CRANFIELD UNIVERSITY

DANIEL SIMON JIMENEZ

REDESIGN FOR SUSTAINABLE MANUFACTURING

School of Aerospace, Transport and Manufacturing
Global Product Development and Management

MSc
Academic Year: 2018 - 2019

Supervisor: Mark Jolly

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ABSTRACT

Sustainable manufacturing is becoming increasingly common and necessary among the different manufacturing industries around the world. It is essential to aim resources at improving the environmental, social and economic issues of manufacturing; if we, as a society, want to achieve a sustainable development. In this thesis project, two cast aluminium components are analysed throughout their product life cycle in order to know which life cycle stages should be targeted so as to improve their overall level of sustainability. These components belong to a product created by Vitsœ, a leading company in the furniture industry. The CES Edu Pack software has been used to conduct life cycle assessments and try to solve the challenge of finding the dominant life cycle phase. During the project, it has been discovered that the material life cycle phase is responsible for nearly 90% of the total energy consumption and CO_2 emissions of the products life, so the next step in the project is finding ways to improve this life cycle phase's sustainability. Related to this issue, another big challenge in this project is finding ways to reduce the high embodied energy and CO_2 emissions that come along with the aluminium industry. Consequently, in the project's discussion and conclusion, different suggestions such as using new manufacturing systems like Wire-Arc Additive Manufacturing, redesigning the product, changing the product's material or evaluating how recycled material affects the product life cycle, are analysed and presented; finding that these suggestions can be good strategies to follow.

Keywords:

Sustainability, product life cycle, aluminium industry, embodied energy, CO_2 footprint,

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CAD	Computer-Aided Design
PLC	Product Life Cycle
TBL	Triple Bottom Line
VOC	Volatile Organic Compound
WAAM	Wire-Arc Additive Manufacturing

1 INTRODUCTION

Sustainable manufacturing is becoming increasingly common and necessary among the different manufacturing industries around the world, and it is necessary to create awareness about how the current industrial processes are done and what needs to be done in order to have a sustainable development.

In this project, two cast aluminium products created by Vitsoe are analysed with the aim of making them more sustainable. These parts, that are called Floor/Ceiling Plate and Stabilising Foot, belong to one of the best-seller products from Vitsoe, the 606 Universal Shelving System. Vitsoe is a reference company in the furniture industry that strives for making long-lasting furniture of exceptional quality and always following the values of good design and being as sustainable as possible (Vitsœ, 2019a).

The issue with the Floor/Ceiling Plate and the Stabilising Foot is that their manufacturing processes are outsourced, consequently causing a lack of control over the sustainability of some of the life cycle processes. For this reason, this project has the main objective of analysing the product life cycle and improving its overall level of sustainability.

1.1 Aim and Objectives

More specifically, the first part of the project is a detailed review and analysis of the current life cycle processes for the two studied parts (Floor/Ceiling Plate and Stabilising Foot) of the 606 Universal Shelving System created by Vitsœ. One of the main goals of this analysis is to define and measure the level of sustainability for the products' lifecycle, using energy consumption and CO_2 footprint as the sustainability indicators.

After analysing the life cycle assessment results, several suggestions are made in order to improve the products' sustainability.

The following points show the objectives that have been defined for this thesis project:

- Review the current practices for evaluating sustainability.
- Have an overview of the current product life cycle processes.
- Carry out a product life cycle assessment, focusing on energy consumption and CO_2 footprint.
- Analise the product life cycle assessment and find the dominant life cycle phase.
- Suggest changes and improvements in the life cycle processes in order to improve the sustainability indicators.

2 LITERATURE REVIEW

2.1 Sustainable Development

It is widely known that the concept of *"Sustainability"* is increasingly gaining importance in today's world and society. Many problems such as climate change, global warming, lack of natural resources, species loss, deforestation, toxic waste accumulation and many others, are warning us that the industrial development has been non sustainable for many years, which could lead to a big catastrophe. For this reason, it is essential that the world wide industry adapts itself to a sustainable development (Krajnc and Glavič, 2003).

As O'Brien explains, the term *"Sustainable development"* was first introduced in 1987 on a report known as the Brundtland Report. This document was created by the World Commission on Environment and Development, and it stated that *"humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs".* As many other concepts, when they first appear they might be ambiguous and not precisely defined, but during the past years, the sustainability concept has been evolving and becoming a more solid concept (O'Brien, 1999).

Although there might still be some confusion around the concept of sustainable development, John Elkington came up with a sustainable development model in 1994 which has been widely accepted. This model is called the Triple Bottom Line (TBL) and it states that sustainability has three dimensions: environmental, social and economic. This means that global sustainability can only be achieved by addressing environmental, social and economic impact, and not just the environmental dimension as many people may think (Elkington, 1997). A good definition for this idea is the one presented by The Lowell Centre for Sustainable Development which says that *"sustainable production is the creation of goods and services using processes and systems that are non-polluting, conserving energy and natural resources, economically viable, safe and healthful for employees, communities and consumers, and socially and* *creatively rewarding for all working people"*. Figure 2-1 shows a graphic definition of the Triple Bottom Line model (Azapagic and Perdan, 2000; Krajnc and Glavič, 2003).

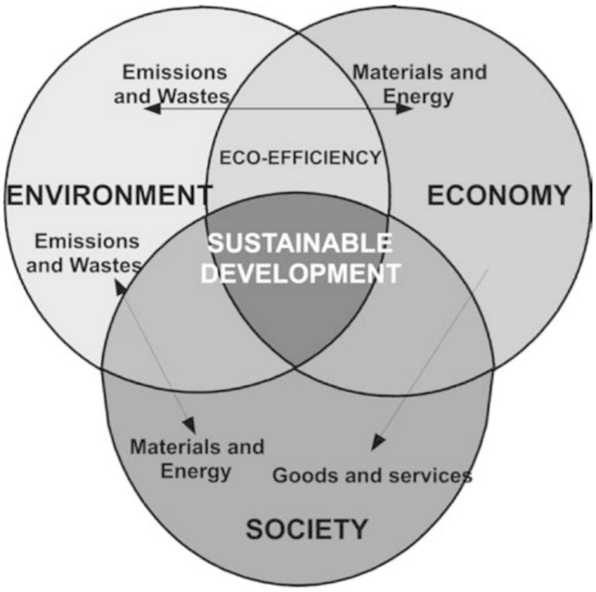


Figure 2-1 Triple Bottom Line model for sustainable development

2.1.1 Sustainable Development Challenges in Industry

As seen previously, during the past years, several organisations have tried to give a proper definition to the sustainable development concept. This is important from a theoretical point of view because it gives a meaning to the concept and it helps define what it actually means. Although necessary, this is not enough to achieve a global sustainable development in industry. Since this project is aimed at analysing a manufacturing company, this chapter presents some of the challenges that the manufacturing industry needs to overcome in order to achieve sustainable manufacturing processes.

As Despeisse et al. mention, it is clear that the manufacturing industry is a big contributor towards making a more sustainable society. Even though it hasn't always been a major priority in manufacturing, recently it has been gaining more and more importance due to increasing concerns on energy and climate change. Not only because becoming sustainable saves the world, but because there are many positive incentives and motivations that come as a consequence to becoming sustainable. Achieving an environmental and social sustainable development typically leads towards a big cost reduction that comes from a more efficient material and energy usage, a more efficient waste disposal, reuse and recycle. Also, most countries are developing legislation incentives, that benefit companies when they go towards being more sustainable. Moreover, society is becoming more aware about the need of sustainable development, so the customers are increasingly demanding cleaner and more ethical products and services. As exposed by Azapagic and Perdan, it has been proved by previous real cases that having a bad sustainability policy and consequently, a bad company reputation, can lead to a bad economic performance of the company (Azapagic and Perdan, 2000; Despeisse et al., 2012).

Presently, the importance of sustainable development is vastly known by most companies and their stakeholders. Knowing this fact, companies are starting to integrate environmental performance into their business strategy and their core values. O'Brien explains that in order to effectively achieve a sustainable business strategy in the manufacturing industry, it is essential to make a complete re-think of the industry's practices, taking into account the entire product life cycle. This includes the design, manufacturing, distribution and dispose or recycle of the products. O'Brien specially emphasizes the importance of a sustainable design and development phase given that it is when the entire product life cycle is defined (O'Brien, 1999). Following O'Brien's work, Krajnc and Glavič developed a set of conditions that need to be fulfilled by a manufacturing company so as to be considered sustainable, and that could suppose certain challenges for some enterprises. This set of conditions is presented below (Krajnc and Glavič, 2003).

- Reduction of material and energy usage in the product and its manufacturing process.
- Close the material loop to optimise resource usage and reduce waste.

- Minimise or avoid waste.
- Reuse and recycle products at the end-of-use phase.
- Disposal of non-recyclable products or waste must be done in an environmental friendly manner.
- Design products with longer life-cycles by making them easy to repair, adaptable and durable.
- Optimise and minimise needs for transportation.
- Adopt cleaner manufacturing technologies and procedures during the entire product life cycle.
- Research, develop and improve the process and the used technologies, making them more sustainable.
- Take into consideration the social role played by the firm and the impact it might have on society.

Since sustainable development is a relatively new concept in manufacturing, the methodologies to achieve the previously presented conditions are still in development. In the next chapter, a literature review about tools for measuring and controlling sustainability in the manufacturing industry is presented.

2.2 Measuring sustainability

Many authors and researchers on the subject suggest that the key tool for developing sustainable practices consists in using indicators to measure and control the different aspects of sustainability. Fan, Carrel and Zhang explain that for many years now, companies have used indicators to determine their business success. Some of these different indicator sets are widely standardised and are applied in the areas of finance, productivity, quality and so on. Regarding sustainability, several indicators have been developed in recent years such as life cycle assessments or carbon footprint, but there is still no consensus in having a standard and universal set of sustainability indicators that include the environmental, social and economic dimensions of sustainability (Fan, Carrell and Zhang, 2010).

On a different paper, Veleva et al. explain how the existing definitions and principles of sustainable manufacturing can help a company have a sustainable vision of the business as well as long term objectives. However, this might not be enough to achieve a sustainable development. Veleva et al. also suggest the need of developing and using a framework with indicators as a tool for companies while facing specific sustainability objectives. In the paper, Veleva et al. define an indicator as a qualitative or quantitative measurement that gives information about different parameters or systems. The main objectives of an indicator are (Veleva et al., 2001):

- Raise awareness and understanding
- Help decision-making by giving information
- Measure progress towards the established goals

In other words, what's essential for companies is to know what to measure and how to measure it, in order to make a progress towards achieving the defined sustainability objectives. It is necessary that these indicators are built in a framework to standardise how sustainability is measured and how the results are interpreted across the different manufacturing companies. Despite not having achieved a global standardised set of indicators some institutions are making big efforts to develop this subject in the near future. Joung et al. lists eleven indicator sets that have been developed with this purpose. Some of these include the *Global Reporting Initiative (GRI),* the *United Nations-Indicators for Sustainable Development (UN-ISD),* the *Core Environmental Indicators (CEI)* of the *Organisation for Economic Cooperation and Development (OECD),* or the *Environmental Performance Evaluation* standards from the *International Organisation for Standardization (ISO 14031)* (Joung et al., 2013).

The sustainability analysis that has been done in this thesis is a product life cycle assessment of the two aluminium parts. This assessment has been done with the CES EduPack software which uses energy consumption and CO_2 footprint as the main sustainability indicators.

3 METHODOLOGY

3.1 Life Cycle Process Flow

3.1.1 Current Life Cycle Processes

The main goal of this project consists in improving the level of sustainability of the Floor/Ceiling Plate and the Stabilising Foot products made at Vitsoe. In order to analyse this and evaluate possible improvement strategies, it is essential to understand what the current processes are and how they are done. Figure 3-1 and Figure 3-2 show an illustration of the 606 Universal Shelving System with the Floor/Ceiling Plate and the Stabilising Foot in the dotted circles, and how the products are used (Vitsœ, 2019b).

