Sustainable footwear solutions for the scrap tyre sector

Catarina Dias Gomez

Thesis to obtain the Master of Science Degree in

Industrial Engineering and Management

Supervisor: Prof. Ana Isabel Cerqueira de Sousa Gouveia Carvalho

Examination Committee

Chairperson: Prof. José Rui de Matos Figueira

Supervisor: Prof. Ana Isabel Cerqueira de Sousa Gouveia Carvalho

Member of the Committee: Prof. Tânia Rute Xavier de Matos Pinto Varela

January 2021

Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Abstract

The increasing demand for resources is raising several concerns on the society, and the scarcity of these resources demands for innovative ideas/products to tackle the current consumption patterns. Circular Economy has emerged with the aim of closing the loop of constant extraction of resources and creating a circular path on how the resources are consumed and disposed.

On this scope the current dissertation focusses on implementing circular economy measures in the tyre market, in Portugal, to create a sustainable sandal that thrives social inclusion and the use of recycled and environmentally friendly alternatives. To achieve this, it is necessary to foster an understanding over the concept of circular economy and its practices as well as understanding the role of design in the conception of a product. Based upon the literature review on circular economy, product design and eco-design a methodology is elaborated to guide the development of a sustainable sandal prioritizing sustainability and social inclusion in the process of creating and developing the product.

This dissertation accomplishes three major goals: extensive literature review, methodology with guidelines for the product development and, results and further recommendations. The literature review is a baseline for the methods proposed in the methodology and the results comprise the outputs obtained from the application of those methods.

Key words: Circular Economy, Sustainable Sandal, Eco-Design, Scrap Tyre, product development

Resumo

A crescente procura por recursos tem levantado alguma preocupação na sociedade, e devido à escasez destes, é necessária a criação de novas ideias/productos que emerjam para mudar o atual padrão de consumo. A economia circular sucede com o objetivo de fechar o ciclo de contstante extração de recursos e criar um trajeto circular na forma como os recursos são consumidos e descartados.

Neste âmbito, a presente dissertação foca em implementar medidas de economia circular no mercado dos pneus usados, em Portugal, por forma de criar uma sandália sustentável que apela pela inclusão social e o uso de materiais recyclados e amigos do ambiente. Para alcançar este objetivo, é necessário desenvolver o conhecimento acerca do conceito de economica circular e as praticas inerentes a este conceito, assim como, perceber o papel do design na concepção de um produto. Com base na revisão de literatura feita no ambito de economia circular, design de produto e *eco-design,* uma metodologia é elaborada para conduzir o desenvolvimento de uma sandália sustentavel que prioriza a sustentabilidade e a inclusão social no seu processo de criação e desenvolvimento do produto.

Esta dissertação completa três principais objetivos: uma revisão de literatura extensiva, uma metodologia com os principios necesssários ao desenvolvimento do produto e, resultados otidos assim como recomedações futuras. A revisão de literatura é a base dos metodos propostos na metodologia, e os resultados contemplam os *outputs* obtidos da aplicação desses mesmos metodos.

Palavras-chave: Economia Circular, Sandália sustentavel, *Eco-design,* Pneus usados, desnvolvimento de produto

Acknowledgements

First and above all, I would like to deeply thank my supervisor, Prof. Ana Carvalho, for finding some extra time to guide me even when all her students had already been selected. Her time, support, guidance, availability and motivational words when no motivation seem to exist, made this journey much easier and possible. For this I have nothing but to thank and appreciate.

I would also like to thank my family and friends who were part of this journey and have always believed in me and supported me directly or indirectly.

Then, I would like to thank all the people who played part in the construction of this product. Thank you to my uncle Pepe who provided the tyre for me to work on. Thank you to José, Bruno and Madalenas, who bear to carry a tyre across half the country for me to work on, while on vacation. Thank you to my mother who kept driving me around and introducing me to relevant people who could help me work on the tyre. Thank you to my father who taught me how to use a sewing machine in an attempt to create a sandal strap. Thank you João and Maria, who contributed with motivation, ideas and actively supported the creation of the first prototype. Thank you to Ricardo and Rosália who were ready to help me without questioning and played a significant part in extracting soles from tyres, contributing with know-how and the necessary tools for this process. Thank you to Sofia for praising my sandals and making me believe in my project. Finally, thank you to my flat mates – Catarina and Edna – who were always there and contributed actively for the development of this project and provided relevant inputs for the improvement of the project.

