for even more accurate calculations. Lastly, the place of use is entered to calculate the environmental impact of the use phase of the product. Here, the local electricity mix is considered.

The bill of materials was used as a foundation for making the eco-audit, meaning that the analysis was not made on the entirety of Bumling but only the relevant parts for the thesis. The information entered in the eco-audit was based on the information from ateljé Lyktan on what processes and materials they used as well as their thoughts on the current end-of-life potential.

3.5 Literature Research

Most of the report consists of research through different literary sources and databases. It is based on a methodological framework centered on source criticism which is critical for ensuring the integrity, reliability and scholarly rigor of the study's findings. In the following section, the methodology and procedure governing the search, the selection, evaluation and integration of sources is described.

3.5.1 Search Strategy

Firstly, a carefully crafted search strategy was devised to systematically explore and identify sources relevant to the investigation. By leveraging both contemporary and traditional repositories, such as specialized journals, academic databases, reputable industry publications, websites of manufacturers and other online platforms a comprehensive coverage of both the scholarly and the practical landscape surrounding the subject was concluded.

3.5.2 Criteria for Source Selection and Evaluation of Sources

Secondly, the source selection was guided by a set of criteria with the aim of guaranteeing their relevance and credibility. The selected sources underwent a critical appraisal based on the CRAAP-test to evaluate its robustness, evidentiary basis and interpretive validity before using its information. CRAAP stands for Currency, Relevance, Authority, Accuracy and Purpose which are all factors to consider in order to argue that a source is trustworthy (*The CRAAP Test - Evaluating Sources - Research Guides at Benedictine University Library, 2024*). Some factors that have been considered in the selection and evaluation process are:

- the authority of the publication outlet
- the residency of the information
- the expertise and reputation of the authors
- the information's alignment with the research objectives
- the year of publication

Sources meeting these standards were considered suitable for inclusion in the analysis. Occasionally, although these criteria were considered, a source can be relevant without, for example, being the most recent source. These were evaluated separately depending on what kind of information was retrieved from the source. Particularly, attention was paid to check the research methodology employed of the source, the objectivity of interpretations and the potential conflicts of interest or biases.

The insights gathered from the various sources formed a base for the outcome of the thesis. By combining theoretical ideas, real-world data and knowledge from the industry, a thorough understanding of several interesting materials to produce indoor lighting luminaires has been acquired. This resulted in new insights and ideas, contributing to the ongoing investigation into how to develop products in this field to be relevant in a future, more circular society. Since material science is constantly expanding it was important to control if the source was up to date when searching for information in this field. This factor was exceptionally relevant when the range of bio-based polymers was explored due to rapid development of this branch of materials.

3.6 Screening of Materials

After the process of searching for materials, they needed to be narrowed down into one or two final, most promising choices. This process was done by screening out materials that do not meet the requirements, and then ranking the remaining materials (Ashby et al., 2014). It was decided that the materials will be evaluated excluding the composites with fiber reinforcements since these can be made in large range of variations. Instead, the metals and polymers were evaluated first, and the different fiber-reinforcement, and how they can be combined with the suitable materials, were evaluated in a second phase of the evaluation process.

The screening process can be done with several methods, but all of them are different ways of systematically evaluating and comparing materials (Jahan et al., 2010). The methods that have been used in the thesis are the chart-method and the questionnaire method.

3.6.1 Chart-method

The chart-method is where charts are made to present the data and how the alternatives relate to each other in a clear fashion (Jahan et al., 2010). The method is useful in the early stages of screening by being a fast, systematic and unbiased way of analyzing. Although it does have its limitations by only considering two or three criteria. The chart in this thesis was made using embodied energy as a key aspect since it is a calculation of all energy that was needed in its production, including mining, manufacturing and transport. On the other axis carbon dioxide footprint was used. The charts were made in the software GRANTA Edupack and are presented in the chapter "Evaluation Results".

3.6.2 Questionnaire Method

Another method appropriate to proceed while screening materials is the questionnaire method that can be particularly useful while confronting the materials with unmeasurable requirements. This method concludes by asking a list of questions in order to ensure that an optimal solution is found (Jahan et al., 2010). The questions should include essential points to consider in the evaluation. Performance requirements can be classified into two groups: rigid (go-no-go) requirements, which are used for initial selection and for eliminating unsuitable options, and more soft, relative requirements that can be negotiated. Questions together with the goal for considering this question are presented in appendix 1. The results are presented in chapter “Evaluation Results”.

3.7 Ranking Materials

After screening and narrowing the possible materials down, the ranking process began. By ordering the remaining alternatives from the screening by their ability to meet the most essential criteria the most promising ones can be selected (Ashby et al., 2014). In this thesis, the crucial criterion is for the material to be sustainable. A great amount of information needs to be considered to determine the most suitable material since sustainability is not only carbon dioxide footprint. Aspects like toxicity, water usage, and lifecycle length should be factored in as well. Multi-criteria decision-making (MCDM) methods and other optimization methods can be used in order to rank the remaining materials (Jahan et al., 2010). When deciding between two or more materials for an engineering design, it should be evaluated from multiple attributes. There are several decision-making methods, one of them is making decision-matrixes.

3.7.1 Decision-matrix

Decision-matrixes are tools for decision making where a list of weighted criteria is presented and the alternatives are evaluated against these criteria (American Society for Quality, n.d.). They can be successfully used when several alternatives of, for example, concepts, designs and materials should be narrowed down to one choice. The method of using a decision matrix is suitable when having several criteria to base the decision on as well as when the alternatives have already been reduced and there is a manageable number of options left. This is useful for determining which material(s) should be chosen as the most appropriate for the indoor lighting application.

The procedure started with brainstorming which criteria are appropriate for the specific application, in this case indoor lighting shade and diffuser (American Society for Quality, n.d.). It was also discussed which of these are the most crucial. Only the most important ones should be included in the decision matrix. Then, the criteria should be weighted based on how relevant and important it is to fulfill for the application. This will be done by assigning the criteria points between 1-3 of how important they are, 3 being most important and 1 being least important. After the criteria is selected and weighted, a matrix was created with criteria on the left edge and the alternatives on the upper edge. The material alternatives were then evaluated against each criterion using a scale of -3 to +3, where -3 means that the criteria are not met in a good way and +3 is that the criteria are met in a good way. In addition, the scale is relative to the original material, with the 0 meaning that the criteria are met to the same extent as for the current material being used. This version of decision-matrix is usually called Pugh-matrix. The result of the matrix was calculated by multiplying the weight of the criteria with the number it was assigned, and lastly summarized to a final number.

It should be noted that the alternative with the highest resulting number is what “won” the comparison of

the matrix but is not necessarily the one to choose (American Society for Quality, n.d.). The method can, however, lead to meaningful discussions and a hint of what materials not to choose. The result of the Pugh matrix is presented in the evaluation chapter.

3.8 Analyzing Suitable Fiber Reinforcements

For the investigation of sustainable materials for the indoor lighting application to be complete, the fiber reinforcements need to be analyzed and compared. This was done with some complementing theoretical research, combined with information from the previous research.

4. Results From the Situation Analysis and Research

In this chapter, the results of the situation analysis methods are presented. There is also a summary of what materials have been found interesting and should be evaluated further if they are suitable for the indoor lighting application.