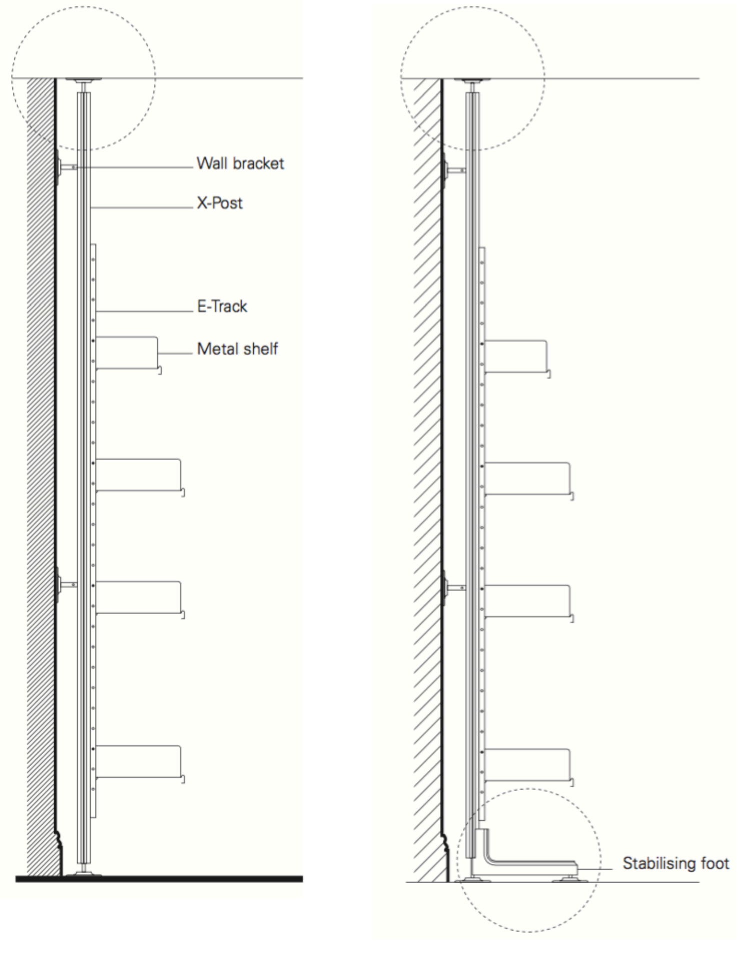


Figure 3-1 606 Universal Shelving System with the Floor/Ceiling Plate and Stabilising Foot in dotted circles

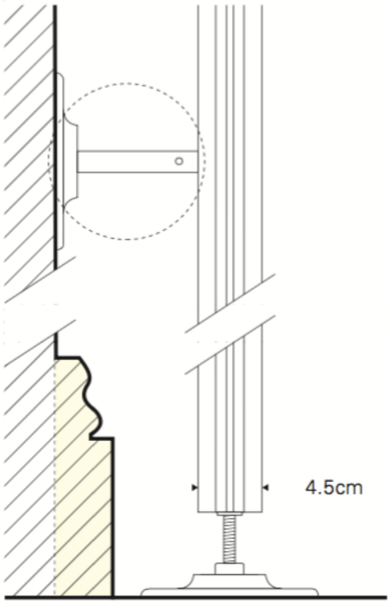


Figure 3-2 Use of the Floor/Ceiling Plate

The processes that are done during the product life cycle are explained in this section. The finality of this explanation is having a general overview of how this product life cycle is, and processes of the product life cycle can be targeted in order to achieve an improvement in the overall sustainability.

Figure 3-3 is a block diagram that shows the process flow of the product life cycle.

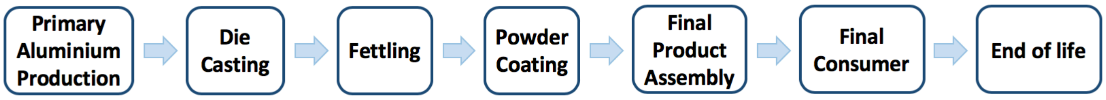


Figure 3-3 Product life cycle process flow

The product life cycle starts with the customer ordering the product. Current sales volume of the company is around 3500 Floor/Ceiling Plate parts and 200 Stabilising Foot parts per year. The entire manufacturing process of these parts are outsourced to a casting company.

First of all, it is necessary to have a primary aluminium production, the process for which is explained in section A.1. Once the primary aluminium is produced, it is shipped to the casting company, where the aluminium is remelted in order to carry out the die casting process. The casted part needs to have the scrap parts removed by trimming or cleaning all of the unneeded material. This process is commonly called fettling and it is a crucial process regarding material yield.

Material yield refers to the percentage of input material that actually ends up forming part of the final product, and values for material yield in die casting are estimated to be, for instance, approximately 67% (Andresen, 2005; Degarmo, Black and Kohser, 2003) or even reach values as low as 50% (Allwood et al., 2011). Figure 3-4 and Figure 3-5 show images of both the Floor/Ceiling Plate and the Stabilising Foot after being casted but before removing the risers and the feeders. These can be compared with the final products' shapes shown in Figure 3-9 and Figure 3-10.

Figure 3-4 Casting of the Floor/Ceiling Plate with riser and feeder

Figure 3-5 Casting of the Stabilising Foot with risers and feeder

After searching for material yield values in the literature and analysing the products studied in this project, an assumption has been made for the material yields, and the values are 55% for the Floor/Ceiling Plate and 60% for the Stabilising Foot.

The last manufacturing process is powder coating which gives the part its final surface finish and visual aspect. Once the parts are coated, they are sent to Vitsoe where they are stored and used in the 606 Universal Shelving System assembly process. After the final product is ready, it is shipped to the costumer, who uses the product until the end of life (Vitsœ, 2019c).

Regarding the end of life phase, there are several option that could be taken into consideration such as recycling, reusing, reengineering or landfilling. Any of these options could feasible, but since the company doesn’t currently have a post-consumer service and due to the lack of post-consumer information, the worst case scenario will be considered for this project: Landfilling will be assumed as the end of life option (Ashby, 2009).

In Appendix A, some of the most critical manufacturing processes are explained in more detail.

3.2 Product Life Cycle Assessment

As its name explains, a product life cycle assessment is in charge of assessing the sustainability impact caused by a product during its entire life cycle. It is a common mistake to just think about the manufacturing and use stages of a product when trying to assess its impact on sustainability. But it is crucial to see the bigger picture and have in mind the entire product life cycle. This includes the stages of material obtaining, manufacture, use, transport and disposal. This way it is possible to see a realistic image of the actual impact the product has during its life cycle. Figure 3-6 shows a schematic view of the product life cycle, that starts with natural resources and material production, continues with product manufacture, product use, and finishes with different options for the product disposal at end of life (Ashby et al., 2009). As seen on the drawing, the product can either be disposed to landfill, it can be reused or remanufactured, or lastly, it can be recycled into new material.

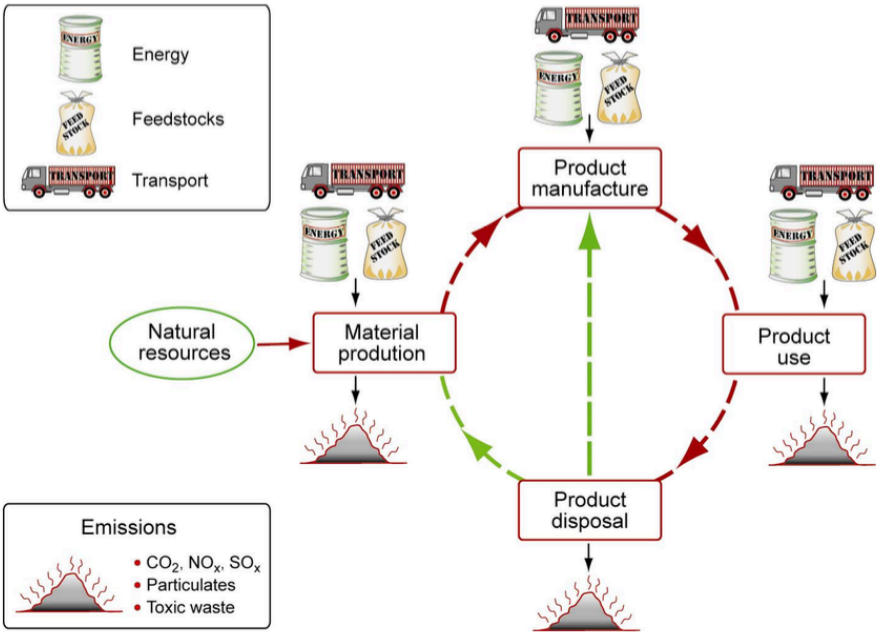


Figure 3-6 Schematic view of the product life cycle with different options for product disposal at end of life

The tool used in this project to assess the product life cycle is the EcoAudit tool from CES EduPack software. As Ashby et al. explain, there are three components to the approach that the software uses to assess the product life cycle (Ashby et al., 2009).

First of all, the software gives the results in the form of two relatively basic but very relevant indicators: Energy consumption and CO_2 emissions. These two indicators are actually related and are the chosen ones because they are easy to understand, they can be applicable to any industry and their value is highly significant.

Secondly, the software breaks down the total life-energy demand of the product into the different life cycle stages and it gives an estimate percentage of total life energy and CO_2 footprint that is linked to each of the different life cycle phases. This information is crucial for the project because it allows the user to know what stages of the product life-cycle are responsible for the environmental impact. Once this information is known, it is straightforward to focus on the correct life cycle stage. To give this information, the software uses a combination of user-defined inputs (that will be explained in section 3.3.1) and data drawn from the software databases. There is a wide range of data in these databases that include embodied energy of materials, embodied CO_2 footprint of materials, process energy and CO_2 emissions, as well as transportation energy and CO_2 emissions.

Moreover, Ashby et al. make two statements that support the use of this methodology. The first one says that normally one of the life cycle phases is considerably dominant compared to the others, in terms of energy consumption, accounting for more than 60% of the total life energy demand. So, important energy savings can be achieved by targeting the dominant phase. The second statement says that due to having this dominant life cycle phase, there is usually a big difference in energy consumption if you compare the dominant phase with the other ones. Consequently, great precision is not needed so it is a smart decision to use a simple but straightforward tool like the EcoAudit on the CES EduPack software instead of using an expensive and time consuming life cycle assessment tool. Figure 3-7 (Ashby et al., 2009) shows six examples of the breakdown that the CES EduPack software does of the total life energy of a product into the different life cycle phases (the disposal phase is excluded for simplification reasons). Ashby's statements are clearly observable on most of these example.

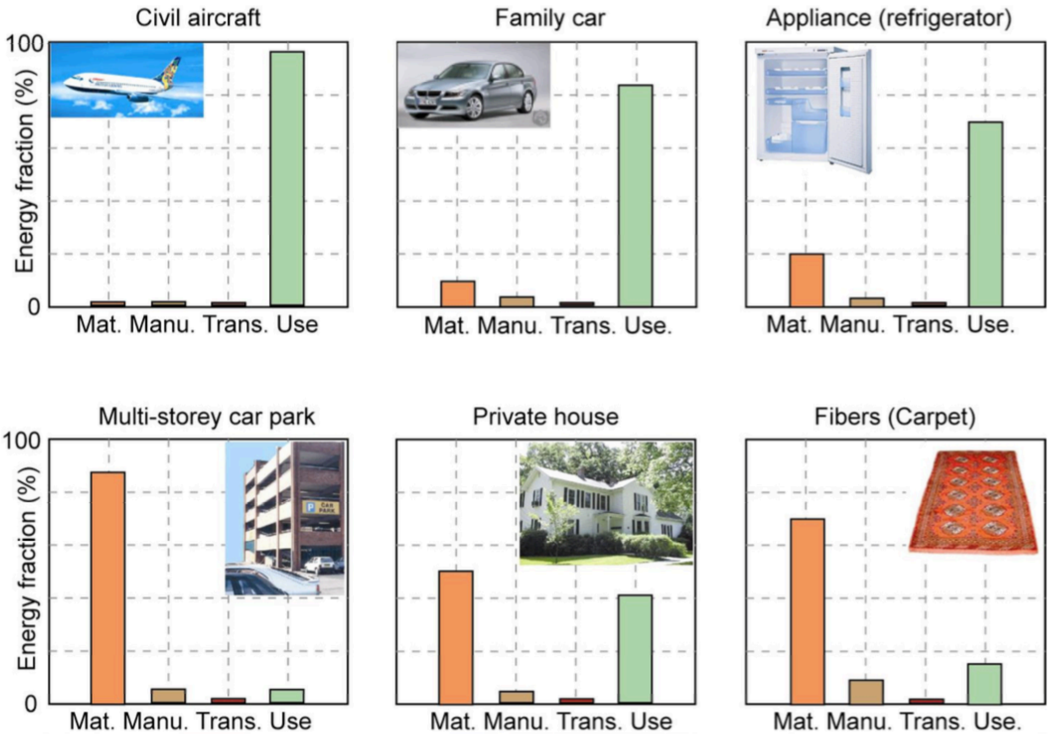


Figure 3-7 Energy consumption values for the different life cycle phases of six different products

In the last place, Ashby et al. talk about the importance of the strategy or actions that must be taken after the life cycle assessment. Ashby et al. suggest focusing on the dominant life cycle phase and they recommend several objectives that should be targeted in order to improve the energy consumption and CO_2 emissions of each of the different life cycle phases.

In the first place, if the dominant life cycle phase is the material production, it is key to minimise the mass of the product and the amount of material used to manufacture the product, as well as choose materials with low embodied energy and low CO_2 footprint.

If the maximum energy consumption happens during the manufacturing phase, the objectives will be focused towards reducing the energy consumption and CO_2 emissions of the manufacturing processes.

If the critical issue is found in the transport phase, the goal will be to minimise the total travelled distance involved in the product life cycle or changing the transportation method to a more sustainable one.

When the use-phase has the highest contribution to the total life energy consumption, the challenges that need to be addressed will be related to the product itself and will depend on the product, its design and its functionalities. Some examples are reducing energy and heat losses or reducing the mass if the product moves.

Finally, if the dominant life cycle phase is the product disposal, it will be crucial to select non-toxic materials, materials that can be easily recycled and reused or, for instance, designing the product in a way that circular economy could be easily implemented. Circular economy is defined as an economic system that has the objective to eliminate waste and the use of resources by recycling, reusing and remanufacturing; achieving a closed material loop (Geissdoerfer et al., 2017).

Figure 3-8 shows a schematic view of the previously explained strategies (Ashby et al., 2009).