Apart from these people who were an active part in the prototypes' development, it must not be forgotten all the people that were there throughout this journey, and whom must as well be mentioned.

Thank you to my partner in crime, Catarina Custódio, who was always there. All those tears, stress, sleepless nights and disappointments would have been unimaginably worst if you were not there to share the pain with me. Thank you Pedro (PP), for all your night rides and for helping relieving the mood during those dark times of projects and studying nights. All also, thank you to all my friends in the Apartamendes group, because you made every project, test and exams way more bearable. To these people, thank you for your friendship and I hope to carry you throughout my life.

Apart from these, I must also thank to my long-lasting friend Joana, who was always there no matter what and is and will be always a part of my life.

Finally, thank you to all the people who were there, for better or for worst, but made this journey happen the way it did. No matter what happens next, at least this chapter is concluded, and more chapters are yet to come.

All the people I mentioned here, I know I will take for the rest of my life, and for that I am grateful.

Table of Contents

List of Figures

List of Tables

List of Acronyms

BMC Business Model Canvas

BPA Bisphenol A

CAD Computer Aided Design

CBM Circular Business Model

CE Circular Economy

CLSC Closed Loop Supply Chain

ED Ecosystem Diversity

ELT End-of-Life Tyre

EPDM Ethylene Propylene Diene rubber

FU Functional Unit

GPP Green Public Procurement

HH Human Health

LCA Life Cycle Assessment

LCI Life Cycle Inventory Analysis

LCIA Life Cycle Impact Assessment

OTR Off-The-Road

RA Resource Availability

SBR Styrene-Butadiene Rubber

SC Supply Chain

SGPU Used Tyres Management Integrated System

TDF Tyre Derived Fuel

TLBMC Triple Layer Business Model Canvas

1 Introduction

The present chapter introduces the master dissertation and is divided into three parts. Section 1.1 presents the motivation of the subject and the context of development of this dissertation. Section 1.2 presents the objectives to be accomplished and Section 1.3 provides a brief description of the chapters in this dissertation.

1.1 Problem Background and Motivation

With the Industrial Revolution companies and consumers have adopted a linear model of value creation that initiates with resource extraction, goes through the processing phase, use by consumers and then disposal. On this scope, the global plastic economy does not fall behind the tendency and relies heavily on non-renewable feedstocks thus consigning overwhelming amounts of plastic to the trash (*Mckinsey&Company*, 2016). The unanimous global trend of plastic consumption increase seems to lack a foreseen end, with amounts of plastic waste reaching millions of tonnes every year (*European Commission*, 2018; Ritchie & Roser, 2018). The utility of plastic is undeniable when it comes to the production of necessary assets to the society, it has been proved the efficiency of plastic either in economic terms and physical (European Commission, 2018). Yet, as good as it might seem, plastic materials are destroying the planet and causing severe consequences to the future of our society and the future of our planet (Webb, 2012). Putting these hazards into numbers it is possible to estimate that 20% to 50% of developing countries' budget is being spent in waste management. Yet, if the right approach was implemented, waste streams could represent income streams yielding economic value with technology available (Engel et al., 2016). Under these concerns, Circular Economy has never made more sense. It is estimated that across the economy, by incorporating circular economy, Europe could improve its resource productivity by 3%. Translating this value into numbers, by 2030 with the adoption of circular economy practices, €600 billion could be saved per year, translating into an increase of up to 7% in the GDP when compared to the current (practically) non-circular scenario (*Mckinsey&Company*, 2016).

Regarding the automobile industry, the ownership of vehicles worldwide has been growing faster than the global population, and in 2010 it surpassed 1 billion units. Besides, according to the projections made by Chaturvedi & Handa (2017) this exponential rise in vehicles could indicate a doubling of cars produced by 2040. Consequently, the tyre industry grows along, and in the year of 2017, it was manufacturing over a billion tyres, meaning almost 12 billion tonnes of natural rubber was being extracted from the environment. To follow the tendency of linear model, dumping and stockpiling of tyres is the most common practice of disposal, loosing significant resources to industries and posing serious hazards to the environment (*Mckinsey&Company*, 2016; Chaturvedi & Handa, 2017). To tackle the major tyre disposal hazards, several countries have created their own system to control the disposal and further use of scrap tyres. In the case of Portugal, *Valorpneu* emerged from this trend. Even though, the problem around the enormous amounts of tyres seems to be taking a good path, there is still more with this product to be done.