4.1 Specification of Requirements

By specifying the requirements, it creates knowledge about what properties a suitable material should have to meet all the requirements for an indoor luminaire. The different requirements, its function, class and limit / notations are presented in table 12. The table is color coded for different types of requirements for the components of a luminaire. The colors and their meaning are presented below:

- Blue – Technical requirements. These are necessary for the product to function and be safe. They also ensure that the product meets the legal requirements.
- Green – Sustainability requirements. These are especially important given the object of the thesis.
- Pink – Design requirements. These requirements describe design aspects of the product, like having several color variants for example. These also include semantic requirements connected to how the product is perceived.

Table 12: Specification of requirements for luminaire

Part of product	Function		Limit / Notations
Feed cable	Adjust	the distance from the ceiling to the light source	Maximum 3m
	Convey	electricity	Maximum 60W, Swedish/European plug
	Carry	the weight of the luminaire	2,3 kg (shade) + 0,48 kg (roof) + 0,45 kg (diffuser) + 0,5 kg (suspension) = 3,73 kg
	Enable	replacement of light source	LED-light 8,5/15 W (socket E27)
	Meet	security demands (electricity)	CE marking and label data
Hook suspension	Attach	armature to the ceiling	
	Carry	the total weight of the luminaire	2,3 kg (shade) + 0,48 kg (roof) + 0,45 kg (diffuser) + 0,5 kg (suspension) = 3,73 kg

Ceiling cup	Hide	hook, cable and other parts of the suspension in the ceiling	Undesirable or cluttering details should be hidden for a more clean-looking attachment to the ceiling.
Shade	Distribute	light	Comfortable light.
	Keep	bright spot	
	Express	classic idiom	Classic idiom of BUMLING
	Express	quality	
	Enable	replacement of light source	LED-light
	Offer	several color variants	Varnishable / paintable surface
	Offer	two sizes in diameter	Ø600 and Ø400 mm
	Offer	two heights	335 and 225 mm
	Enable	recycling	Material fulfils recycling requirements EN 13430 and there is a relevant infrastructure located in Sweden
	Enable	industrial composting	Material fulfils European standard EN 13432 and there is a relevant infrastructure located in Sweden
	Reduce	transport-related carbon emissions	A whole supply chain for material production is located in the European Union
	Eliminate	risks for environmental poisoning	Material does not include any harmful chemicals that can be released during the whole life cycle of the part
Diffuser	Diffuse	light	lumen
	Enable	recycling	
	Offer	several color variants	

Luminaire (in total)	Meet	standards	IP20 – touchproof and resistant to dust or objects larger than 12 mm.
	Demonstrate	durability	Lifecycle that is at least 20 years long
	Encourage	product care actions	All parts of the product are easily accessible for user when cleaning or maintenance are proceeded. The material is resistant to cleaning products common in public spaces.

Although the specification of requirements covers all parts of the product, they will not all be considered in the remaining parts of the luminaire. In agreement with ateljé Lyktan, the main focus of the thesis is the shade, the circular louvers and the upper diffuser, which was also stated in the limitations of the thesis. According to this agreement a list of constraints and objectives has been developed for only these components. The first part contains requirements covering the whole product while the second part describes requirements typical for the shade and diffuser. These lists are important when screening and ranking materials since they clearly state what is needed, how it can be done and what free variables there are. The lists are presented below in tables 13-15.

Table 13: List of constraints and objectives common for the shade and the diffuser.

Luminaire (shade + diffuser)			
Function	Constraint	Objective	Free variable
Enable a sustainable end-of-life stage.	Components must be recyclable using the relevant infrastructure in Sweden. Components made of different materials must be easy to separate by user before throwing out them.	Minimize the volume of materials that are used for energy recovery or disposal. Minimize variety of materials in the product. Minimize additives that can have negative impact on the recycling process.	Choice of material. Compostability of the chosen material.
Maintain high quality and prolong use stage of product life cycle.	Components must seem appealing throughout the whole use stage. Components must fulfill their functions for at least 20 years. Material must be resistant to the cleaning products. Components must be accessible for user to clean and maintain them.	Maximize the length of product life cycle. Minimize the aesthetical degradation of product.	Choice of material. Choice of maintaining recommendations.

	Construction must enable replacement of the light source.		
Decrease the environmental impact of material and manufacture stage.	Components must be produced of materials with lower embodied energy than Aluminum 1050A. Material must be derived and produced in EU or EEA. Material and product manufacturing must be carried out in accordance with the principles of social sustainability. Material does not include any harmful chemicals that can be released during the whole life cycle of the component.	Maximize usage of materials derived from renewable, biobased or recycled resources. Minimize greenhouse gas emissions caused by transport in material production and product manufacture. Minimize the embodied energy of the material.	Choice of material. Choice of the origin of the material considering the energy mix in each country of EU or EEA. Choice of production method.

Table 14: List of constraints and objectives for the shade.

Shade			
Function	Constraint	Objective	Free variable
Express the signature form and aesthetical value of Bumling.	Component must be shaped in a form that is easy to identify as Bumling. Component must have following dimensions: diameter of Ø600 mm and height of 335 mm.	Minimize the visual difference with the already produced versions of Bumling. Maximize timelessness of the produced design.	Choice of material. Choice of manufacturing method. Choice if the product should be available in several color variants. Choice if the product should be available in smaller size (dimension of Ø400 mm and height of 225 mm).
Distribute light in a controlled way.	Component must limit the casted light to a bright spot. Component must cast the light that feels comfortable. Component must cast the light downwards in a scattered form.	Maximize the possibility for the producer to control the light parameters.	Choice of material. Choice of the transparency of the material.

Table 15: List of constraints and objectives for the diffuser.

Diffuser			
Function	Constraint	Objective	Free variable
Diffuse the light additionally.	Component must diffuse the light.	Maximize the light comfort feeling. Maximize the feeling of high-quality design.	Choice of material. Choice of manufacturing method. Choice if the product should be available in several color variants. Choice if the product should be available in several pattern variants. Choice of the light intensiveness.

4.2 Bill of Materials (BOM)

The bill of materials was created to structure the different components (and their current materials) that is found in the luminaire. It also states manufacturing methods, masses and end of life potential. The bill of materials is presented below in table 16.

Table 16: Bill of Materials for the three relevant parts of Bumlung

Qty	Component name	Material	Manufacturing methods	End of life	Mass (kg)	Primary process	Length (m)	Secondary process	% removed	End of life	% recovered
1	Shade	Aluminum, commercial purity, 1050A	Pressure turning	Recycle	2,3	Casting		Fine machining	10	Recycled	100
1	Circular louver (Diffuser)	CAS 9010-79-1 (PP)	Injection molding	None	0,45	Injection molding	0,03		10	Downcycled	100
1	Upper diffuser	Aluminum, commercial purity, 1050A	Pressure turning	Recycle	0,48	Casting			10	Recycled	100

4.3 GRANTA Eco-audit

Combined with product information provided from ateljé Lyktan, a simple life cycle analysis was conducted, this is presented in appendix 2

For a luminaire, the use stage is crucial, which is apparent in the eco-audit. All three aspects considered, energy consumption, carbon dioxide footprint and cost, are many times larger in the use stage than in the other stages. This means that making energy efficient products is of outmost importance since it is responsible for such a large part of the product's environmental impact. Decreasing the carbon dioxide emission at this stage depends mostly on energy mix in the country where the lighting product will be used. User behaviors are also vital, and these can be stimulated by product design or intelligent lighting control systems. Apart from that, luminaire producers, such as ateljé Lyktan, have a quite low impact on the environmental impact in the use stage other than prolonging the use stage, increasing the energy efficiency and creating products developed for reuse and recycle.