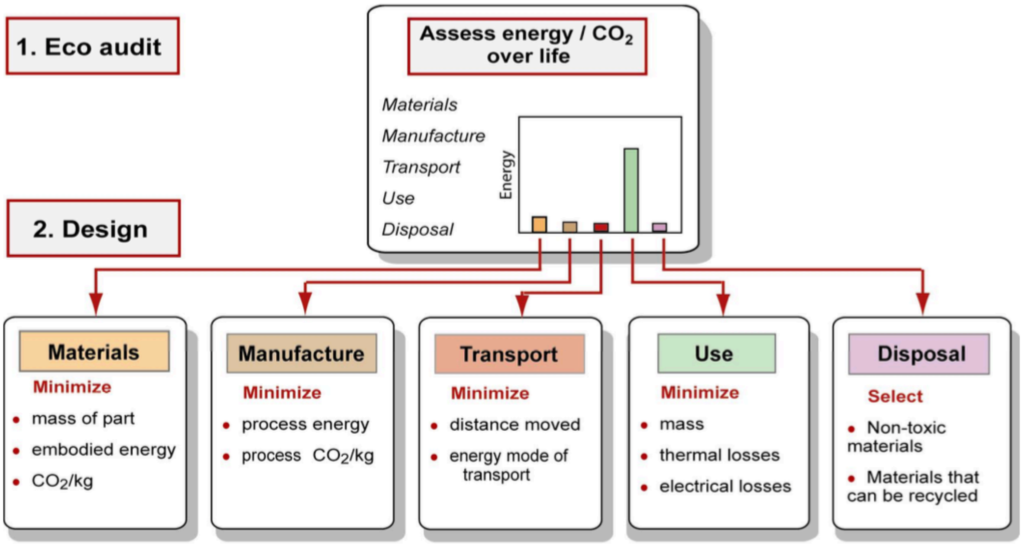


Figure 3-8 An example of the EcoAudit result and the suggested strategies to follow

3.3 Life Cycle Evaluation

The following sections explain how the life cycle assessment has been carried out, including what data has been given to the software and what calculations and assumptions have been made.

3.3.1 CES EduPack software - EcoAudit

The first data that needs to be introduced in the software is related to the product itself. Firstly, it is necessary to define all of the components that belong to the product, but since the products analysed in this project just have one component, there will only be one component introduced into the software for each of the products.

The selected material has been LM6 aluminium alloy which can also be named A413.0 aluminium alloy. The software has the option to introduce the recycled content of the raw material. Even though, according to the International Aluminium Institute (IAI), there is a 32% of average recycling input rate in the manufacturing industry (International Aluminium Institute, 2009), in this case the die casting supplier works only with virgin aluminium, so for the life cycle assessment a 0% of recycled material has been selected. Finally, the software asks for the mass of the component. Since this was initially unknown, CAD drawings on SolidWorks have been developed using the original blueprints, which have been ceded by the company. Developing these CAD drawings has helped understand the products better, their shape and functionality. Also, SolidWorks gives the volume of the part so it has been possible to calculate the mass of both products, using equation (3-1) and considering that LM6 aluminium alloy density is 2650 $\frac{kg}{m^3}$ (Granta Design, 2018). Figure 3-9 and Figure 3-10 show the CAD drawings of the Floor/Ceiling Plate and the Stabilising Foot.

$$Density\left[\frac{kg}{m^3}\right] = \frac{Mass\ [kg]}{Volume\ [m^3]} \tag{3-1}$$

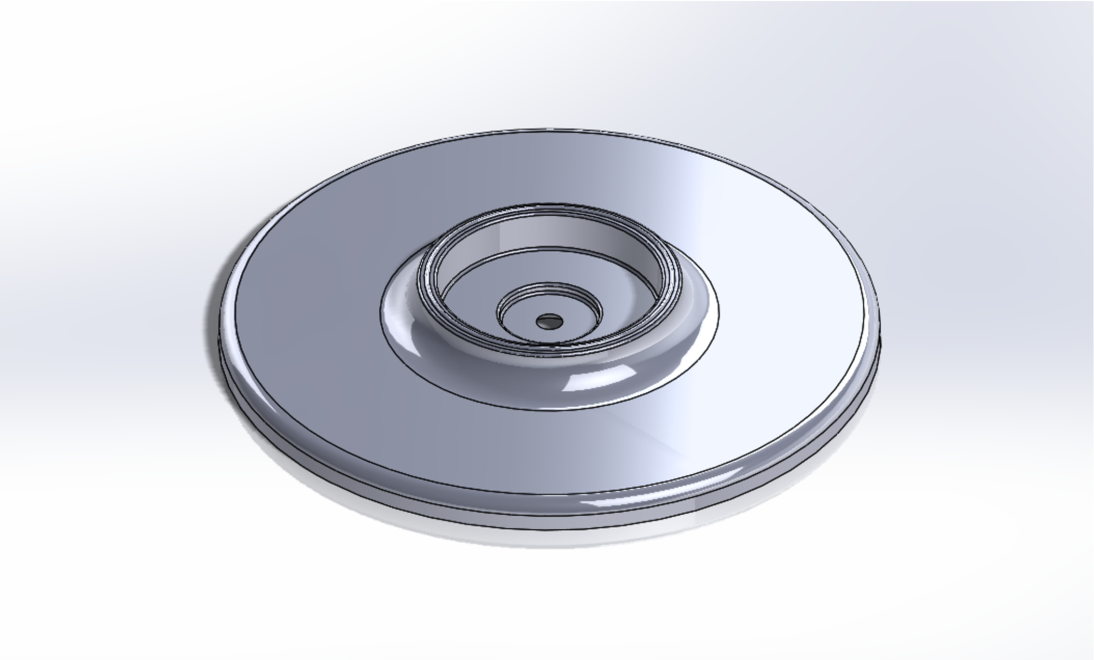


Figure 3-9 CAD drawing of the Floor/Ceiling Plate on SolidWorks

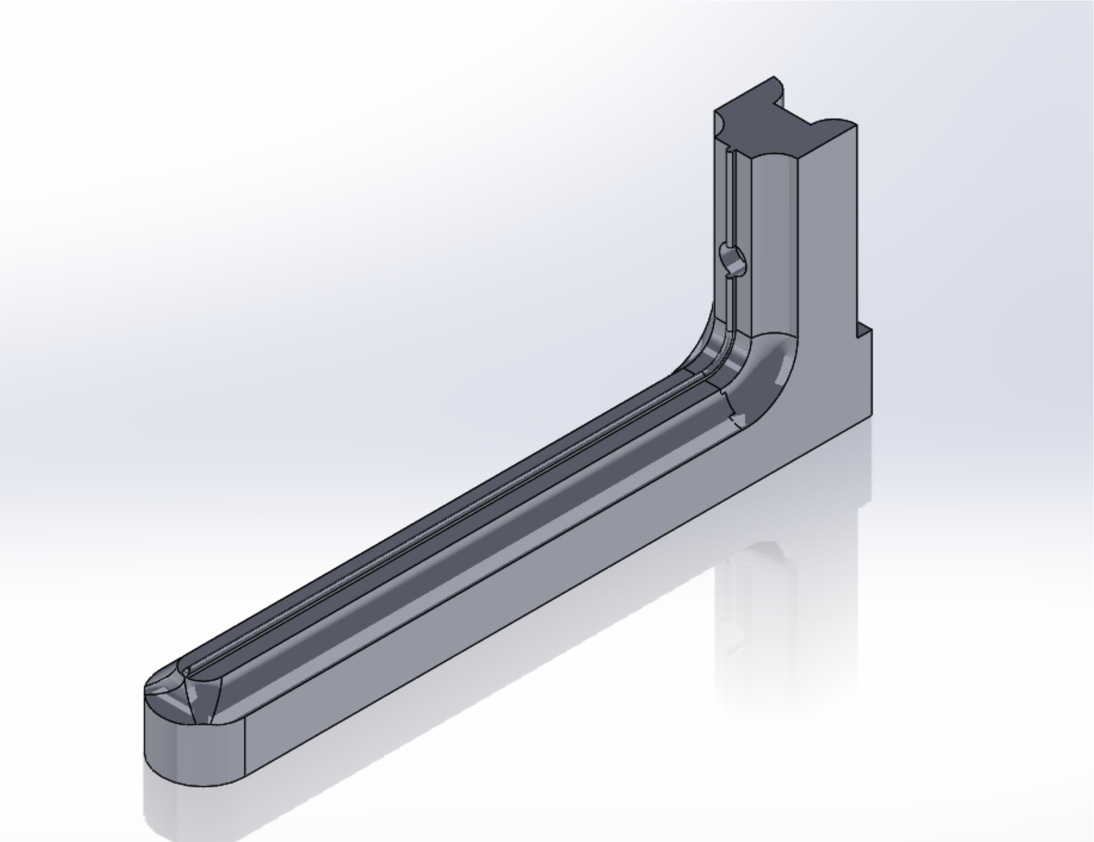


Figure 3-10 CAD drawing of the Stabilising Foot on SolidWorks

Using the methodology previously explained, the mass of both products has been calculated and introduced into the software. The value for these are 0.18 kg for the Floor/Ceiling Plate and 1.28 kg for the Stabilising Foot.

Regarding the manufacturing process, the software allows two types: the primary process and the secondary process. As seen previously, both parts are made from LM6 aluminium alloy and are manufactured by die casting. The primary process has been selected as casting, whereas the secondary one, has been selected as cutting and trimming. This secondary process simulates the fettling process that takes place after the die casting which is done in order to remove the scrap from the casted part. It is also necessary to indicate what percentage of material has been removed in the process. In other words, the software asks for the material yield rate of the manufacturing process. Allwood, Ashby et al. mention in a paper that the discarded material throughout these manufacturing processes can be up to 50% (Allwood et al., 2011). Other authors have estimated an average material yield value of 67% (Andresen, 2005; Degarmo, Black and Kohser, 2003). Having these values as references, and estimation of the material yield for this process has been done in section 3.1.1, obtaining an approximate material yield value of 55% for the Floor/Ceiling Plate and 60% for the Stabilising Foot.

To evaluate the product life cycle it is important to consider the disposal phase of the product and analyse what happens at its end of life. Since there is no available information about the actions that the final consumer takes at the end of life of the product, it has been considered that the product is landfilled, so as to consider the worst case scenario.

The following information that needs to be introduced in the software is related to the finishing post processes that the product undergoes at the end of the manufacturing. Any painting, coating, welding, joining or any other finishing post processes also need to be taken into consideration for the life cycle assessment. In this case, the only process done to both of the parts is the powder coating. As seen in chapter A.3 the impact of the powder coating on the product life cycle can be negligible, but in order to improve the accuracy of the analysis, it has been added to the product life cycle assessment. Since the powder coating goes on the surface of the product, it has been necessary to calculate the surfaces of both products. The SolidWorks CAD drawings shown previously in Figure 3-9 and Figure 3-10 have given this information which is approximately 0.03 m^2 for the Floor/Ceiling Plate and 0.102 m^2 for the Stabilising Foot.

Regarding the impact of the transportation during the product life cycle, there is an option to select the type of vehicle the transportation is done and how much distance is covered. The travelled distance during the manufacturing processes has been estimated to be 65 kilometres.

Since these products belong to the furniture industry and don’t need any additional energy to function, the section about the usage energy has been skipped. Moreover, after talking with the product experts at Vitsoe, it has been considered that the average life duration of the product is around 20 years.

4 LIFE CYCLE ANALYSIS RESULTS

In this chapter, the results from the product life cycle assessment done with the CES EduPack software are analysed. As explained in section 3.2, the goal of this analysis is finding out how the total life energy of the product is distributed throughout the different stages of the product life cycle. The analysis is divided in two different sections for each of the products, the Floor/Ceiling Plate and the Stabilising Foot respectively.

4.1 Floor/Ceiling Plate

Figure 4-1 shows a graph with the relative contribution of each life phase regarding energy consumption and CO_2 footprint. The specific values given by the software for energy consumption and CO_2 footprint are shown in Table 1.