According to *Liberty Tyre Recycling* (2019) it is still of great scepticism the (small) size of tyre' recycling operators when compared to tyre manufacturers.

Developing products for circular economy aids in eliminating waste and creating value (*Mckinsey&Company*, 2016). Through the literature research a significant gap between the reuse processes of scrap tyres and the environmental analysis of such processes was noticed. Accordingly, the creation of a sustainable process, using disposable tyres to create a product able to enter the market is the major goal of this dissertation. This dissertation aims at accomplishing this task by designing and bringing to life an environmentally friendly product entirely made from sustainable materials. The designing process of the product will consider the major practices used in product design that focus on building sustainable products. Besides, the product will be developed under the main principles that build up an eco-design product. Tyres are the major material to incorporate in the product and a transformation of these into a manageable asset is essential. This product is crucial to create a value stream that thrives from the waste in this industry.

1.2 Dissertation Goal

The ultimate goal of this dissertation is to study and develop a marketable product based upon the circular economy strategies and product design metrics. The objective of this product is to reflect the potential of reusing waste streams and providing another life to end of life products, always in the light of the Eco-design practices that will be studied. This main objective will be achieved with the completion of two parts of this dissertation. The first part has three major goals which are essential for the development of the methodology necessary to complete this dissertation:

1. Introduce, contextualize and characterize the plastic market problems and current trends, and the tyre industry in the world and, specifically, highlight its current status in Portugal;
2. Elaborate a comprehensive and relevant scientific literature review to clarify and discuss circular economy practices with an enhanced focus on product design and eco-design, to foster the comprehensive theoretical knowledge necessary to support and elaborate a framework for the development of the master dissertation;
3. Contextualize, in the scope of the literature review performed, the most adequate methodologies to adopt in the chapters ahead to accomplish the ultimate goal of the work.

The second part's goal is to apply the methodology proposed and accomplish the following objectives:

1. Investigate the problem scope, design and materials to be incorporated;
2. Execute a virtual and physical prototype with the materials studied and the procedures indicated throughout the process;
3. Market analysis of the acceptance of the product and guidelines for the improvement and further introduction in the consumers' market.

1.3 Structure of the Dissertation

This dissertation is divided into six sections, detailed next.

Section One - Introduction

Introduction over the dissertation with a brief contextualization and motivation that have led to the problem. The project goals to be developed are also highlighted in this section.

Section Two - Contextualization

Theoretical contextualization of the problem, introducing the current trend on plastic consumption, usage and consequences to the human health. This is followed by an understanding on synthetic rubber which is a type of plastic highly used in the tyre manufacturing as well as an overview over the scrap tyre market, more specifically in Portugal.

Section Three – Literature Review

Extensive literature review that covers the most important topics to consider for the continuation of the dissertation. These topics concern the circular economy framework along with its most important characteristics and practices, followed by an introduction on product design which is a major keystone for the development of the product. Product design is deeply analysed, and its most important considerations and methods are also discussed. This concept with circular economy gives way to the introduction of eco-design which is a combination of the two pillars. Eco-design is presented in the end of this chapter along with its practices, requirements and considerations.

Section Four – Methodology Adopted

A schematic model with the main steps and sub steps is introduced. Plus, an extensive methodology with the detailed guidelines, methods and different processes to be applied in each step is presented along with the correspondent theoretical basis.

Section Five – Results and Discussion

Results of all the steps indicated in the methodology are presented in this section. Along with the presentation of the outcomes obtained from each step, a brief discussion of these is provided.

Section Six – Conclusion and Further Recommendations

This final section presents major conclusions drawn and recommendations to take on the further work to be developed.

2. Contextualization

This chapter is divided into three main sections. Section 2.1 is a contextualization of the current status of plastic production and consumption, followed by an overview over the processes of plastic waste management. Section 2.2 introduces one important material for the proceeding of this dissertation - rubber. This section initializes with a brief description of this main material and consequent production and consumption. Finally, Section 2.3 gathers an introduction over the tyre industry, composition and main environmental problems subject to the disposal of this product. Section 2.3 is concluded with an overview of the current levels of tyres disposal and treatment across Europe, an overview over the situation in Portugal and a characterization of this market and examples of tyre processes.