In the production phase, the material stage is the most significant for the product Bumling, according to Eco audit. This is because of the demanding processes of mining new aluminum. Therefore, selecting more sustainable materials is essential in reducing the energy consumption and overall emissions of the production.

4.4 Literature Research

The extensive literary research resulted in several potential materials which were to be further evaluated. They can be divided into three main groups: Metals, Polymers and Plastic composites and are listed below.

Metals

- Zinc-alloy
- Brass
- Bronze-alloy

Polymers

- PLA
- PHA
- Bio-based PVC
- Bio-based ABS
- Recycled LDPE
- Reclaimed plastics (many variants but PC is main focus)
- Biodolomer I

Plastic composites (with fiber reinforcements)

- Textile-based composites
- Wood-based composites (WPC)

For an easier overview of the main aspects of the materials, they were assembled in table 17-19. In the tables the composites (or fiber reinforcements) are not presented since they can be made in several variations of plastics.

Table 17: Overview of mechanical properties of investigated materials (1/3)

	Aluminum	Zn-Al-alloy	Brass	Bronze	PLA
Price per unit volume (SEK/m ³)	7,5e ⁴ -1,07e ⁵	2,29e ⁵ -3,14e ⁵	6,26e ⁵ -6,89e ⁵	8,3e ⁵ -9,75e ⁵	3,64e ⁴ - 4,97 e ⁴
Density (kg/m ³)	2,68e ³ -2,74e ³	6,45e ³ -6,65e ³	8,18e ³ -8,35e ³	8,55e ³ -8,56e ³	1,2e ³ - 1,29e ³
Tensile strength (MPa)	166-184	150-235	400-420	470-540	45 - 72
Young's modulus (GPa)	69-72	75-95	97 - 103	123-128	2,4 - 3,6
Melting point (°C)	645-658	380-390	882-902	1,01e ³ -1,03e ³	135 - 181
CO ₂ footprint (kg/kg)	8,13-9,48	3,16-3,57	3,64 - 4,18	4,53-5,21	2,15 - 2,4
Recyclability (Yes/No)	Yes	Yes	Yes	Yes	Yes
CO ₂ footprint, recycling (kg/kg)	2,48-2,74	0,935-1	1,23-1,36	1,46-1,61	0,738 - 0,816
Biodegradable (Yes/No)	No	No	No	No	Yes
Origin in EU (Yes/no)	Yes	Yes	Yes	Yes	Yes

Table 18: Overview of properties of the materials (2/3)

	PHA	Bio-PVC	Bio-ABS	RC LDPE	Ocean-bound plastic (PC)
Price per unit volume (SEK/m ³)	4,71e ⁴ - 6,25e ⁴	?	?	18,3 - 20,3	?
Density (kg/m ³)	1,23e ³ - 1,25e ³	1,08e ³ - 1,12e ³	1,03e ³ - 1,06e ³	917 - 932	1,2e ³
Tensile strength (MPa)	35-40	7,43 - 9,25	37,9 - 51,7	13,3 - 26,4	50
Young's modulus (GPa)	3,5-4	6,01 - 9,38	2,07 - 2,76	0,172-0,283	2,29 - 2,31
Melting point (°C)	171- 182	158 - 169	159 - 274	98-115	280-320

CO₂ footprint (kg/kg)	0,86 - 0,94	?	?	1,94-2,15	?
Recyclability (Yes/No)	Yes	Yes	Yes	Yes	Yes
CO₂ footprint, recycling (kg/kg)	0,292 - 0,32	?	?	0,673 - 0,745	2 - 2,18
Biodegradable (Yes/No)	Yes	?	?	No	No
Origin in EU (Yes/no)	Yes	Yes	Yes	?	?

Table 19: Overview of properties of the materials (3/3)

	Biodolomer I
Price per unit volume (SEK/m³)	?
Density (kg/m³)	1,3e3
Tensile strength (MPa)	400
Young's modulus (GPa)	2,022
Melting point (°C)	170 - 210
CO₂ footprint (kg/kg)	?
Recyclability (Yes/No)	No
CO₂ footprint, recycling (kg/kg)	?
Biodegradable (Yes/No)	Yes (+ compostable)
Origin in EU (Yes/no)	Yes

The overview served as an aid in the evaluation process for easy comparison.

5. Evaluation Results

In this chapter the findings of the literary research were evaluated, resulting in the most suitable materials being chosen. The evaluation process was divided into two main parts, screening and ranking. Furthermore, an analysis and comparison of fiber reinforcements were performed to make a conclusion on which may be suitable to lengthen the lifecycle of the materials.

5.1 Screening

In the screening process, the materials are evaluated primarily by taking the specification of requirements into account. Important questions to answer are what materials meet the requirements, especially the requirements connected to sustainability, and which materials do not. Screening can be performed according to several methodologies. In this thesis, the chart and questionnaire method performed, and the results are presented below.

5.1.1 Results From the Chart-method

The chart was made using GRANTA Edupack and its database of materials for easy comparison, presented below in figure 4 and 5 (Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024). On the x-axis the carbon dioxide footprint is presented, and on the y-axis, the embodied energy is presented. The red dots represent the three metal alternatives included in the screening, the blue are the polymers, and the purple is aluminum, the currently used material in Bumling.