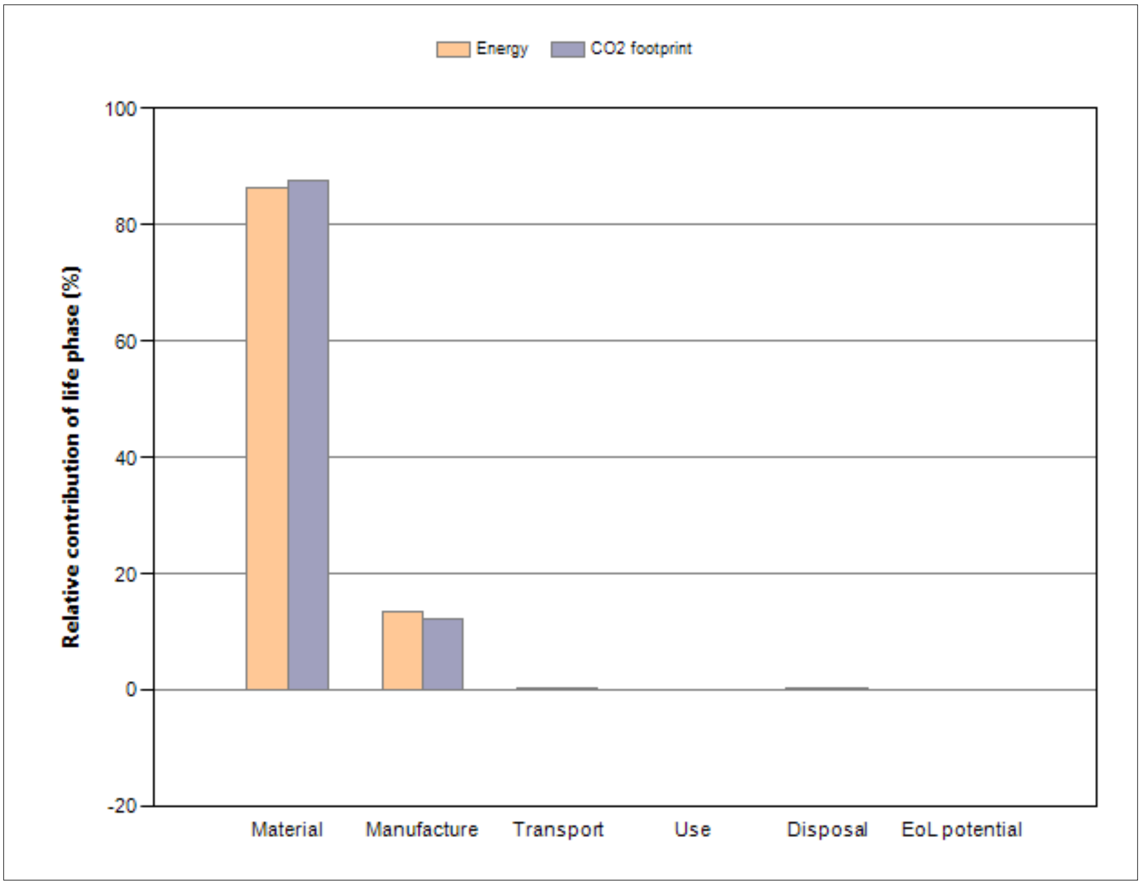


Figure 4-1 Relative contribution of life phase for energy consumption and CO_2 footprint of the Floor/Ceiling Plate

Table 1 Product life cycle assessment results of the Floor/Ceiling Plate

Phase	**Energy (MJ)**	**Energy (%)**	**CO_2 footprint (kg)**	**CO_2 footprint (%)**
Material	38.2	86.4	2.49	87.7
Manufacture	5.97	13.5	0.346	12.1
Transport	0.0176	0.0	0.00126	0.0
Use	0	0.0	0	0.0
Disposal	0.036	0.1	0.00252	0.1
Total (for first life)	**44.2**	**100**	**2.84**	**100**
End of life potential	0		0	

As seen on Figure 4-1 and **Error! Reference source not found.**, 86.4% of the total life energy and 87.7% of the total CO_2 footprint of the Floor/Ceiling Plate corresponds to the material phase. This validates Ashby's statement mention in section 3.2 that says that typically, the dominant life cycle phase corresponds to more than 60% of the total life energy demand of a product (Ashby et al., 2009). Also, it is possible to confirm that the material phase is the dominant phase in terms of energy consumption and CO_2 footprint, so it will be the targeted phase in order to cause the biggest impact possible towards improving the sustainability level of the product life cycle. Regarding the entire product life cycle, the total life energy consumption values adds up to 44.2 MJ per product or in other words, 245.5 MJ per kilogram of product.

The manufacturing phase of the product life cycle has a 13.5% and 12.1% contribution to the total life energy consumption and CO_2 footprint respectively. Regarding the phases of transport, use and disposal, they can be considered as negligible due to having just a 0.2% contribution.

The energy consumption value for the material phase corresponds to the embodied energy in the material that comes from the aluminium production and is 38.2 MJ. This value has been converted to know what is the embodied energy per kilogram of aluminium and it is 212.01 MJ per kilogram. With the finality of validating whether this value is representative or not, the literature has been searched in order to find other values for embodied energy in aluminium. Allwood et al. state that embodied energy for aluminium ranges in between 190 and 230 MJ per kilogram (Allwood et al., 2011), whereas in the book *Sustainable Materials with Both Eyes Open* it is stated that commonly, the embodied energy that comes from producing aluminium is 168 MJ per kilogram (Allwood and Cullen, 2012). The value obtained by the CES EduPack software is somewhat higher than the values found on the literature but still in an acceptable range. Consequently, the calculated consumption energy present in Table 1 can be considered as acceptable.

Likewise, the CO_2 footprint for the material phase is 2.49 kilograms of CO_2 per part and during the product life cycle it adds up to 2.84 kilograms of CO_2 per unit. In order to verify this value, the average world CO_2 footprint per GJ of energy has been taken, with a value of 63 $\frac{kg\ of\ CO_2}{GJ}$ (Jolly and Salonitis, 2017). This value has been multiplied by 0.0442 GJ of energy, the energy consumption during the product life cycle. The result is 2.78 kg of CO_2 for the entire product life cycle. Since there is just a 2.16% of error, the results of the software will be considered as acceptable. The equivalent CO_2 footprint per kilogram of product is 15.78 kg of CO_2.

In case more specific information is needed, a more detailed report on the product life cycle assessment of the Floor/Ceiling Plate is presented in the Appendix chapter B.1.

4.2 Stabilising Foot

The same procedure explained in section 4.1 has been applied for the Stabilising Foot. Figure 4-2 and Table 2 show the relative contribution to energy consumption and CO_2 footprint of each of the product life cycle phases as well as the corresponding values.

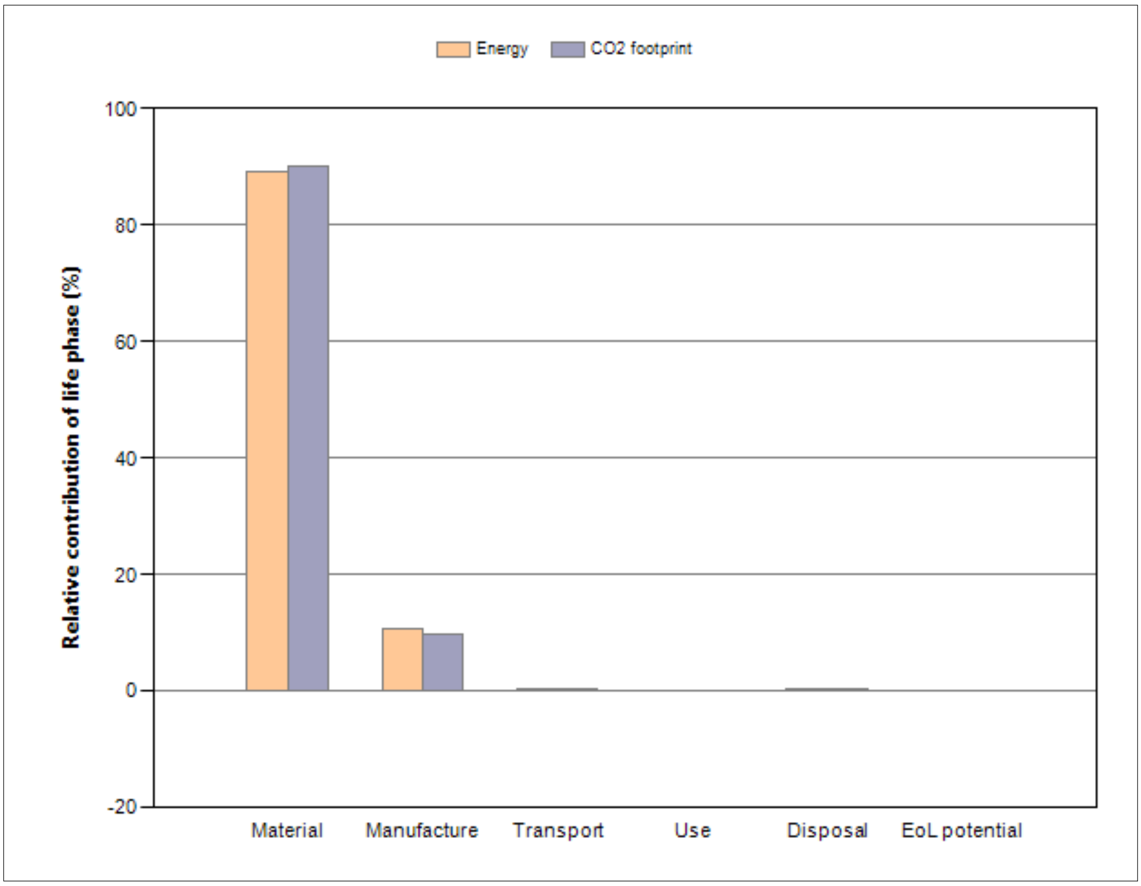


Figure 4-2 Relative contribution of life phase for energy consumption and CO2 footprint of the Stabilising Foot

Table 2 Product life cycle assessment results of the Stabilising Foot

Phase	**Energy (MJ)**	**Energy (%)**	**CO_2 footprint (kg)**	**CO_2 footprint (%)**
Material	265	89.2	17.2	90.1
Manufacture	31.8	10.7	1.87	9.8
Transport	0.125	0.0	0.00899	0.0
Use	0	0.0	0	0.0
Disposal	0.256	0.1	0.0179	0.1
Total (for first life)	**298**	**100**	**19.1**	**100**
End of life potential	0		0	

In the case of the Stabilising Foot, the material phase has an energy consumption of 265 MJ which corresponds to 89.2% of the total life energy demand and 17.2 kg of CO_2 which corresponds to 90.1% of the total CO_2 footprint. So once again, it is the material phase that stands for the dominant life cycle phase. These values are equivalent to saying that the energy consumption and the CO_2 footprint of the material phase are 207.03 MJ and 13.44 kg of CO_2 per kilogram of aluminium, respectively.

When looking at the entire product life cycle, the energy consumption and the CO_2 footprint are 298 MJ and 19.1 kg of CO_2 per unit which correspond to 232.8 MJ and 14.9 kg of CO_2 per kilogram of product.

Using the equivalent values per kilogram of product, it is straightforward to compare both products and say that they present very similar values, but a bit higher for the Floor/Ceiling Plate. This makes sense because both products are made from the same material and undergo the same processes, with the difference that the material yield is 5% smaller for the Floor/Ceiling Plate.

In case more specific information is needed, a more detailed report on the product life cycle assessment of the Stabilising Foot is presented in the Appendix chapter B.2.

5 DISCUSION

5.1 Life Cycle Analysis Result Discussion

During the life cycle assessments presented in section 4.1 and section 4.2 one of the main goals of the project has been achieved. The energy consumption and CO_2 footprint of both products have been studied and broken down into the different life cycle phases. It has been demonstrated that the material phase is the dominant life cycle phase, accounting for over 85% of the total life energy demand and CO_2 footprint.

As explained in section 3.2 and following the methodology exposed by Ashby et al., in order to achieve a meaningful improvement of the level of sustainability in the product life cycle, the dominant life cycle phase should be targeted. In this case, since the material phase is the dominant life cycle phase, it is a crucial objective of the project to suggest and evaluate possible strategies that can reduce the energy consumption and CO_2 footprint that come along with this dominant life cycle phase.

As explained by Ashby et al., a strategy followed to reduce the energy consumption and CO_2 footprint of the material phase is related to reducing the embodied energy that comes with the materials that compose the product. To do so, Ashby et al. suggest to change the materials to others with less embodied energy, minimise the mass of the product or minimise the quantity of material present in the product. Since most every material has embodied energy, the fewer material there is in the product, the fewer embodied energy the product will have (Ashby et al., 2009).

Similarly, Milford et al. say that a good way to reduce the embodied energy in a product is by improving the material yield of the different processes that take place during the product life cycle. As mentioned previously in this report, material yield refers to the percentage of output material with regard to the input material of a process. By improving the material yield of a manufacturing process, a higher material efficiency is achieved. This way, there is less material scrapped and it is straightforward to conclude that the higher the material efficiency is, the lower the embodied energy will be for a same product. To achieve an increase in material yield, Milford et al. suggest three possible strategies.

The first strategy consists in finding new manufacturing processes that are able to achieve better material utilisation values. In the second place, it is suggested to improve the efficiency of current processes. Finally, Milford et al. propose making modifications in the design of the product. These design modifications should always be focused towards improving the sustainability level of the product and can include a material change to one with lower embodied energy or a complete redesign of the product to reduce the mass and quantity of material used to manufacture it (Milford, Allwood and Cullen, 2011).

To conclude with, the last strategy presented in this project is integrating the utilisation of recycled aluminium as a raw material input. Allwood and Cullen state that the recycled content of the input liquid metal have a direct influence on its embodied energy, so increasing the recycled content of the input material will decrease its embodied energy. Recycling aluminium just requires 5% of the energy needed to produce primary aluminium, so every time aluminium is recycled, its embodied energy gets considerably reduced. Since the products studied in this project only use virgin aluminium, implementing the use of recycled raw material would potentially be a good strategy (Allwood and Cullen, 2012).

All of the ideas previously mentioned have been grouped into three possible strategies to follow in order to reduce the energy consumption and CO_2 footprint of the material phase of the products' life cycle. These three strategies are:

- Modify the design of the product in order to reduce material embodied energy or minimise the mass and volume of the product.
- Evaluate other manufacturing systems which could improve the material yield.
- Implement the use of recycled aluminium as an input raw material.

5.2 Sustainability Improvement Strategies

5.2.1 Product Redesign

One of the methods for reducing energy consumption and CO_2 footprint of the product life cycle is making a sustainably focused product redesign. For this project, two possible strategies have been taken into consideration for the product redesign.

The first one consists in redesigning the shape of the product in order to minimise the weight and material quantity in the manufactured part. Reducing the quantity of material used will naturally reduce the amount of embodied energy present in the product. For this to be effective it is necessary to maintain or improve the material yield during the manufacturing processes. For instance, if a redesigned product increases its process material yield as well as its process scrap, having reduced the weight will be useless because the overall sustainability level will have worsened.