2.1 The Plastic Industry

2.1.1 Plastic Production and Consumption

Plastic has become an ubiquitous asset in our day lives *(United Nations Environment Programme*, 2018). Plastic first came to live in 1869 as a substitute for ivory. Since then with the urge to preserve natural resources with a feasible alternative prioritised the massive production of plastic (*Science Matters: The case of Plastics*, n.d.). Since 1960 plastic has revolutionised the world with its production growing exponentially over the years as it is shown in **Figure 1** bellow. In 2015 the total plastic production reached 322 million tonnes in a global scale with an expectation of doubling this number in the next 20 years if action is not to be taken.

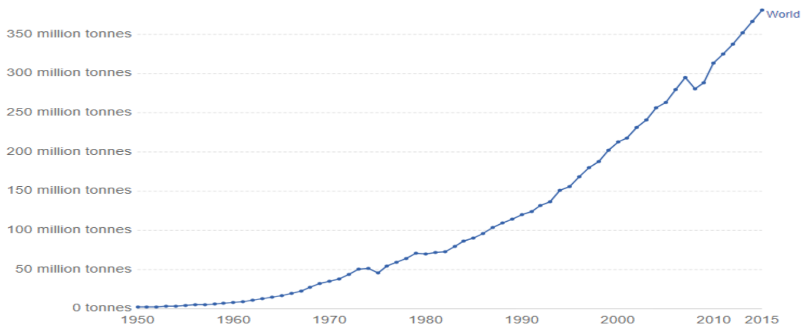

Figure 1 - Plastic production growth over the years (Richie & Roser, 2018)

In the European Union approximately 25.8 million tonnes of plastic waste are generated annually, however the great economic benefits have outpaced the liabilities with a turnover of 340 billion Euros only in 2015. Plastic has become a trend in industrial manners due to its undeniable features such as its lightweight, cheapness and easiness of handling *(United Nations Environment Programme*, 2018). With the exponential growth of plastic production since the 1950s there has been a global shift from the production of long-term plastics to single used ones. The latter is seen mostly in business to consumer applications (i.e. packaging for instance) (*United Nations Environment Programme*, 2018). Single-use plastics is a term referring to “items intended to be used once before being discarded or recycled”. The disposing of plastic has not yet reached a consensus among the population, with a potential to be used more than once, single use plastics are being disposed daily with consequences to the economy, i.e., 70 to 105 billion EUR is lost annually due to the early discard of plastic materials (*European Commission*, 2018).

2.1.2 Plastic Environmental Impact

The resilience of plastic to prevail in the environment for many years until decomposition, is what makes it so harmful to the environment. Plastic can degrade by four different manners: photodegradations, thermo oxidative degradation, hydrolytic degradation and biodegradation by microorganisms. When dumped into the environment, ultraviolet light from the sun provides the activation energy necessary for the polymer to incorporate oxygen atoms, increasing the fragility of the plastic allowing this to break into smaller pieces until it can be metabolised by microorganisms. This is a very cumbersome process, significantly prolonged when the plastic is in contact with sea water due to the lack of oxygen and lower temperature (Webb, 2012). In beaches the fragmentation of large plastic items into microplastics is very easily achieved due to the high UV exposure and wave abrasion, however, once in contact with the water the degradation process is much longer *(United Nations Environment Programme*, 2018). Plastic debris in oceans release toxic compounds to the environment thus posing a serious threat to human health (Webb, 2012). On another hand, landfilling is highly used to dispose plastic, yet these facilities are kept for a minimum of 20 years and usually present low levels of oxygen which slows down the process of plastic degradation. Landfills are also connected with a release of several environmental pollutants. For instance, Bisphenol A better known as BPA is a substance used as a plasticizer which have raised concerns lately among the population due to its risk of adverse effects on our health and environment. BPA release to the environment is shown to lead to an increase in hydrogen sulphide production hence reducing bacteria in soil populations. Furthermore, high concentrations of this compound revealed to be potentially lethal. Incineration is also used to eliminate plastic, which outweighs the drawbacks related to landfilling once it does not take as much space as the previous and the process of incineration can be used to recover the heat to generate energy. However, the great drawback is the release of several harmful compounds into the atmosphere, including significant quantities of greenhouse gases (Webb, 2012). Plastic waste compounds (secondary and primary) produced between 1950 and 2015 account for 6300 Mt yet only 30% is currently in use. Of this value only 12% has been incinerated and 9% recycled. Thus, circa 60% of the plastics produced since 1950 which were discarded and are still accumulating in landfills or the natural environment (Geyer et al., 2017). This is expected to increase according to the current consumption.