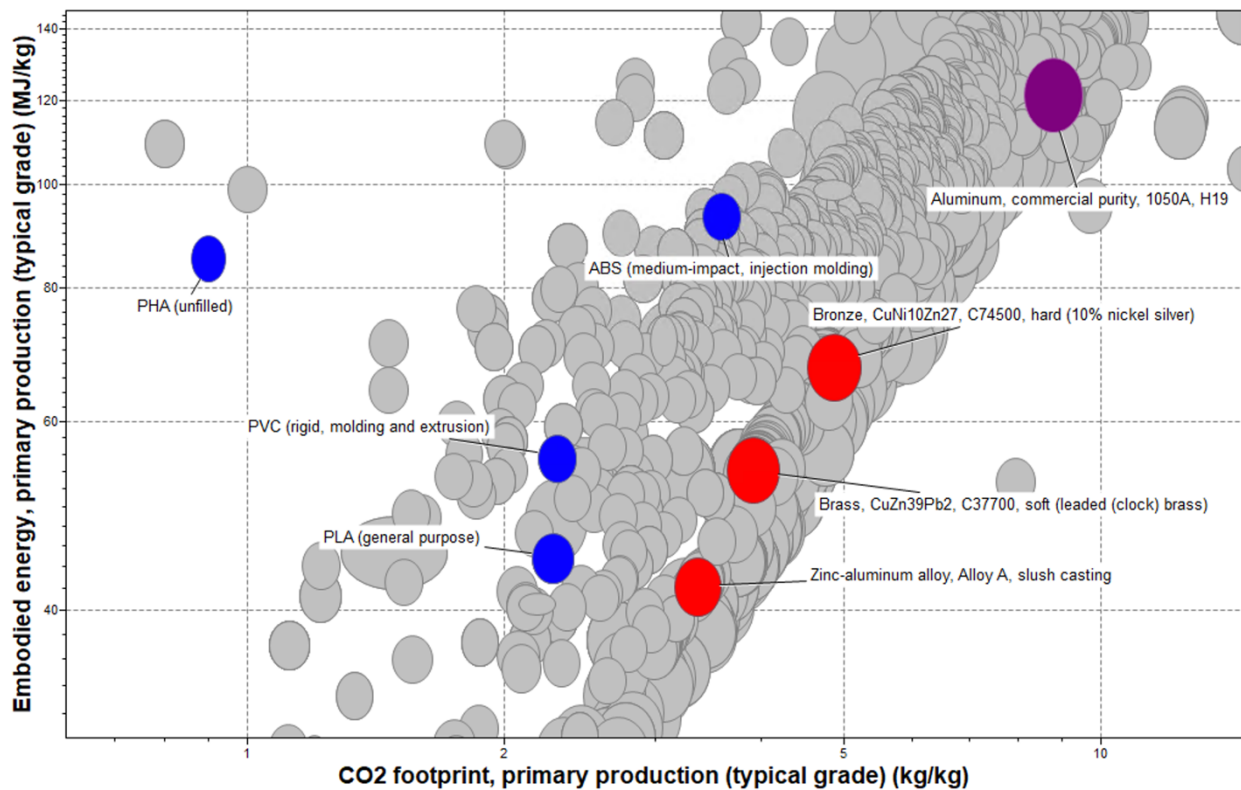


Figure 4: Materials compared by considering their embodied energy and carbon dioxide footprint for primary production and typical grade

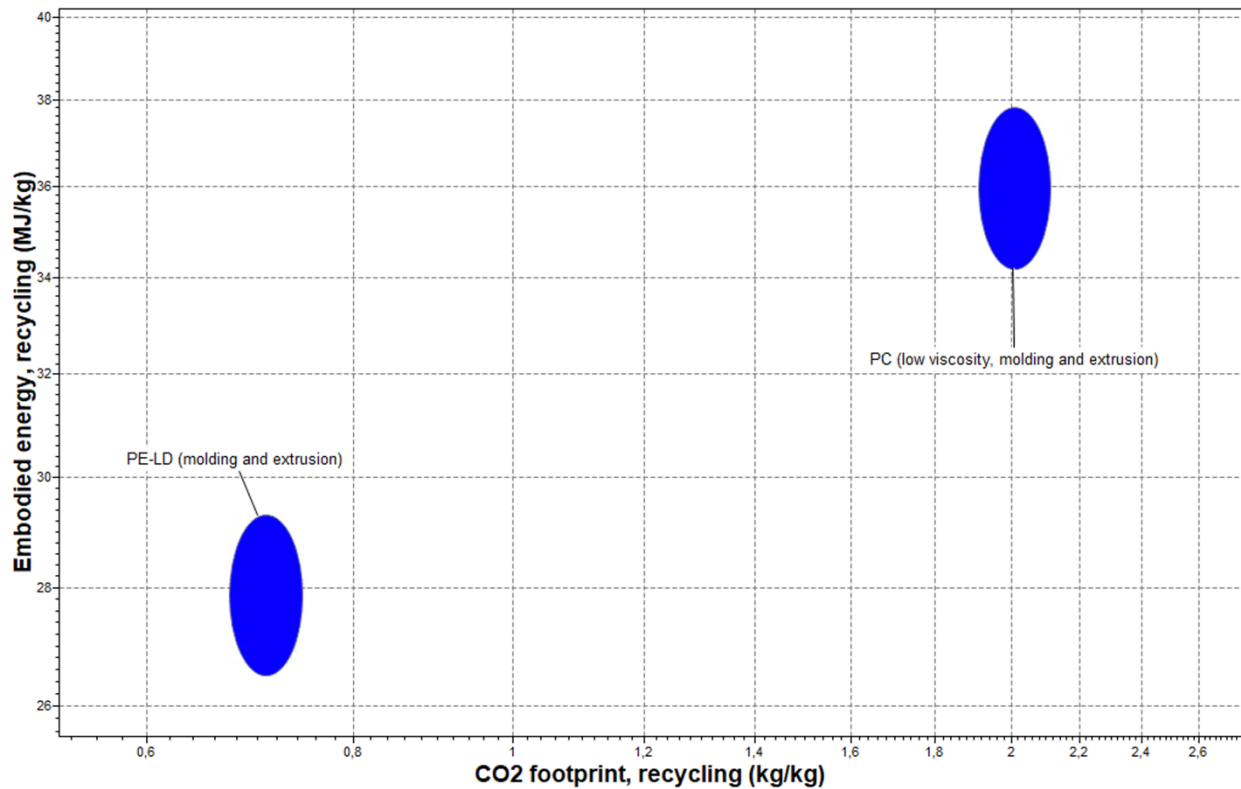


Figure 5: The recycled materials compared with regards to embodied energy and carbon dioxide footprint

Biodolomer I is not included in the charts due to the materials being extremely new. Although having been in contact with the company, there are no estimations on its embodied energy or emissions yet because of the recentness of its development. The information obtained is that the emissions are lower than petroleum-based plastics but there are no specific figures. This is seen as negative, since the embodied energy and carbon dioxide footprint are two important aspects when selecting a sustainable material. Nevertheless, the material is not eliminated before being evaluated further on other aspects.

An interesting aspect is that aluminum has both the highest embodied energy and the highest carbon dioxide footprint out of all the investigated materials. This means that, generally, any other choice will be better, at least when considering embodied energy and CO₂ emissions.

PHA stands out with its very low carbon dioxide footprint, in the same range as recycled LDPE. However, it does have a high embodied energy, meaning that the location of production can play a big role in its total environmental impact.

From the charts, it is clear that the metals have a quite high carbon dioxide footprint, while still less than aluminum. Additionally, because of many metals being either mined or processed in other parts of the world it is a challenge finding locally sourced metals. After also considering the cost of the zinc-alloy, brass and the bronze, which is higher than aluminum, it was decided that the metals were to be eliminated.

5.1.2 Answers and Reflections to the Questionnaire Method

The result from the questionnaire method is presented below in table 20 as answers to the previously set questions.