Regarding this redesign strategy, it has ended up not being evaluated in this project due to the company's requirements. The products at Vitsoe have iconic designs that have been created by designer Dieter Rams and add much value to the products. For this reason, a product redesign will not be considered in this project and it will just be suggested as possible future works (Vitsœ, 2019c)

The second redesign strategy consists in maintaining the same design, but changing the material used for the product. For this project's case, there could be other materials besides aluminium that match the design requirements whilst having a lower embodied energy.

As seen on Figure 5-1, aluminium clearly has one of the highest embodied energies of the commonly used materials in manufacturing, followed by plastics which have approximately half of the embodied energy (Allwood and Cullen, 2012).

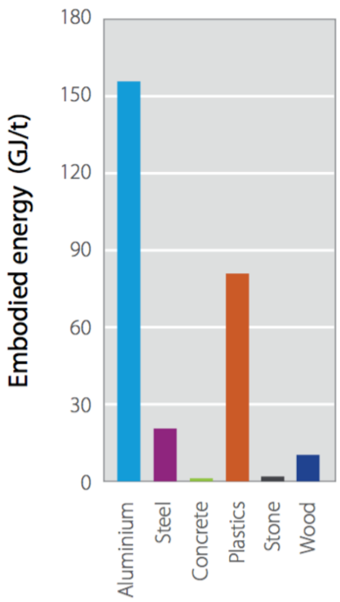


Figure 5-1 Embodied energy of different key materials

The main condition that needs to be accomplished in order to have a successful material change is meeting all of the product requirements. These requirements may include, stress and structural needs, visual aspect or cost requirements.

In order to evaluate the impact a material change would cause on the product's sustainability, new product life cycle assessments have been done considering stainless steel as the material used in the product. As Allwood and Cullen explain, stainless steel is a suitable material to substitute some aluminium products. Naturally, some of the product properties will change but as long as the product requirements are still accomplished, the material change will be valid. As possible future works it would be interesting to test prototypes of these products with other materials in order to see if the requirements are fulfilled.

The finality of this analysis is to compare the new energy consumption and CO_2 footprint with the current ones, to see what potential improvement can be achieved by changing the product material. The analysis has been done with the CES EduPack software, although some conditions of the analysis have needed a modification.

On the one hand, the product volume has been maintained as a constant value but the weight has been adapted using the different densities. As seen previously, the LM6 aluminium alloy density has been considered 2650 $\frac{kg}{m^3}$, whereas the stainless steel has been considered 7900 $\frac{kg}{m^3}$ (Glenn Elert, 2004). Using equation (3-1), the new masses of the products have been calculated, which are 3.82 kilograms for the Stabilising Foot and 0.54 kilograms for the Floor/Ceiling Plate.

On the second hand, typical material yield values differ from aluminium to steel. Following Allwood and Cullen's investigations, the material yield for steel casting has been considered 74% (Allwood and Cullen, 2012).

Also, in order to compensate the density difference between both materials, the energy consumption an CO_2 footprint data are shown per kilogram of material.

Table 3 Life cycle assessment comparison between stainless steel and LM6 aluminium alloy

Product	Material	Material phase energy demand [MJ/kg material]	Material phase CO2 footprint [kg CO2/kg material]
Floor/Ceiling Plate	Stainless Steel	72.1	4.9
	LM6 Al Alloy	212.2	13.8
Stabilising Foot	Steel	77.5	5.4
	LM6 Al Alloy	207.1	13.4

Table 3 shows the comparison between the results of the material phase of the life cycle assessments for the two different materials, steel as the new one and LM6 aluminium alloy as the current material. The results show that using stainless steel could potentially reduce the energy consumption and CO_2 footprint of the material life cycle phase by 65% and 62%, respectively.

5.2.2 New Manufacturing Systems

It has been seen previously that the values for the material yield of the Floor/Ceiling Plate and the Stabilising Foot are 55% and 60% respectively. Despite having all this aluminium scrap remelted and reused in the manufacturing process, there will always be a 40% or 45% of material that never makes it to the final product and that is always constantly circulating in an internal loop. This supposes a big and inefficient energy consumption and CO_2 footprint. For this reason, improving the material yield, and consequently, improving the material efficiency of the manufacturing process is a good strategy to reduce the energy consumption and CO_2 footprint of the material phase of the product life cycle (Allwood and Cullen, 2012).

With the objective of finding alternative manufacturing systems that can improve the material yield, two different options have been analysed: Machining and additive manufacturing.

5.2.2.1 Machining

Machining is a conventional manufacturing system that manufactures a part with the desired shape and size by cutting and removing material from an originally bigger material block. This manufacturing system is widely used, especially with metallic raw materials and it is part of a group of manufacturing systems commonly known as subtractive manufacturing systems (Sreejith, 2008).

To calculate an estimation of the material yield of this process it is essential to define what the shape and size of the original material block is. For the Floor/Ceiling Plate, it has been considered that the raw material block should have a cylindric shape with a 150 millimetre diameter and 15 millimetres of height. Regarding the Stabilising Foot, the material block should be rectangular with 360x150x50 millimetre dimensions. These dimensions have been chosen in such a way so that the original raw material block is as small as possible (Sandvik, 2019).

Material yield can be defined as the percentage of output material regarding the input material, so it can be calculated with equation (5-1) (Allwood and Cullen, 2012).

$$Material\,Yield\ [\%] \ = \frac{V_{output}[m^3]}{V_{input}\ [m^3]}\ x\ 100 \tag{5-1}$$

The defined dimensions for the input raw material blocks have been used to calculate the input material volume, whereas the output material volumes have been given by the CAD drawings developed in Solidworks. The material yield results are shown, compared and discussed in section 5.2.2.3.

5.2.2.2 Additive Manufacturing

Additive manufacturing is a relatively innovative group of manufacturing systems which consist in adding material in order to create a part, instead of removing material from a material block. Naturally, this is very interesting in terms of material yield because nearly all of the input material ends up in the final product (Allwood and Cullen, 2012).

There are different technologies regarding additive manufacturing, so it has been necessary to search the literature in order to find which would be the right technology for the applications presented in this project. Garcia-Colomo et al. published a paper comparing different additive manufacturing technologies which has been very useful for finding the right technology. Finally, Wire-Arc Additive Manufacturing (WAAM) has been chosen as the appropriate technology for the applications in this project. It is stated that material efficiency is between 90%-100%, placing WAAM as one of the best available technologies in terms of material efficiency. The selected value for material yield of additive manufacturing is 90% in order to choose the worst case scenario (Garcia-Colomo et al., 2018).

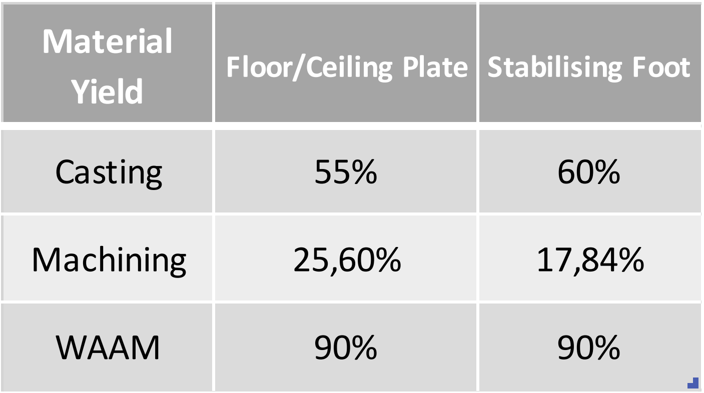
The main drawback of using additive manufacturing compared to traditional manufacturing systems such as die casting is the increase of the cost it may suppose. Additive manufacturing technologies are still under development and not widely used so they suppose a much higher cost compared to other conventional technologies due to economies of scale. Nonetheless, using WAAM as the manufacturing process would suppose a major improvement regarding material yield which could drastically reduce the embodied energy and CO_2 footprint that come along with the material phase of aluminium product life cycles.

Another major issue of using WAAM is the fact that the products could not be made of the same aluminium alloy. As mentioned previously, the Floor/Ceiling Plate and the Stabilising Foot are made of LM6 aluminium alloy which is a casted alloy, and WAAM only works with wrought aluminium alloys. After discussing this issue with the product experts at Vitsoe, it was concluded that a possible solution would be changing the material of the products to 6063 aluminium alloy, which is a feasible material for WAAM (Lei et al., 2017). 6063 aluminium alloy is the material used for the metallic parts that are attached to the Floor/Ceiling Plate and the Stabilising Foot. By using this material it would be possible to achieve a uniform visual aspect which is a positive achievement for the company’s interests. To achieve this uniform visual aspect it would be necessary to add an anodising process which could easily replace the powder coating process (Vitsœ, 2019c).

5.2.2.3 Manufacturing Systems Comparison

In Table 4 the material yield results for the different manufacturing systems are shown and compared.

Table 4 Material yield values for different manufacturing systems



Material Yield	Floor/Ceiling Plate	Stabilising Foot
Casting	55%	60%
Machining	25,60%	17,84%
WAAM	90%	90%

As seen on Table 4, the yield values for machining are noticeably worse than for casting so this manufacturing process has been discarded. On the other hand, WAAM increases the material yield, placing this technology as an attractive option in order to reduce the embodied energy and CO_2 emissions of the material phase of the product life cycle.

5.2.3 Recycling Input Aluminium

Recycling is the process used to recover materials at their end-of-life phase and turn them into usable materials again. It is a highly known and developed concept, especially for easily recycled materials such as aluminium. Recycling materials, usually demands less energy than obtaining virgin materials, plus, it helps reduce or even avoid earth exploitation for extracting raw materials. This is why recycling is a widely encouraged option for improving the sustainability in the manufacturing industry (Ashby, 2009).

The theoretical value of energy consumption demand when recycling aluminium is just 5% of the energy needed to produce primary aluminium. After seeing a practical case study from the book *Sustainability With Both Eyes Open* it has been demonstrated that this value can be higher, even reaching 26% or more when looking at the complete manufacturing process of the final product (Allwood and Cullen, 2012).

To evaluate the impact that recycled aluminium would have on the life energy consumption, an analysis has been done using the CES EduPack software. Different percentages of recycled content have been selected for the input raw material, allowing the possibility to see how this influences the energy consumption that comes along with the material phase of the product life cycle.

To begin with, the analysis has been done for the Floor/Ceiling Plate. Table 5 shows the embodied energy and CO_2 footprint of the material phase of the product's life cycle for different percentages of recycled content in the input raw material. Figure 5-2 and Figure 5-3 display graphs showing the information presented in Table 5.

Table 5 Embodied energy and CO_2 footprint of the material phase of the Floor/Ceiling Plate for different recycled content

Recycled content of raw material	Embodied energy of material [MJ]	CO2 Footprint [kg]
0%	38.2	2.49
10%	35.4	2.33
20%	32.7	2.16
30%	29.9	1.99
40%	27.1	1.83
50%	24.4	1.66
60%	21.6	1.49
70%	18.9	1.33
80%	16.1	1.16
90%	13.3	0.994
100%	10.6	0.827

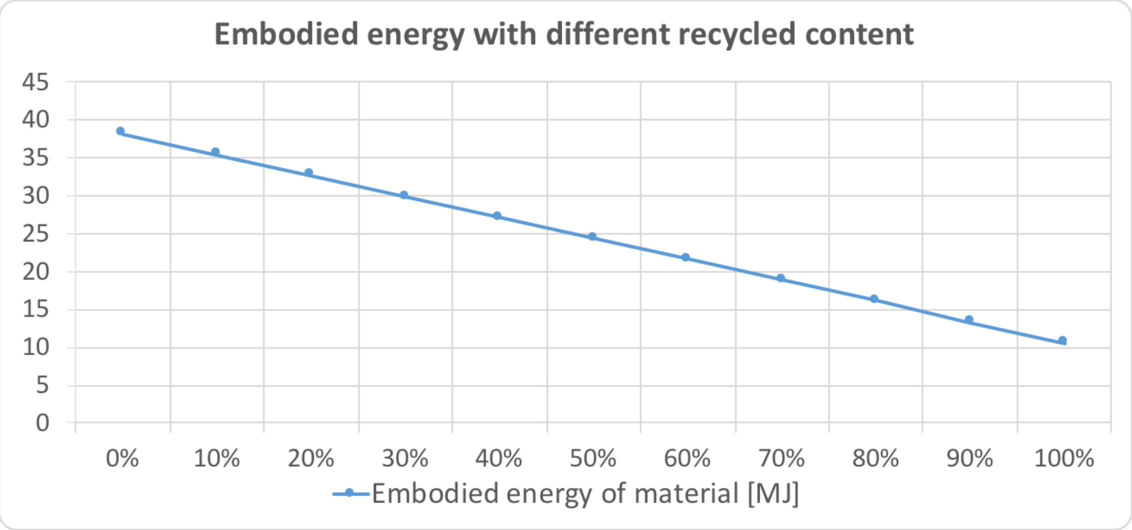


Figure 5-2 Embodied material energy of the Floor/Ceiling Plate for different recycled content