2.1.3 Plastic Waste Management

In 2015, the major part of plastic waste was being discarded into the environment and only a small percentage was being recycled (Ritchie & Roser, 2018). The problem with the amount of plastic in the environment is its waste mismanagement, which means a material is highly probable of entering the oceans through wind or tidal transport and eventually into our consumption chain.

This mismanaged waste accounts for all the material littered to the ocean or inadequately disposed. **Figure 2** shows the production, use and faith of all plastic produced in 2015.

Littered material stands for plastics “dumped or disposed without consent in an inappropriate location” whereas inadequately disposed plastic materials stand for waste intended to “being

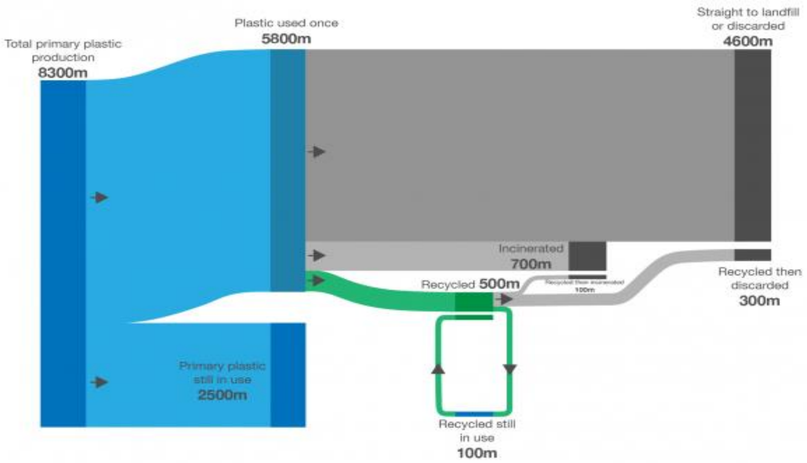

Figure 2 - Production, use and faith of plastic produced in 2015 (Richie and Roser, 2017)

properly managed through waste collection or storage sites but is ultimately not formally or sufficiently managed” (Ritchie & Roser, 2018). There are very different rates of plastic production across the globe, however, the efficiency in waste management infrastructure does not follow the rate of production of each country. Developed countries present very effective waste management systems, plastic waste is stored in secure and closed landfills. However, these countries still contribute to plastic pollution by littering. Conversely across countries with lower incomes, such as countries in South Asia and Sub-Saharan Africa the levels of inadequately disposed plastic reach 80 to 90% hence there is a higher risk of pollution (Ritchie & Roser, 2018). Plastic consumption can be dealt through three different manners. The best option to eliminate plastic would be not to consume it. However, to avoid further waste generation, the best options to deal with used plastic would be recycling or reprocessing used plastics. Yet, not all types of plastic can be recycled, and many types of plastics can become contaminated or mixed with other types of plastic generating secondary plastics with low technical and economic value. Recycling can reduce future plastic waste generation if it avoids primary plastic production but due to its features this displacement is very difficult to achieve. A second option is to deal with this material thermally whether with energy recovery or without. This option can be very harmful for the environment and human health due to the amount of emissions it releases to the atmosphere. Yet this depends on how and where the incineration is proceeded, and the technologies used. The last option, and mostly used is the discard of plastics into a landfill, an open dump or in the natural environment (Geyer et al., 2017). Even though the recycling process tackles major issues it is still a very expensive and inefficient process (Webb, 2012).

All in all, plastic materials can be found in the most diverse products due to the great variability these have. One of these materials is synthetic rubber, which is highly used in tyres nowadays, for instance. In the next section the rubber market is introduced to understand more in detail this type of plastic and its consequences to the environment.