Table 20: Questions and answers from the questionnaire method

Question	Answer
<p>What is the origin of the material and how does this affect the sustainability aspect of material deriving?</p>	<ul style="list-style-type: none"> • PLA has European companies producing them, for example FKUR Kunststoff GmbH from Germany (and perhaps Denmark with Dansk algeplast). Biological feedstock can origin from other places, which is something to take into account in all bioplastics. • PHA are produced by companies based in Germany and France. If their actual production is in these countries is unclear (PHA may be produced in Denmark considering Dansk algeplast) • The ocean-bound plastic from Oceanworks is stated to be mostly sourced in Asia, but they have suppliers all over the world including Europe. If the PC investigated is from Asia or somewhere else is unclear. • Recycled LDPE can be provided through the companies that collect waste and recycle it into a pellet. Waste that has its origin in the common recycling system (for example in Sweden) has poor quality if different types and colors of LDPE were not sorted enough. • Bio-ABS and Bio-PVC are made in Germany but biobased feedstock such as sugarcane used in production can be harvested outside EU, such as Asia. • Biodolomer I originates from Helsingborg, Sweden. <p>The energy mix of Germany is below the average of the EU in terms of percentage of low-carbon energy production. It is better than many Asian countries, especially if the transport is considered as well. Germany is close to Sweden and the two have good relations.</p> <p>The Danish energy mix is cleaner than the mix of Germany and the EU and is the neighboring country to Sweden, creating short transportation distances.</p> <p>The energy mix in Asia is generally less clean than that of the EU. It would also mean long distances of transportation, resulting in more emissions than necessary.</p> <p>The Swedish energy mix is among the cleanest in the world meaning that production in Sweden results in a very low carbon footprint from its energy consumption. It is as local as it gets, since ateljé Lykan's production is in the south of Sweden, close to where Biodolomer I is produced.</p>
<p>How accessible is the material's data sheet?</p>	<ul style="list-style-type: none"> • Technical properties of PLA are easily accessible and include environmental aspects as well. In purpose of this thesis work data from Granta Edu Pack is used. The datasheets from specific manufacturers contain less information. • Technical properties of PHA are easily accessible and include environmental aspects as well. In purpose of this thesis work data from Granta Edu Pack is used. The datasheets from specific manufacturers contain less information.

	<ul style="list-style-type: none"> • Gaia BioMaterials, producer of Biodolomer I is a transparent company that provides designers with the requested information. However, since the material is relatively new there are no LCA proceeded which leads to lacking environmental impact information. • It is challenging to find suppliers in Europe that can provide more information about recycled LDPE. However, when recycling polymers, the properties are the same or get worse compared to the virgin material. • Ocean-bound plastic offers varying data sheets depending on what kind of polymers is collected from the ocean. Information about the environmental impact of the collected and recycled material was not included. • More details were provided after contacting INEOS producer of the biobased ABS. However, after deeper research the information about material’s biobased origin was misleading which is described in chapter 2.2.2. • Bio-PVC had accessible data sheets provided by its manufacturer.
<p>Is it possible to achieve 20 years of product lifecycle length while keeping functionality and aesthetics of the product in good condition?</p>	<ul style="list-style-type: none"> • It is challenging to determine if the product manufactured of PLA will be able to provide a lifespan of 20 years. However, usage of additives can prevent damage caused by UV-light or air humidity which helps prolong the expected lifespan. • Biodegradable PHA can be degraded if exposed to the “right” conditions, like high humidity as well as high temperatures. • Biodolomer I is a compostable material so achieving a product lifecycle length of 20 years might be challenging. However, fiber-compounding and keeping the product in indoor conditions can delay the biodegrading process but some damage to the aesthetical aspects of the product may appear after a few years. • Despite the main application area of LDPE which is packaging industry, this material is also used to produce furniture pieces. However, LDPE is not as strong as other plastics and usage of industrial waste is preferred than the recycled resin due to the better control of the received quality. • The ocean-bound plastic (PC) is often industrial waste and is quite pure. These should be able to hold a similar lifecycle length to virgin plastics, which should last more than 20 years. • Bio-ABS and Bio-PVC are expected to perform similar physical properties as its fossil-based alternative that is recognized for high durability and long lifespan. Since the designed parts will not be exposed to mechanical loads there is a high possibility of producing a part that will be useful in 20 years.
<p>Does the material contain any harmful substances that can be emitted during production, usage and end-of-life stage?</p>	<ul style="list-style-type: none"> • PLA which is biologically based should not be harmful to the health. In comparison to production of synthetic materials, there are no harmful gases being emitted for example. Depending on the feedstock being used in production of PLA, there could be harmful chemicals which are affecting the environment they are planted in. • PHA – If 100% biodegradable: It should not be harmful to the health, they are usually safe to use with food for example. Depending on the feedstock being used in production of PHA, there could be harmful chemicals which are affecting the environment they are planted in.

	<ul style="list-style-type: none"> • Biodolomer I contain biopolymers PLA and PBAT that bring the environmental concerns due to chemicals used in harvesting the biobased feedstock that are affecting the environment where the feedstock is planted in. • Recycled LDPE – Micro and nano plastics are a problem when producing and using synthetic plastics. Recycled plastics are harder to control in terms of content, and sometimes it might be unknown where the material came from and furthermore what it contains. • Ocean-bound plastic (PC) – microplastics are always an issue when synthetic plastics are used. There may be uncertainties regarding content in the plastics. • Bio-ABS odes contain some petroleum-based plastic, which means that it releases microplastics, although not as much as if the material was all petroleum-based. • Bio-PVC is said to be completely bio-based, using sustainable forests to produce its feedstock. <p>In biologically based materials it is necessary to be aware of the origin of feedstock. There is an extensive use of fertilizers when producing plants, and these are contributing to the increasing concentrations of phosphor and nitrogen in the environment. Other chemicals, like pesticides and herbicides, are increasing toxicity indicators. These factors can cause bio-based materials to be less sustainable.</p> <p>Consciousness about what additives, fillers and other chemicals used in the production of materials and products is crucial to ensure that the end-product is truly sustainable.</p>
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After performing the questionnaire-method, the ocean-bound plastic and the recycled LDPE were eliminated. This is because of the many uncertainties with the materials, like what they contain and their origin.

In the research, there was no recycled LDPE found that certainly is from the EU. There should be suppliers, since the EU certainly is no stranger to plastic waste, but in this time frame they have not been identified. There are several other issues connected to sustainability with synthetic plastics, as mentioned above. Preventing the release of microplastics from synthetic materials is close to impossible, and this is harmful for both the environment and organisms. In the best of worlds, this should be eliminated from nature, which can only be done by stopping the use of these materials.

After the two screening methods were finished, some materials were eliminated. These were the metals since they have a quite high carbon dioxide footprint, mainly from mining.

5.2 Ranking

In this stage of material selection process those materials that fulfill requirements can be compared and proceed to be narrowed down to the final recommendation. The ranking process is made up by using a decision matrix, or more specifically a Pugh-matrix, to rank the alternatives in a structured fashion.

5.2.1 Pugh-matrix

The result of the Pugh-matrix is presented below in table 21. There were seven criteria being used and these were weighed according to their perceived importance, however, all of them are essential.

Aluminum is the material used today of the louver, which is also accounted for in the comparison by using a 7-point scale with 0 meaning that the criteria is met to the same extent as aluminum and then using 3 positive or negative points for solutions which meets the criteria in a better way or worse way. The highest number, meaning the criteria is met to a high extent or in a very good way, is +3 whereas the lowest number, meaning that the criteria is not met or at least not in a good manner, is -3.