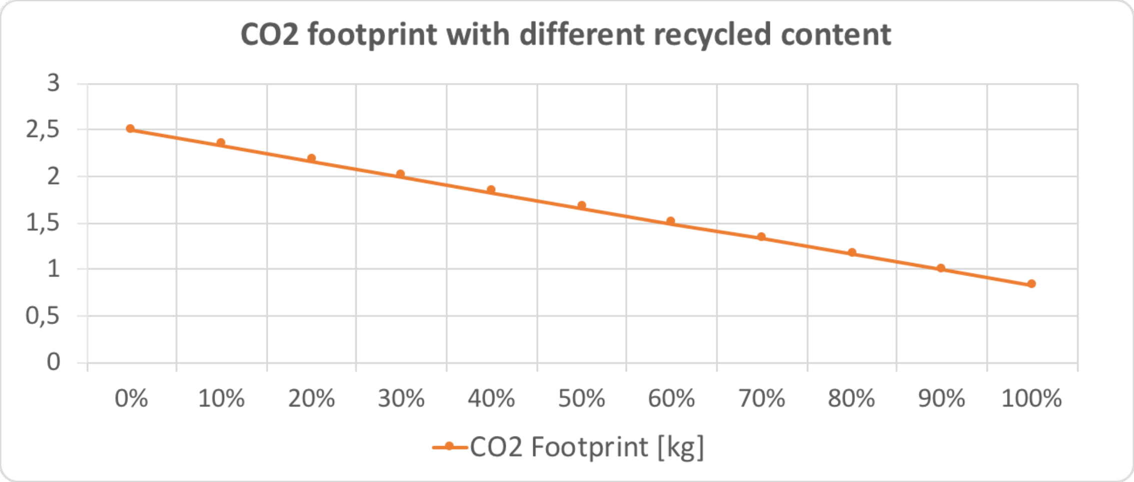
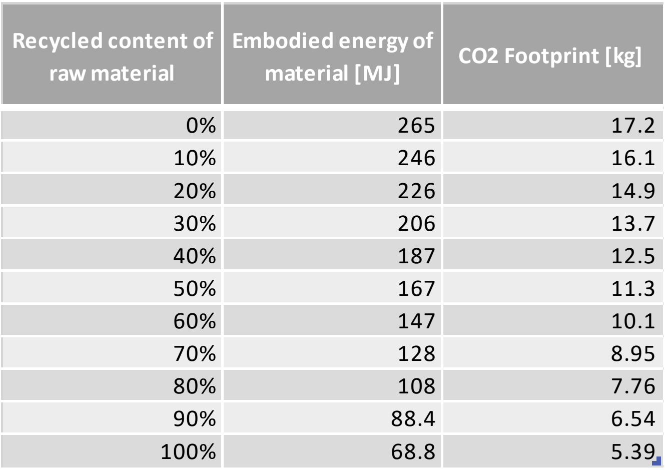


Figure 5-3 CO_2 footprint of the material phase of the Floor/Ceiling Plate for different recycled content

The same procedure has been followed for the Stabilising Foot. Equally to the previous case, Table 6 shows the embodied energy and CO_2 footprint for different recycled content. Also, Figure 5-4 and Figure 5-5 display this information graphically.

Table 6 Embodied energy and CO_2 footprint of the material phase of the Stabilising Foot for different recycled content



Recycled content of raw material	Embodied energy of material [MJ]	CO2 Footprint [kg]
0%	265	17.2
10%	246	16.1
20%	226	14.9
30%	206	13.7
40%	187	12.5
50%	167	11.3
60%	147	10.1
70%	128	8.95
80%	108	7.76
90%	88.4	6.54
100%	68.8	5.39

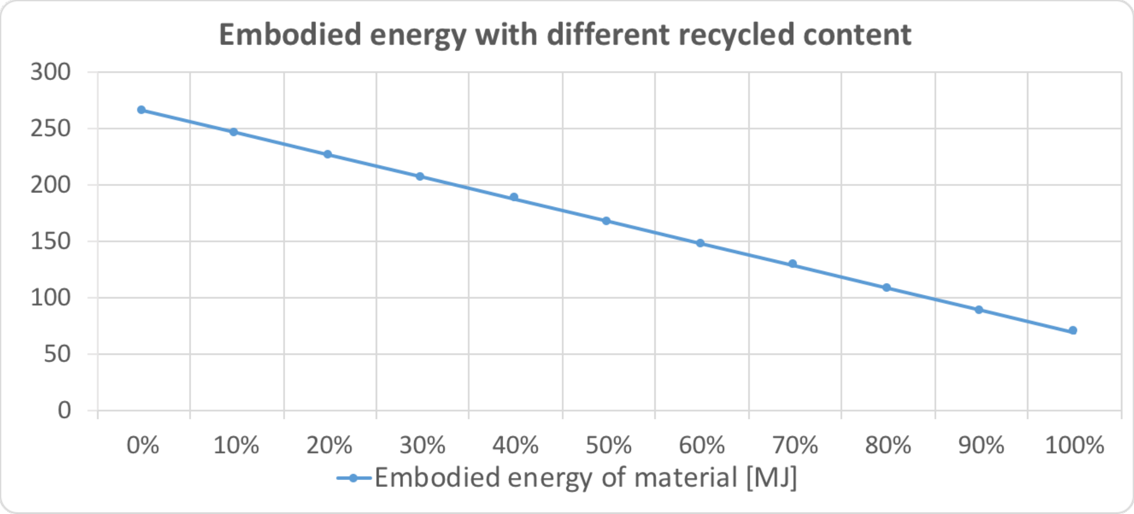


Figure 5-4 Embodied material energy of the Stabilising Foot for different recycled content

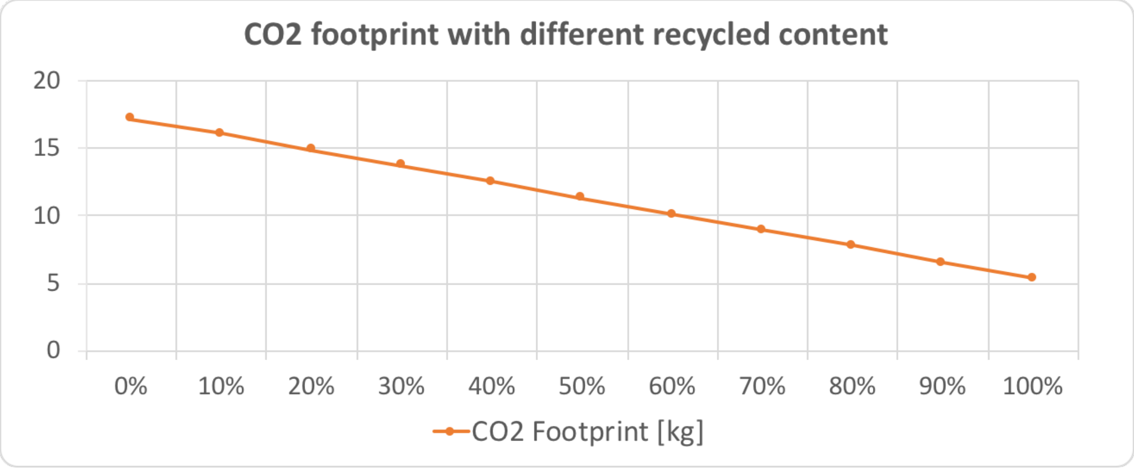


Figure 5-5 CO_2 footprint of the material phase of the Stabilising Foot for different recycled content

With the analysis done, it is straightforward to confirm that using recycled aluminium as input raw material has a positive effect on the products' sustainability. For the Floor/Ceiling Plate, the energy consumption and CO_2 footprint of the material phase can be reduced by 72.25% and 66.79% respectively. Whereas for the Stabilising Foot, the energy consumption and CO_2 footprint of the material phase can be reduced by 74.04% and 68.66% respectively. Achieving these levels of energy consumption and CO_2 footprint reduction can be considered as a success in improving the products' overall sustainability.

Despite these results, as Allwood and Cullen explain, it is not common to manufacture products with 100% of recycled aluminium. Typically, the composition of recycled aluminium coming from post-consumer waste is not precisely known. This fact could have some negative effects on various material properties such as strength, resistance or even its visual aspect. The common procedure is mixing virgin aluminium alloy with recycled aluminium, and the factors that should define the amount of recycled material that is used are the product requirements and specifications (Allwood and Cullen, 2012).

After discussing these issues with the product experts at Vitsoe, it has been known that both the Floor/Ceiling Plate and the Stabilising Foot are highly over dimensioned so the variation in mechanical properties shouldn't be a major problem. Regarding the visual aspect, it should be the company that decides if recycled aluminium meets the requirements or not, but the product receives a powder coating at the end of the manufacturing process, so the look of the recycled aluminium shouldn't be a problem either. Moreover, having products that are made from recycled materials could increase the products' value, increasing social acceptance and consequently the volume of sales.

5.3 Future Works

During the discussion chapter, different strategies have been suggested and analysed in order to reduce the energy consumption and CO_2 footprint that come along with the material phase of the life cycle of the Floor/Ceiling Plate and the Stabilising Foot products that are made by Vitsoe. In the project, these suggestions and analysis have been done in a theoretical basis. Before the implementation of these suggestions it would be highly recommended to test them in order to compare the theoretical results with real data, and then evaluate the validity of the suggested actions.

An interesting investigation path would be redesigning the products with the goals of making them more sustainable. Some considerations for this are:

- Change the product materials to more sustainable ones.
- Minimise the mass and quantity of material in the product.
- Design the product with a sustainable focus and in a way that the manufacturing processes will have higher material yields.
- Simulate and test the new design in order to have it meet all of the requirements.

As seen in chapter 5.2.2.2, changing the manufacturing system to WAAM is a good strategy to improve the material yield of the process. It has been shown that material yield can be increased for the Floor/Ceiling Plate and Stabilising Foot by 35% and 30% respectively, improving the product sustainability in the same proportion because of the material's embodied energy reduction. Despite this fact, there has not been an analysis of the trade-offs and other impacts this can suppose. As future works, in order to implement WAAM as the main manufacturing process, it would be interesting to analyse the other impacts besides sustainability that this action would have towards the company. Possible workstreams could include analysing the cost, lead time or feasibility of the manufacturing process, as well as the products' quality, visual aspect or properties.

6 CONCLUSION

In this thesis project the product life cycle of the Floor/Ceiling Plate and the Stabilising Foot, two aluminium alloy products made at Vitsoe, have been analysed. The main focus of this analysis has been to improve the level of sustainability of the products and the processes that occur during their life cycle.

A literature review has been done with the finality of understanding what the current sustainability evaluation practices are, how they are executed, and how they can be applied to this specific case. The product life cycle assessments have been carried out using the CES EduPack software, and two simple but effective and relevant indicators have been used to measure what the current state of the products' sustainability is: Energy consumption and CO_2 footprint.

The analysis has provided information about the sustainability along the product life cycle and what the relative contribution from each life cycle phase (material, manufacture, transport, use and disposal) is to the total energy consumption and CO_2 footprint. By using this methodology, it has been found that the dominant life cycle phase is the material one, contributing by nearly 90% to the total energy consumption and CO_2 footprint. This information shows what life cycle phase should be targeted in order to achieve a meaningful impact on the products' sustainability.

To conclude with, the following strategies have been suggested and analysed from a theoretical point of view, showing positive results towards reducing the energy consumption and CO_2 footprint that comes along with the material phase of the product life cycles:

- Modify the design of the product in order to reduce material embodied energy or minimise the mass and volume of the product.
- Evaluate other manufacturing systems which could improve the material yield.
- Implement the use of recycled aluminium as an input raw material.

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Vitsœ (2019b) ‘*606 Universal Shelving System Planning Guide*’

Vitsœ (2019c) *Meeting with product experts at Vitsoe*,

APPENDICES

Appendix A Manufacturing Processes

A.1 Primary Aluminium Production

Obtaining the raw materials is the first step of the manufacturing process. For the products studied in this project, their material is LM6 aluminium. LM6 is an aluminium alloy which has silicon as its main alloying element. The quantity of silicon in LM6 aluminium ranges from 10% to 13%, which gives it good resistance to corrosion. This alloy is commonly used in casting processes and its equally suitable for sand and die casting (both pressure and gravity die casting) (MRT Castings, 2019).

The process starts with the primary aluminium production which starts with the extraction of dry bauxite mineral from the mine. Once the dry bauxite is mined, alumina, which is an aluminium oxide compound, is chemically extracted from it undergoing the Bayer process. During this process, a solid waste residue, that comes from different impurities, called red mud is formed. Red mud is an alkaline (pH = 13) and difficult to dispose substance, which can be harmful for the environment. This supposes a major issue for primary aluminium production. Areas where red mud is disposed lose their capability to be farmed and built on as well as harming their existing ecosystems, so it is important to find a proper way to treat it so as to achieve sustainable development (Jolly et al., 2016).

Once the alumina is produced, it is dissolved in a molten cryolite bath within a special carbon lined steel pot, and mixed with carbon anodes. This is one of the key processes in primary aluminium production, it is an electrolysis process and it is called the Hall-Héroult process. An electric current is passed through the dissolved alumina and carbon anodes bath, causing the oxygen to separate from the alumina and react with the carbon anodes and generating CO_2. The alumina stays at the bottom of the steel pot and it is periodically extracted. This alumina is then casted into primary aluminium ingots, that will be used further on to manufacture aluminium products (The Aluminum Association, 2019).

Figure A-1 shows a bloc diagram of the primary aluminium production process.