2.2 The Rubber Market – Production and Consumption

Rubber is a very common commodity due to its high elasticity, toughness and resistance to heat and cold (Ophardt, 2019). Rubber is a moisture of several particles of latex, coagulated to originate the natural rubber, yet, it only accounts for 30% of the total rubber production nowadays. Synthetic rubber, made from oil products, is competing with natural rubber. Synthetic rubber or a combination of natural and synthetic is mostly preferred, due to technical and economic factors. This type of rubber comes from petroleum, so its production prices are highly variable according to the world energy prices. However, natural rubber is still in use, and by 2010, 68% of the total natural rubber consumption was destined to the production of tyres, tubes and other items associated with the transportation industry (Verheye, 2010). **Figure 3** shows de dispersion of usage of natural rubber in 2010.

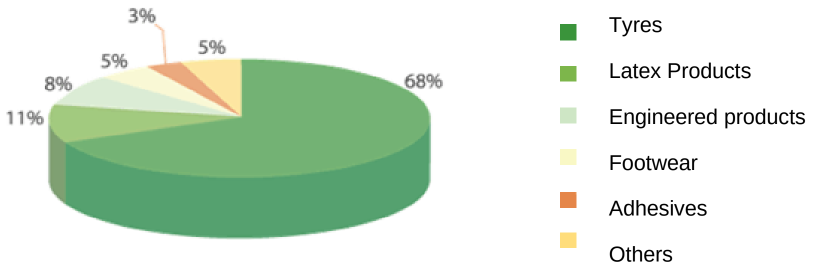

Figure 3 – Natural rubber usage in 2010 (Verheye, 2010)

Synthetic rubber is the major one petroleum by-product. Many types of synthetic rubber have been studied, yet, the most common ones are Santroprene and Styrene-Butadeine (SBR) rubber. These types of rubber are usually preferred by the manufacturers due to its processing easiness allowing a convenient reproduction and remanufacturing, additionally it is also cost-effective when it comes to the system cost and sustainability issues. Santroprene synthetic rubber is very commonly used in automotive, construction, electrical and healthcare applications due to its specific characteristics. This thermoplastic is a cross link of a type of synthetic rubber (EPDM – Ethylene Propylene Diene rubber) with polypropylene originating a product with great flexibility and durability features. The manufacturing process of this thermoplastic is very similar to the production of plastic and this material exhibit great resistance to extreme temperatures which explains the preference for this material over others. Styrene-Butadiene rubber (SBR) is mainly used in automobile tyres, toys, shoe soles and chewing gum thus being one of the most versatile synthetic rubber types. This material is essentially composed by a blend of styrene and butadiene, a transparent liquid and a reactive transparent gas, respectively. An increase in the amount of styrene decreases the elasticity is the rubber. This material exhibits great abrasion resistance features and, similar to Santropene, heat resistance as well. However, contrarily to Santropene it preforms poorly in terms of elasticity and when in contact with low temperatures. Both materials are very valuable in many industries due to its irreplaceable features and cost effectiveness, allowing a reduction in the use of adhesives, chemicals and heat processing, namely in the automotive industry. This industry uses these materials for the manufacturing of tyres, for instance. The use of synthetic materials in substitution of natural rubber enables the recycling of some components (RubberCal, n.d.; Gent, 2016).

Having introduced the concept of rubber and the differences between the two types of rubber it is important to explain how the tyre industry has been evolving. Tyres are mainly composed by synthetic rubber and this product has become an issue since the early 2000 due to its increasing amount in landfills giving way to pollution and other hazards for the population.

2.3 The Tyre Market

2.3.1 Tyre Industry

Tyres consist of slightly less natural rubber then synthetic rubber, metal and other composites. The production of tyres is one major pollutant industry due to the continuous deforestation and usage of fossil fuels in the production of synthetic rubber and assembly process. A car tyre demands for 27 litres of petroleum whereas a truck tyre demands for 83 litres (Root, 2019). The composition of a tyre according to the vehicle in which it is used is shown in **Table 1.**

Table 1 - Tyre composition according to its vehicle (Scott, 2015)

Product Yield	**Car tyre (%)**	**Truck Tyre (%)**	**OTR Tyre (%)**
Crumb rubber	70%	70%	78%
Steel	17%	27%	15%
Fibre and Scrap	13%	3%	7%
Total	**100%**	**100%**	**100%**