Table 21: The result of creating a Pugh-matrix for decision making

Criteria	Weight	PLA	PHA	Biodolomer	Bio-ABS	Bio-PVC
CO₂ footprint	1	+2	+3	+2	+1	+1
Embodied energy	2	+3	+1	+3	+1	+2
Hazardous chemicals	1	+2	+2	+2	0	+1
Water usage	1	+3	+1	+3	+1	+1
Length of transport	1	+1	+1	+2	0	+1
End-of-life potential	3	0	+1	+1	0	0
Potential lifespan	2	-1	-2	-3	-1	-2
Total of points		10	7	10	2	4
Total with weight		12	8	12	2	4
Number of advantages		11	9	13	3	6
Number of disadvantages		1	2	3	1	2

All the materials have a lower carbon dioxide footprint than aluminum, resulting in positive points for all of them. PHA has the lowest of all alternatives. All the investigated material alternatives also have a lower embodied energy than aluminum. Both embodied energy and carbon dioxide footprint were considered in the chart-method but it was determined that they should be considered when ranking materials as well. PLA has the lowest embodied energy, from what we know for certain, but since Biodolomer contains PLA and PBAT, and although the embodied energy is not entirely known it should be somewhere around the same amount as PLA.

Aluminum has quite a lot of hazardous chemicals which are used in the production, resulting in these bioplastics being less harmful according to this aspect. Currently, Bio-ABS does contain some synthetic ABS which can be hazardous.

Production of aluminum requires over a thousand liters of water per kg metal (*Ansys GRANTA EDUPACK Software, ANSYS, Inc., 2024*). None of the bioplastics are close to using this amount of water. In comparison, PLA is stated to only use about 20 liters, and PHA about 200.

In the length of transport refers to where the production is located and what amount of distance the material would have to be transferred. This is probably the least important criteria if only talking about the total impact on the environment, although still something to strive for. Biodolomer is produced in Sweden, and even in the same region as the production of Bumling, resulting in a very short transportation distance. PLA, PHA, bio-PVC and bio-ABS are produced by north European companies, which should mean that their production is also in Europe considering its small scale. Bio-ABS also contains a small proportion of virgin, petroleum-based ABS which is unknown where it comes from.

The end-of-life potential was weighted as the most crucial criteria since highly biological materials are not much better than fossil fuel-based materials if they cannot be taken care of properly after their lifecycle. If only contributing to the waste incineration together with other unsorted garbage the only advantage is that it may not release harmful gases into the air but still contributes to global warming by releasing greenhouse gases. Therefore, it is important to consider the infrastructure as well as the material's ability to be recycled or composted, which is all accounted for in the end-of-life potential. Unfortunately, there are challenges in this area today and no material found in the investigation has sufficient infrastructure for an up-scaled recycling or industrial composting of bioplastics, explaining the low grading of the alternatives. In comparison to aluminum, which is recycled at a high degree today, biologically based plastics are not advantageous in this area. However, the Biodolomer and PHA earned 1 point for being compostable, meaning that the waste will dissolve entirely if it were to be left in nature or in other unattended places.

The lifespan is also an essential aspect in products like luminaires since they should have a long lifecycle, both functionally and aesthetically, to be sustainable in the long run. Aluminum is a very durable material and has a life length of tens of years in a product like a luminaire. All bio-based plastics probably have a shorter lifecycle than that. Some may even change their appearance after only 2 years, for example Biodolomer. However, there is a chance that fiber reinforcements could lengthen the stability of the biological materials.

In conclusion, Biodolomer and PLA were the most promising alternatives after the ranking process while bio-PVC and bio-ABS are the least promising.

5.3 Evaluation of Fiber Reinforcements

It is crucial that environmentally friendly materials are as close to 100% sustainable as possible, otherwise risking being an example of greenwashing. For example, a biologically based material can only be called this if the additives and fillers in the material are also biologically based. Moreover, according to the requirement specification and list of constraints and objectives that set the ambition to eliminate fossil-based materials, plant-based fibers are preferred to evaluate.

Both PLA and Biodolomer I, also partially PLA based, can be reinforced with fiber in order to achieve higher mechanical properties. This will allow the product to offer high customer value and gain an extended lifecycle, hopefully around 20 years or more, which the bioplastics alone cannot provide given present production technologies. Deriving a PLA-based composite reinforced with plant-based fiber can extend materials tensile modulus with almost 58% in comparison with the pure PLA Klicka eller tryck här för att ange text.. Following composites are developed and researched: PLA/Jute, PLA/Coir, PLA/Banana, PLA/CF³/PALF⁴, PLA/PALF/CF, PLA/Sizal, PLA/Hemp, PLA/Flax. Considering the preferred European

³ Citrus fibers

⁴ Pineapple leaf fibers

origin of the fiber, jute, hemp, flax and banana should be taken into consideration. Flax cultivation is present across the European Union and is sustainable and suitable in many European countries (Stavropoulos et al., 2023). Over the past few years has hemp cultivation developed widely, even in Northern Europe and gave new agricultural opportunities for Latvia and Estonia (Runno-Paurson et al., 2023). Banana cultivation is not that common in Europe and is particularly limited to fruit production on Canary Islands, Spain while jute cultivation is experimental and non-commercial at the moment Klicka eller tryck här för att ange text..

In the next step material properties and application area of the composites was compared. Flax/PLA composite provides a perfect balance between stiffness and damping (Akter et al., 2024). However, this composite tends to be more effective for enzymatic degradation and creates better environment for fungal colonization which should be avoided while designing products with long lifespan. Fibers similar to flax, when it comes to cellulose richness, chemical composition and retting procedure, is hemp. Due to its stiffness, length and thickness hemp fiber can be used in challenging applications such as automotive industry and PLA/Hemp composite is already present in ateljé Lyktans Superdupertube. The next type of fiber is jute, also similar to flax and hemp in its chemical composition and retting processes. However, PLA/Jute has poorer value of tensile properties and is less stiff than PLA/Flax composite. When usage of those two fibers is under investigation, the mechanical properties can be improved by hybridization of flax and jute and compounding those with PLA Klicka eller tryck här för att ange text..

Fiber reinforcement of Biodolomer I® has not yet been investigated thoroughly by the producer but there are some directions supplied. Chosen fiber must fulfil four requirements: small size of the fiber, temperature resistance up to 200°C, the fiber must be dry and that the compounded material will be stored in closed packaging. Some fibers with potential are paper and hemp but further investigation is necessary to match the composite's properties with the product specification.

Another recommendation is to check the combability of PLA and Biodolomer I® with two Swedish fibers: FibraQ and OnceMore. The first one is a wood-based fiber made of biomass coming from sustainably managed forests in Sweden and produced by Biofiber Tech Sweden AB, presented previously in chapter fiber-reinforced plastic composites as WPC. This material can be customized and fits a variety of production methods. The second type of fiber consists of 20% recycled textiles and 80% wood pulp, creating a pure and high-quality pulp. The producer of OnceMore, the Swedish company Södra, has fulfilled the requirements to receive PEFC & FSC® certificates for the wood-based part of the product and an RCS certificate for the recycled part.

6. Discussion

In this chapter, the results and the evaluation are reflected and discussed. The overall methods and the process used are also evaluated. The aim of the thesis has been achieved by expanding knowledge of some materials on the market and their sustainability, recommending two materials that are promising as well as how well they could be implemented in the indoor lighting industry by the company ateljé Lyktan.

6.1 Thoughts Regarding the Result

Biodolomer and PLA were the winning alternatives in the screening and ranking process. Biodolomer is a very new composite material which sounds promising but there is a need for more information regarding its emissions throughout the life cycle for instance. PLA is not a new material; however, it is one of the more advanced biopolymers, and is a compound of Biodolomer. Ateljé Lyktan has recently been using PLA with hemp fibers in their newly developed product SuperDuperTube, meaning that PLA is not unfamiliar to the company, and neither are fiber reinforcements. Both Biodolomer and PLA are adapted to injection molding, a processing method familiar to ateljé Lyktan which has been used before through their cooperation partners. In other words, there is no need for new partnerships or processing machines to be purchased to switch materials, only the feedstock should be switched.