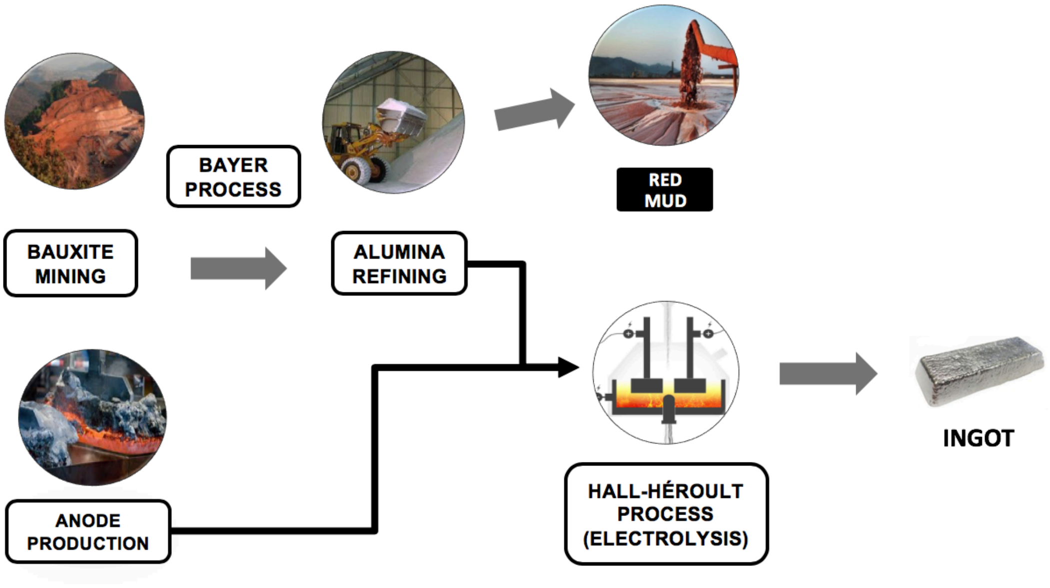

Figure A-1 Primary aluminium production process

A.2 Die Casting

Die casting is a metal casting manufacturing process invented in 1838, that consists in introducing liquid metal into a cavity or mould (also called die) that has the shape of the part that wants to be produced. There are many different variants of die casting, but it is common that the molten metal is forced into the mould by applying pressure, that's why it is usually called high pressure die casting. The die casting process is composed of four main steps: die preparation, filling, ejection and shakeout (Andresen, 2005; Degarmo, Black and Kohser, 2003).

First of all the mould needs to be made with the desired shape. Usually the mould is separated into two halves: the "cover die half" and the "ejector die half". When these two halves are put together, the inner cavity has the final product's desired shape, but this design allow the mould to be open in half facilitating the removal of the casted metallic part. Once the mould or die is created and the die casting process is ready, it is necessary to prepare the mould cavity. Lubricants are applied on the die to ease the extraction of the material as well as helping control the temperature (Andresen, 2005; Degarmo, Black and Kohser, 2003).

The second step is closing the die and injecting liquid metal into it until it has been filled up. The liquid metal is typically injected at a pressure in between 10 and 175 megapascals, until the material fills the die and has solidified. Next, the mould is opened and the ejector pins eject the shot. Finally, the shakeout step consists in removing all of the scrap from the shot and can also be called the fettling process. This scrap can include elements such as burr, runners, risers or the feeder, and it can be a bigger issue than what it may look like (Andresen, 2005; Degarmo, Black and Kohser, 2003).

To analyse this subject deeper, it is important to know that a feeder is the channel through which the liquid metal is injected into the cavity of the mould, and a riser is a reservoir built into the die to prevent defects on the casting due to shrinkage. When metals solidify and cool down they shrink and if the casting doesn’t have any extra material to fill the mould, defects will appear in the form of cavities on the metal part. To avoid this, risers are added to the casting system in order to have some extra material during the shrinkage. This can be a big problem in terms of die casting manufacturing sustainability because the material from the risers are separated from the final product and considered as scrap, so there is a lot of material that is not being used in the final product (Degarmo, Black and Kohser, 2003).

Risers and feeders are usually removed after the part has cooled down and re-melted to be recycled. Since this process needs a big energy consumption, it is important to design properly and seek to minimize the risers and feeders, or in other words, if the objective is improving the sustainability, it is interesting to find the way to maximize the material yield of the die casting process.

A.3 Powder Coating

After the casting parts are ready they go through a surface treatment called powder coating in order to have the desired aspect and properties. Powder coating is a process invented around 1945 that consist in coating that is applied on finished products (typically metal but it is possible apply it on other materials such as medium-density fibreboard using innovative methods) instead of paint and comes in a form of dry powder. The powder coating process is made of three simple steps: preparing the coating, applying and curing (Bayards et al., 2004).

Powder coatings gives the part a hard surface finish that is even tougher than conventional paint, reducing the risk of chipping, corrosion, abrasion, scratches or other surface wear issues. Also, powder coating doesn´t contain any solvents nor releases volatile organic compounds (VOC) into the atmosphere. It also has a smaller carbon footprint than conventional liquid paint coatings and it doesn't generate any hazardous waste (The Powder Coating Institute, 2016).

Regarding the sustainability analysis done in this project, the powder coating process shouldn't suppose any problems. Since its impact is really small compared to the rest of the product life cycle it can be considered negligible.

Appendix B Life Cycle Assessment Reports

B.1 Floor/Ceiling Plate Results

Eco Audit Report

Product name	Floor/Ceiling Plate
Country of use	World
Product life (years)	20

Summary:

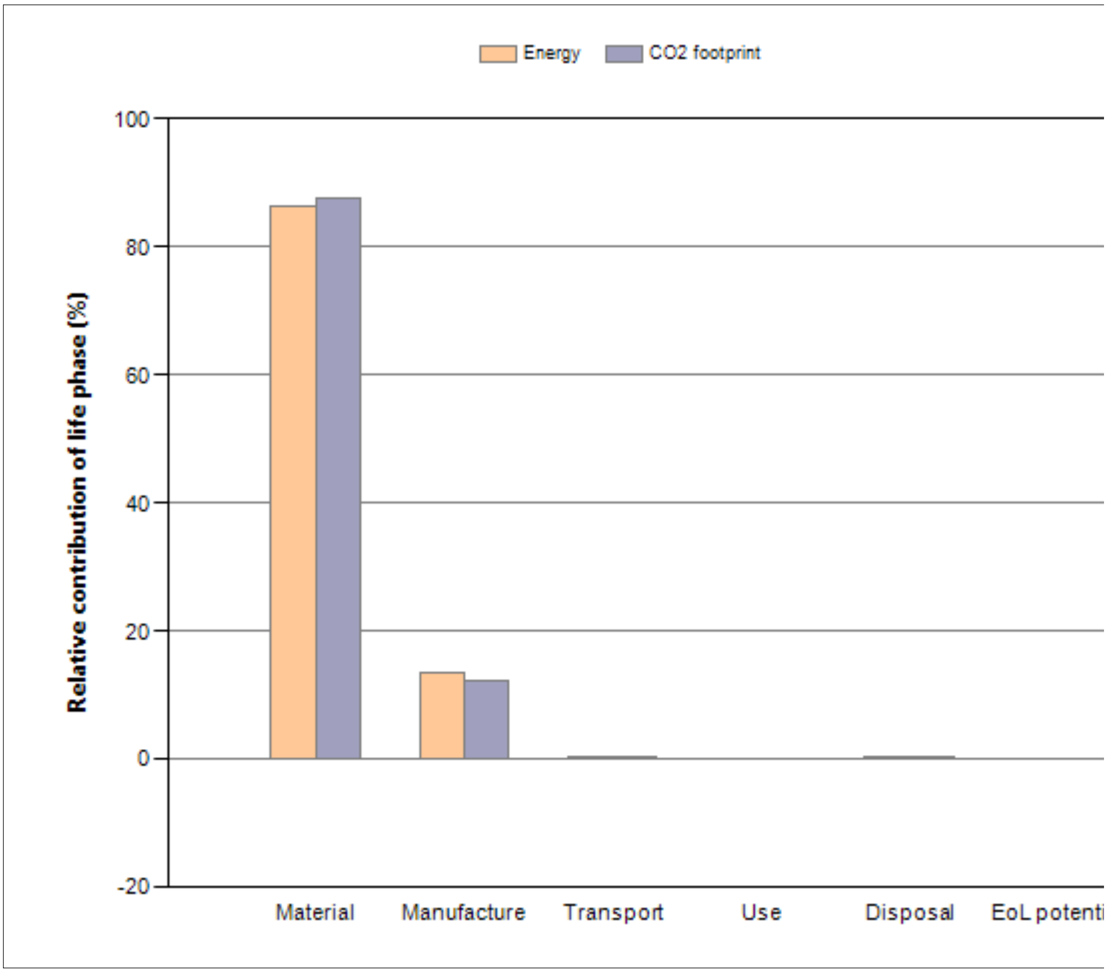

Figure B-1 Relative contribution of life phase

Energy details CO2 footprint details

Phase	**Energy (MJ)**	**Energy (%)**	**CO_2 footprint (kg)**	**CO_2 footprint (%)**
Material	38.2	86.4	2.49	87.7
Manufacture	5.97	13.5	0.346	12.1
Transport	0.0176	0.0	0.00126	0.0
Use	0	0.0	0	0.0
Disposal	0.036	0.1	0.00252	0.1
Total (for first life)	**44.2**	**100**	**2.84**	**100**
End of life potential	0		0	

Table B-1 Summary of life cycle assessment results

Energy Analysis

Summary

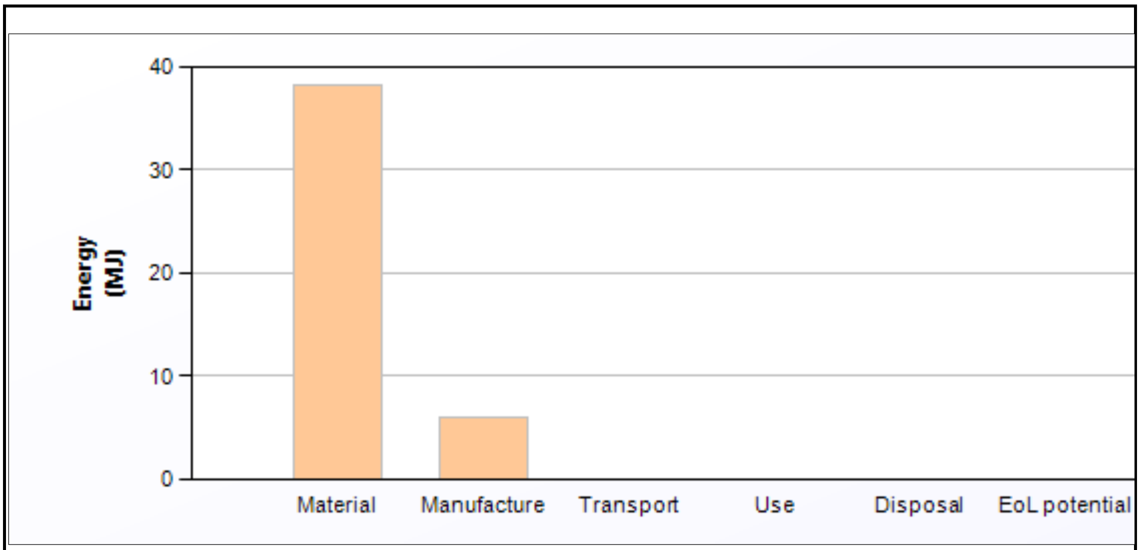

Figure B-2 Energy consumption breakdown

	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 20 year product life):	2.21

Table B-2 Annual environmental burden

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Floor/Ceiling Plate	Aluminum, A413.0, die cast, F	Virgin (0%)	0.18	1	0.33	38	100.0
Total				**1**	**0.33**	**38**	**100**

Table B-3 Material phase results

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Floor/Ceiling Plate	Casting	-	0.33 kg	3.6	61.1
Floor/Ceiling Plate	Cutting and trimming	45	0.15 kg	0.044	0.7
Powder Coating	Powder coating (polymer)	-	0.03 m^2	2.3	38.2
Total				**6**	**100**

Table B-4 Manufacture phase results

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Manufacturing to Vitsoe	14 tonne (2 axle) truck	65	0.018	100.0
Total		**65**	**0.018**	**100**

Table B-5 Transport phase results

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Floor/Ceiling Plate	0.18	0.018	100.0
Total	**0.18**	**0.018**	**100**

Table B-6 Transport phase results

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Table B-7 Use phase results

Disposal:

Summary

Component	End of life option	% recovered	Energy (MJ)	%
Floor/Ceiling Plate	Landfill	100.0	0.036	100.0
Total			**0.036**	**100**

Table B-8 Disposal phase results

CO_2 Footprint Analysis

Summary

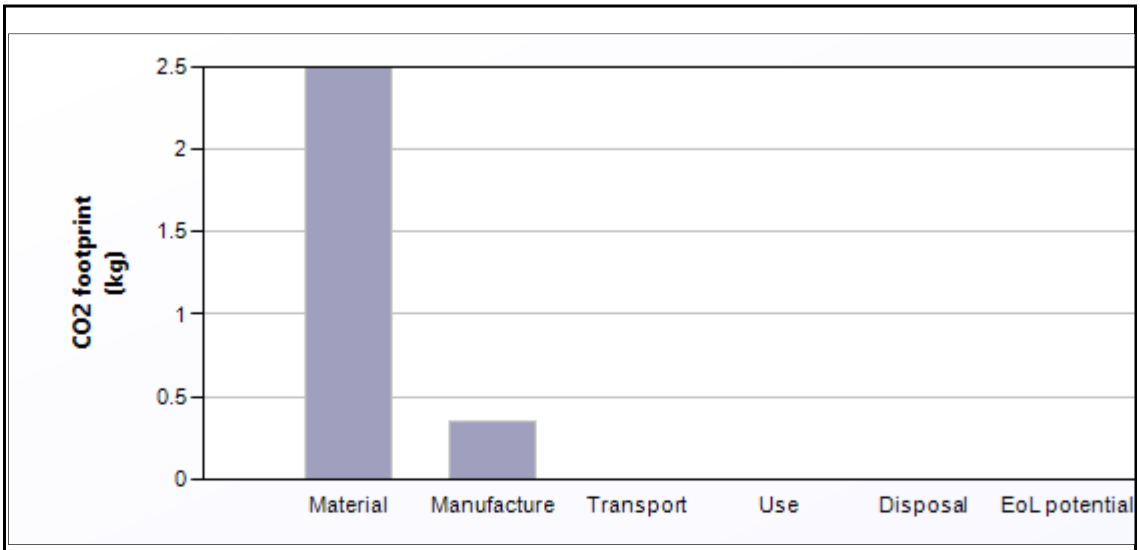

Figure B-3 CO_2 footprint breakdown

	CO_2 (kg/year)
Equivalent annual environmental burden (averaged over 20 year product life):	0.142