Nowadays 1.6 billion tyres are generated and 1 billion of waste tyres emerge, each year. Yet, only 100 million tyres are recycled every year. Tyres have been constantly improved to last longer in the cars thus undergo through many complex processes to make it indestructible. This reflects in the recycling process imposing great difficulties in recycling a tyre with such features (Goldstein Research, 2020). A tyre is mainly composed of various rubber compounds, carbon black, clay and silica to fill up the tyre, and chemicals and minerals to enable a faster vulcanisation. To reinforce the tyre, several types of steel compounds are twisted and implemented in the format of a mesh. After use, tyre composition slightly changes from the original and differs according to the type of tyre. This composition is presented in **Table 2**. OTR tyres stands for “Off-The-Road” tyres and refer to tyres meant to perdure against high weights and harsh conditions (Evans, 2006).

Table 2 - Composition of a tyre after usage (adapted from Evans, 2006)

Ingredients (%)	**Car Tyre (%)**	**Truck Tyre (%)**	**OTR Tyre (%)**
Rubber/Elastomers	47%	45%	47%
Carbon Black	21.5%	22%	22%
Metal	16.5%	25%	12%
Textile	5.5%	0%	10%
Zinc Oxide	1%	2%	2%
Sulphur	1%	1%	1%
Additives	7.5%	5%	6%
Total crumb rubber materials	**78%**	**75%**	**78%**
Total	**100%**	**100%**	**100%**

In **Table 2**, Crumb rubber includes all the rubber, carbon black, sulphur, additives – which can include types of clay or recycled rubber crumb – and zinc oxide (Evans, 2006). The increasing usage of tyres have led to a multiple way of dealing with this material. One common manner to deal with scrap tyres is to convert it into energy, i.e. generating tyre derived fuel (TDF) from scrap tyres. This process is based on a controlled incineration of the tyre to extract its heat content. Usually, the heat content of a whole tyre can exceed coal heat. Another common method is rubber recycling which is basically a decomposition of the scrap tyre to exploit the rubber in the tyre and use it mainly in the manufacturing asphalt and other surfaces, but also for new tyres. In this process the scrap tyre is grinded into cumber rubber removing the steel, fibres and other contaminants the tyre might have. Additionally, tyres can also be reused for civil engineering applications to replace some construction material due to their properties, such as reduced density, improved drainage and great thermal insulation (Reschner, 2003). Finally, another common method to deal with the used tyres is disposing these is landfills, legal or illegally. By 2003, in Europe, 2 to 3 billion scrap tyres were estimated to be in illegal landfills or abandoned. One of the worst hazards related with this issue is the appeal to mosquitoes which can spread several bacteria. The shape and lack of permeability of tyres might allocate water for long periods of time allowing mosquito to develop. This issue is aggravated when stockpiling of tyres occur in large quantities. (*US Environmental Protection Agency*, 1991). Other issue is related to fire, burning tyres are very hard to extinguish, if not impossible. The great release of gases and smoke makes the fire extremely hard to be managed (Reschner, 2003). This phenomenon happens due to the high percentage of empty space (75%) – oxygen filled space - a tyre possesses, hardening the task of putting out the fire with water or by cutting off the oxygen supply. The water present in the tyres also intensifies the production of pyrolytic oil and serves as a transportation mode for it, increasing soil and water potential contamination (*US Environemntal Protection Agency*, 1991).

2.3.2 Tyre Current Disposal Status

Despite these pollution consequences, many advances have been made so far, and Europe is moving towards a zero-waste scenario in the tyre sector, being the one of the best managed and efficient in its recovery systems. In 2013, 3.6 million tonnes of tyres were registered as used tyres in the EU, whereas 2.7 million tonnes of this were end of life tyres (ELT), which were recovered and recycled. These values represent a treatment of 96% of the tyres in the markets (Scott, 2015). Besides these excellent results in Europe, USA has also been improving with a shift from 1 billion scrap tyres in stockpiles, in 1991, to 60 million in 2018. This represents a 94% decrease (Smalley, 2018). **Figure 4** shows the flow of ELT tyres and used tyres since 2001 until 2013.