There are many benefits with Biodolomer and PLA. They are both biologically based, have a low carbon dioxide emission compared to fossil-based plastics and are biodegradable. The main issues with the materials are the insufficient end-of-life infrastructure and the uncertainties connected to the life cycle of the material. However, with increasing demands for sustainable materials the infrastructure should be developing in the coming years, and fiber reinforcements can be utilized to stabilize and prolong the life of the materials.

Biodolomer is a specific combination of materials in one composition, while PLA, or polylactic acid, is a type of plastic. PLA can therefore be made from several renewable sources, like sugarcane, sugar beet, cassava and corn starch and its overall sustainability is affected by which of these feedstocks are used. To fairly compare the origin of a fossil-based material with a biologically based material the mining should be compared to the farming and harvesting of biological feedstock. Firstly, there are differences in how much pesticides and fertilizers are used for different plants which can affect the biological diversity and ecosystem of the location. These can later be spread and affect a bigger area by the rain. Secondly, there are also differences in how much water plants need, which is particularly important in areas that are often plagued by drought. Thirdly, the overall sustainability of the final material, and furthermore a finished product made of this material, is where the original feedstock is farmed. Many plants need specific conditions to thrive, and therefore an effort should be made to find locally farmed plants as feedstock to minimize the transport.

Bioplastics finds its primary applications in packaging for the food and medical industry as well as for single-use products today. This is probably because these are constantly being produced and then hastily turned into litter which is at an increased risk of being misplaced in nature. If these were biologically based and even compostable, this would dramatically decrease the amount of pollution in the environment. However, the research and exploration of bioplastics in other industries are not as far ahead resulting in bioplastics not being used as much there. If society is moving away from fossil fuels and more towards biomaterials, more research on biologically based hard plastics needs to be conducted. Moreover, the infrastructure of the biomaterial end-of life solutions, whether it is recycling or industrial composting, must develop for a circular economy to become reality. Although many bioplastics are already in use, they

are not entirely sustainable unless they are properly taken care of at their end-of-life. The same goes for composites, which can be hard to separate with today's technology.

Metals were eliminated early in the screening process. They are quite expensive compared to the other options which have been investigated as well as more expensive than the current material that is used (aluminum). Neither brass, bronze nor the zinc alloy investigated are viewed as better alternatives in terms of recycling or carbon dioxide footprint. All of these materials are possible to be made in the special shape that is Bumling, however, because of the high cost and not gaining anything regarding sustainability by switching to these materials, these were not the primary choice in this investigation.

Recycled LDPE and ocean bound plastics were also eliminated before ranking started. This was due to them being based on fossil fuels, which should be avoided if society should switch to a circular economy. Fossil fuels are not only a finite source, but they are also harmful to the environment and organisms when used because of the release of micro and nano plastics. There was also a discussion whether or not the ocean bound plastic, and other industrial waste plastics, can be considered recycled since it has not been used or had a purpose yet. It can be argued that it is better for companies to reduce their waste as much as possible instead.

In the thesis, there were hopes of finding an innovative material where all, or most, of the demands were met. Unfortunately, society is in a state of development and the miracle solutions have not yet been discovered. There are many materials that could possibly be a part of the solution to the environmental issues but there is a prominent need for more research, more end-of-life options and more companies focusing on switching to "green" production.

The thesis does not include any materials that are entirely useless for the application. During the investigation process the product analysis, eco-audit and the specification of requirements were already created. It was already considered in the searching process and some materials were dismissed before any deep dive in its properties was made.

Throughout the process, the design aspect of materials has been considered as well as their processability and impact on the environment. Some materials that have been investigated but did not make the cut for inclusion in the thesis are materials made from fungi. This material was rejected due to several aspects, including the fact that the production of many of the alternatives was seemingly far from industrial scale still, and that it is difficult to ensure a uniform quality of the products. Another aspect was that some of the fungi-based materials were not "aesthetically pleasing". This is connected to the issue of ensuring consistent quality since there can become irregularities in color or shape in some cases. There are also limitations connected to what additives can be used, like colorants, that can increase the aesthetic properties of the product. Many colorants would have a negative impact on the biodegradability or the overall environmental friendliness of the product.

For society to be transformed from the current linear economic system to a circular one, the consumption behavior will need to change. Moreover, the way of thinking and behaviors overall will need to change. In this transition, what is considered aesthetically pleasing or a good-looking design may have to develop to fit into the circular economy. Nowadays, most people praise new, clean colored, shiny products, all aspects that are demanding to maintain in products that have a high usage and a long lifecycle. If the product is a part of a circular system, it could be difficult to eliminate all signs of usage on all products. In the future, what is desirable might differ from today, like appreciating the beauty of something that has a bit wear or appreciating the natural colors of different materials.

For sustainable reasons, there probably will be a reduction or even elimination of all use of harmful chemicals in materials and products. As new technologies are created, more environmentally friendly

manufacturing processes, materials and additives can be invented. There may also be an increase in using older methods which may not be as effective but more environmentally friendly. For example, natural colorants may be used more.

The thesis has resulted in the frontier of knowledge being moved forward by realizing where the industry is today and what challenges lie ahead for society. The use of sustainable materials is increasing and the demand on infrastructure for recycling and industrial composting of these materials must pick up pace in developing. Several materials and manufacturers have been evaluated throughout the process with the conclusion that detailed and methodical investigations are required to find the truly sustainable materials and filter out those who may be greenwashing.

6.2 Discussion Regarding Methodology and Process

While comparing the sustainability data it is necessary to agree about the right selection of environmental impact parameters that will make the material selection process fair and reliable. The sustainability of a given product is a complex question, and the ambition of this study was to include aspects that are primarily correlated with greenhouse gases emission but also to provide solutions that follow guide of social sustainability and help avoid emission of hazardous chemicals. One of the most relevant criteria for this process is the value of embodied energy since only carbon dioxide emission data may include a high level of assumptions and significant differences between suppliers when it comes to how to measure and report the data. However, the supplier of Biodolomer I could not provide the data covering embodied energy of their product, but it is reasonable to assume that it could be relatively low since the Swedish energy mix consists of renewables in around 70% (*Elproduktion Och Förbrukning i Sverige*, n.d.).

The software GRANTA Edupack is a great aid for executing different analyses and evaluations, like lifecycle analyses and making charts. It does have a large database, and even a number of different, more specialized databases which can be utilized depending on the desired application of the material. As an example, there are databases specialized for eco-design, one for sustainability as well as different levels depending on how detailed information about the materials is desired. The databases are quite updated, however, in this some of the materials that have been investigated are extremely new and could not be found in the software. This complicated the evaluation process, particularly when executing the chart-method which was done in the software. The company producing Biodolomer I did not have the exact details for embodied energy or carbon dioxide emissions which resulted in us not being able to include it in the method more than assuming that it is lower than for metals for example.