Table B-9 Annual environmental burden

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO_2 footprint (kg)	%
Floor/Ceiling Plate	Aluminum, A413.0, die cast, F	Virgin (0%)	0.18	1	0.33	2.5	100.0
Total				**1**	**0.33**	**2.5**	**100**

Table B-10 Material phase results

Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO_2 footprint (kg)	%
Floor/Ceiling Plate	Casting	-	0.33 kg	0.22	63.4
Floor/Ceiling Plate	Cutting and trimming	45	0.15 kg	0.0034	1.0
Powder Coating	Powder coating (polymer)	-	0.03 m^2	0.12	35.6
Total				**0.35**	**100**

Table B-11 Manufacture phase results

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO_2 footprint (kg)	%
Manufacturing to Vitsoe	14 tonne (2 axle) truck	65	0.0013	100.0
Total		**65**	**0.0013**	**100**

Table B-12 Transport phase results

Breakdown by components

Component	Mass (kg)	CO_2 footprint (kg)	%
Floor/Ceiling Plate	0.18	0.0013	100.0
Total	**0.18**	**0.0013**	**100**

Table B-13 Transport phase results

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Table B-14 Use phase results

Disposal:

Summary

Component	End of life option	% recovered	CO_2 footprint (kg)	%
Floor/Ceiling Plate	Landfill	100.0	0.0025	100.0
Total			**0.0025**	**100**

Table B-15 Disposal phase results

B.2 Stabilising Foot Results

GRANTA CES 2018 EDUPACK

Eco Audit Report

Product name	Stabilising Foot
Country of use	World
Product life (years)	20

Summary:

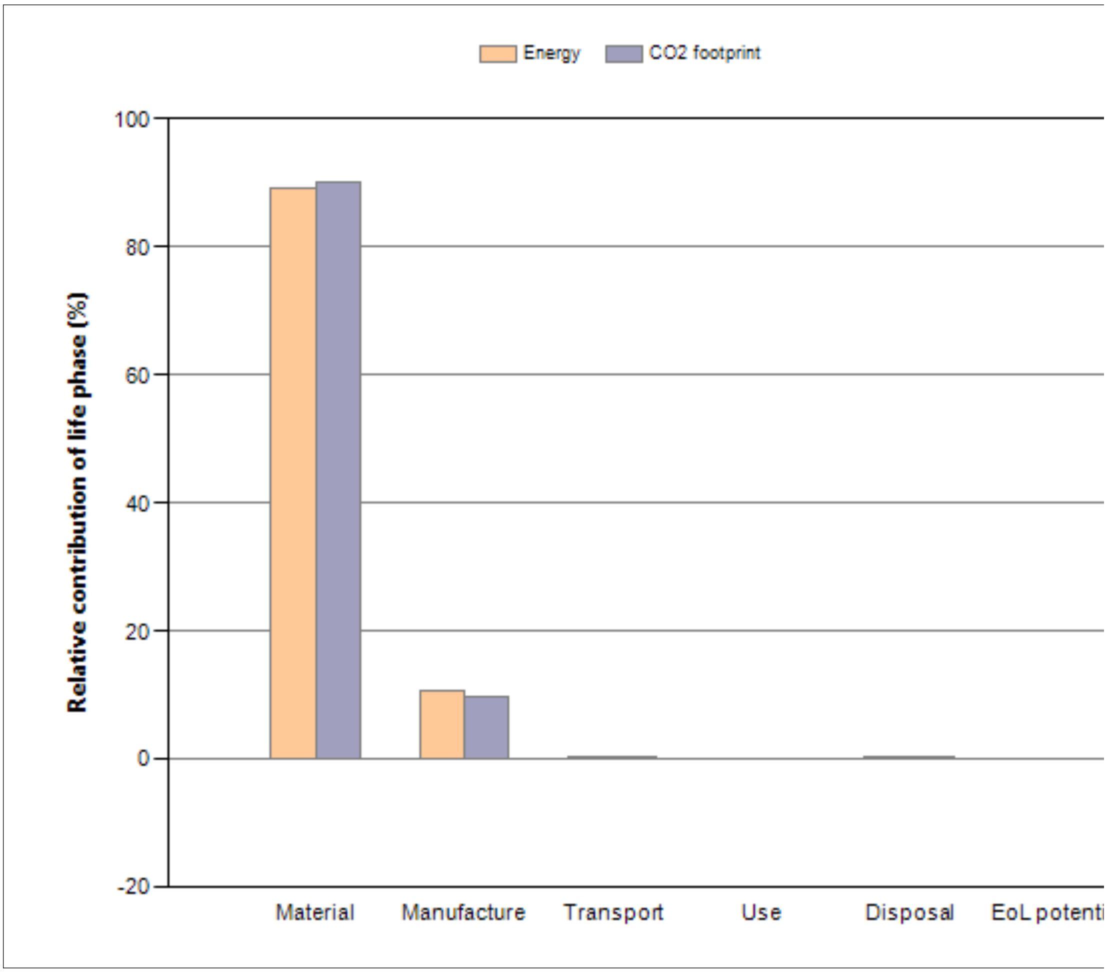

Figure B-4 Relative contribution of life phase

Energy details CO2 footprint details

Phase	**Energy (MJ)**	**Energy (%)**	**CO_2 footprint (kg)**	**CO_2 footprint (%)**
Material	265	89.2	17.2	90.1
Manufacture	31.8	10.7	1.87	9.8
Transport	0.125	0.0	0.00899	0.0
Use	0	0.0	0	0.0
Disposal	0.256	0.1	0.0179	0.1
Total (for first life)	**298**	**100**	**19.1**	**100**
End of life potential	0		0	

Table B-16 Summary of life cycle assessment results

Energy Analysis

Summary

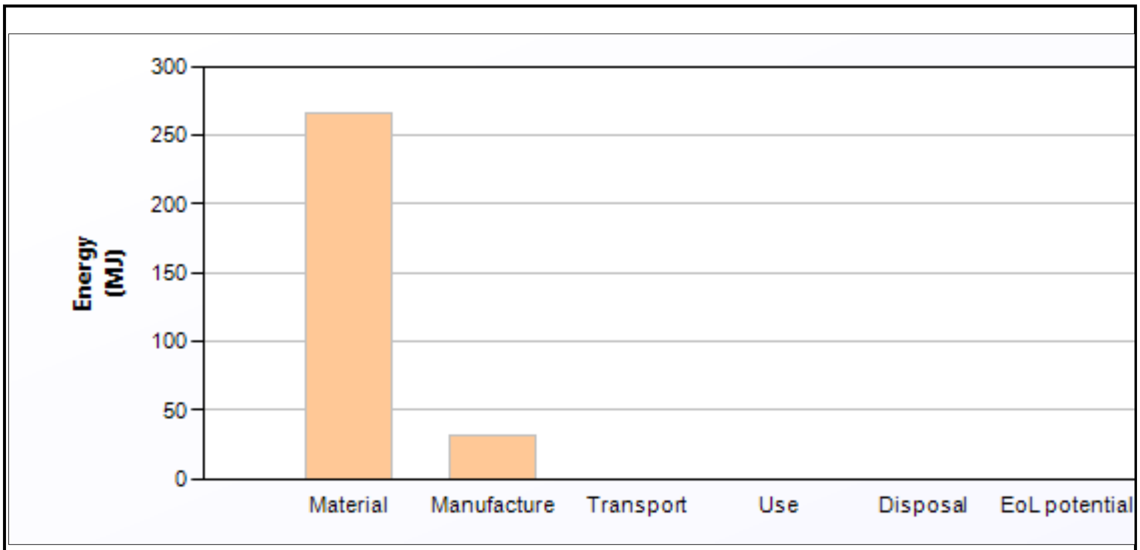

Figure B-5 Energy consumption breakdown

	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 20 year product life):	14.9

Table B-17 Annual environmental burden

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Stabilising Foot	Aluminum, A413.0, die cast, F	Virgin (0%)	1.3	1	2.1	2.7e+02	100.0
Total				**1**	**2.1**	**2.7e+02**	**100**

Table B-18 Material phase results

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Stabilising Foot	Casting	-	2.1 kg	24	74.8
Stabilising Foot	Cutting and trimming	40	0.85 kg	0.26	0.8
Powder Coating	Powder coating (polymer)	-	0.1 m^2	7.8	24.4
Total				**32**	**100**

Table B-19 Manufacture phase results

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Manufacturing to Vitsoe	14 tonne (2 axle) truck	65	0.12	100.0
Total		**65**	**0.12**	**100**

Table B-20 Transport phase results

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Stabilising Foot	1.3	0.12	100.0
Total	**1.3**	**0.12**	**100**

Table B-21 Transport phase results

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Table B-22 Use phase results

Disposal:

Summary

Component	End of life option	% recovered	Energy (MJ)	%
Stabilising Foot	Landfill	100.0	0.26	100.0
Total			**0.26**	**100**

Table B-23 Disposal phase results

CO₂ Footprint Analysis

Summary

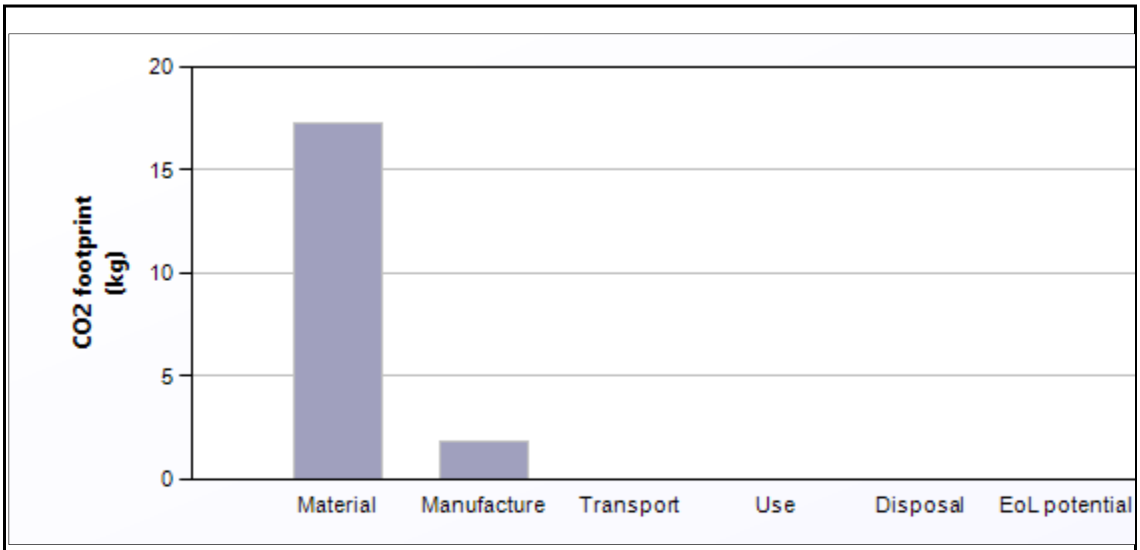

Figure B-6 CO₂ footprint breakdown

	CO₂ (kg/year)
Equivalent annual environmental burden (averaged over 20 year product life):	0.957

Table B-24 Annual environmental burden

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO_2 footprint (kg)	%
Stabilising Foot	Aluminum, A413.0, die cast, F	Virgin (0%)	1.3	1	2.1	17	100.0
Total				**1**	**2.1**	**17**	**100**

Table B-25 Material phase results

Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO_2 footprint (kg)	%
Stabilising Foot	Casting	-	2.1 kg	1.4	76.5
Stabilising Foot	Cutting and trimming	40	0.85 kg	0.02	1.1
Powder Coating	Powder coating (polymer)	-	0.1 m^2	0.42	22.4
Total				**1.9**	**100**

Table B-26 Manufacture phase results

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO_2 footprint (kg)	%
Manufacturing to Vitsoe	14 tonne (2 axle) truck	65	0.009	100.0
Total		**65**	**0.009**	**100**

Table B-27 Transport phase results

Breakdown by components

Component	Mass (kg)	CO_2 footprint (kg)	%
Stabilising Foot	1.3	0.009	100.0
Total	**1.3**	**0.009**	**100**

Table B-28 Transport phase results

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO_2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Table B-29 Use phase results

Disposal:

Summary

Component	End of life option	% recovered	CO_2 footprint (kg)	%
Stabilising Foot	Landfill	100.0	0.018	100.0
Total			**0.018**	**100**

Table B-30 Disposal phase results