The evaluation process was stalled by finding mechanical and sustainable details about the specific materials being considered. All the manufacturers mentioned were contacted, however, some were time-consuming to get in touch with and some never responded at all, despite several tries. This is problematic, not only for the information search in the thesis but also for other private people or companies trying to receive more information in preparation for possible purchases. It is imaginable that possible customers would be prioritized and get answers more quickly than students writing a thesis, nevertheless, if a highly suitable material would present itself, it is possible that this thesis would result in a new customer for them.

Connected to the difficulties getting in contact with some companies, there were some struggles with investigating the companies in terms of their supplier chains and the more detailed information,

particularly regarding sustainability, on some materials. Transparency is crucial in choosing suppliers and manufacturers to ensure a sustainable, ethical production, both ecologically and socially. Unfortunately, this is hard to investigate when the companies do not state all the information that is relevant.

When it comes to the evaluation process there were some challenges, one of them being how to take the additives into consideration when evaluating the materials, particularly plastics. Additives and fillers can make a sustainable material less environmentally friendly if hazardous or toxic additives are used, like some flame retardants for example. Details about exactly what additives are used are currently unknown, but the specific manufacturer should be consulted about this before the material is used in a product.

Another obstacle when evaluating was how to compare the emissions of recycled materials to virgin ones as well as compostable materials. When evaluating a virgin material its process from raw material to finished material is considered, and the rose the question whether only the emissions from the recycling process should be considered in the evaluation of recycled materials or if the production of the virgin material should be taken into account as well. It was decided that only the recycling process would be considered when calculating the emissions, however, because the only recycled materials in the investigation are based on fossil fuels they were eliminated anyway. Another aspect to consider when further evaluating the biomaterials is how to consider composting since it does generate some CO₂-emissions.

The next step in the process of finding sustainable materials for indoor lighting is to further research PLA, Biodolomer and eventual fiber reinforcements. This thesis can serve as a basis for deeper investigations and further testing of both PLA and Biodolomer. Biodolomer is produced by the company Gaia BioMaterials and can be contacted for samples. Ateljé Lyktan will then be able to perform their own aging test, filament test and EMC-test to determine whether the material is of use to them. Since the two companies are located close to each other this may facilitate communication and cooperation.

Given the materials that were found promising in the investigation, additive manufacturing and 3D-printing could be an investment opportunity for the future in the indoor lighting business. PLA works well as filament for printing and the range of products could be expanded with new shapes by adopting the process into the production of luminaries. The circular louvers of Bumling could also be printed in many different versions giving opportunity for personalization of this iconic piece.

7. Conclusions

In conclusion there are several more sustainable materials that theoretically can be used to produce Bumling and similar indoor lighting products. Based on the research conducted in the thesis the biologically based polymer PLA, coupled with fiber reinforcements to enhance its durability and other mechanical properties, is a tested and promising choice. Biodolomer is a new, locally produced material which is interesting and should be evaluated and tested further. Both materials can be used in the familiar processing method injection molding in order to achieve the proper shape of the shade. These materials can also be used to produce circular louvers by injection molding.

If a switch from a linear economy to a circular one should be made, it is crucial for society to make efforts to develop new materials, processing methods and end-of-life infrastructure that are sustainable.

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Appendixes

Appendix 1: Questions for screening according to the questionnaire method.

Question	Goal
What is the origin of the material and how does this affect the sustainability aspect of material deriving?	To consider if the material is derived in EU or EEA, how the origin affects the type and length of transportation, what is the electricity mix in this country, what are the social conditions in the deriving location and how is the quality correlated with the country of origin.
How accessible is the material's data sheet?	To determine if there are fairgrounds to consider the given material as sustainable in comparison to others.
Is it possible to achieve 20 years of product lifecycle length while keeping functionality and aesthetics of the product in good condition?	In agreement with ateljé Lyktan material must maintain its good quality for at least 20 years, implying that cleaning and reparation should be allowed.
Does the material contain any harmful substances that can be emitted during production, usage and end-of-life stage?	To protect the workplace environment and facilitate recycling processes.
How recyclable is the material considering available or in-development infrastructure in Sweden?	To avoid materials that technically are recyclable but there are no industrial recycling processes developed in Sweden.

Appendix 2: GRANTA Edupack's Eco Audit Report

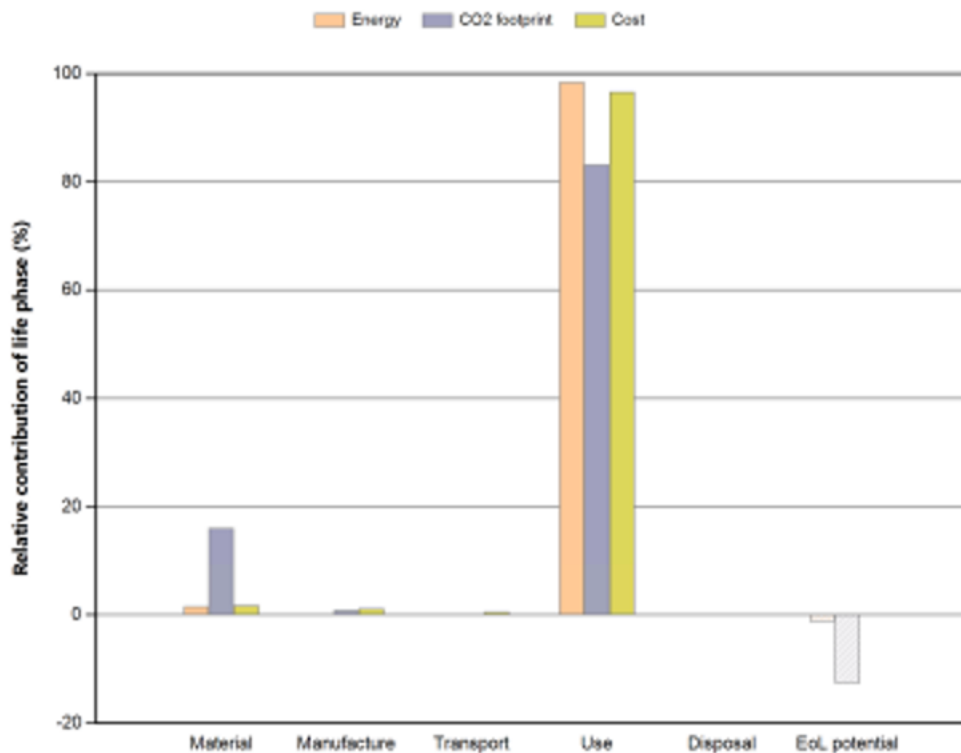


Eco Audit Report

GRANTA EDUPACK

Product name: BUMLING (utan motor)
 Country of manufacture: Sweden
 Country of use: Sweden
 Product life (years): 20

Summary:



[Energy details](#)

[CO2 footprint details](#)

[Cost details](#)

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)	Cost (SEK)	Cost (%)
Material	568	1,5	39,6	15,9	118	1,68
Manufacture	24,8	0,1	1,96	0,8	81,4	1,16
Transport	1,16	0,0	0,0725	0,0	36,2	0,515
Use	3,65e+04	98,4	207	83,2	6,79e+03	96,6
Disposal	2,17	0,0	0,152	0,1	0,221	0,00314
Total (for first life)	3,71e+04	100	249	100	7,03e+03	100
End of life potential	-449		-31,2			

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