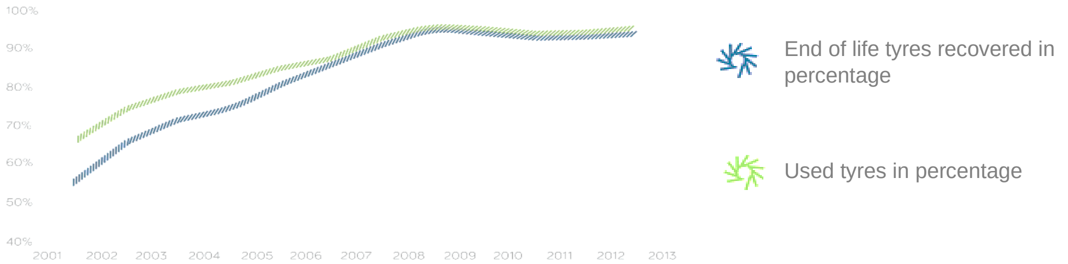

Figure 4 - End of life tyres recovered Vs Used tyres treated over 10 years (Scott, 2015)

With the general economic growth since 2004 there has been an increasing level of end of life tyres throughout Europe, with values from 2.48 million tonnes to 2.64 million tonnes in 2011. In 2012 the 2.76 was the value registered and in 2013 this value reached the 2.88 million tonnes. This growth has not been constant due to the variable economic growth during the economic crisis leading to a negative impact on the transportation sector. Even so, the numbers have been increasing and are prone to remain (Scott, 2015; ETRMA - European Tyre & Rubber Manufacturers' Association, 2019). **Figure 5** presents the evolution of EL Tyres arising in Europe until 2017.

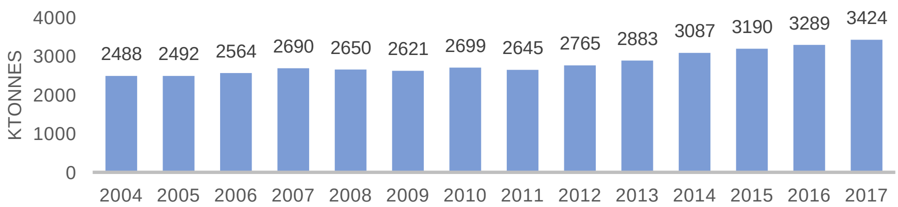

Figure 5 - Evolution of end of life tyres arising in Europe (Adapted from Scott, 2015 and ETRMA, 2019)

End of life tyres can be used in different areas; however, the statistics show that the purposes have been changing throughout the years. In 1994, in Europe, 32% of the tyres were used for material recovery and 68% for energy recovery whereas in 2007 these values changed to 54% and 46% respectively. This shift continued and in 2013, 48% was being recovered while 52% was due to energy recovery. These values do not present ELT going to landfills since the EU has created a legislation to prevent these tyres from going to landfills. Materials' recovery from tyres comprise all the components that can be set apart from the tyre and used in different applications. However, markets for recycled rubber, for instance, have been lagging behind energy recovery since there is a lack of large-scale processes to consume or reuse the materials that compose the tyres (Scott, 2015).

2.3.3 Portuguese Scrap Tyre Status

In 2013, Portugal marked a 100% rate of collection of tyres with 40% of the tyres being recovered for energy purposes and 60% of the tyres for recovery for other purposes such as recycling or civil engineering works (Scott, 2015). In Portugal, *Valorpneu* is the company that manages and organizes the flow of used tyres, from collection to disposal. This company manages the Used Tyres Management Integrated System – SGPU - a system whose production started in 2003. *ValorPneu* aims at developing an efficient system to cope with scrap tyres on a yearly basis, thus the creation of the SGPU was a necessity for the company. This system is an articulation of processes and responsibilities with the purpose of amending the journey of ELT avoiding the necessity of landfills and promoting collection, separation, retake and recovery of tyres. This company is a non-profit private company, which is financed by an Ecovalue, i.e., a monetary value collected whenever a tyre is commercialized in the market, plus, any company that acquires tyres must celebrate a contract with *ValorPneu*. This Ecovalue is used to finance all the processes managed by *ValorPneu*: collection, transportation and recovery, which comprises reuse, retread, recycling and energy recovery. Retreading is the process that replaces old treads in the tyre by new ones and is the only tyre process that maintains the full potential of the value remaining in the scrap tyre (Sasikumar et al., 2010). The collection of ELT is made by the tyre owners whom deliver the tyres in the reception centres *ValorPneu* owns throughout the country. This system is exemplified in **Figure 6**.

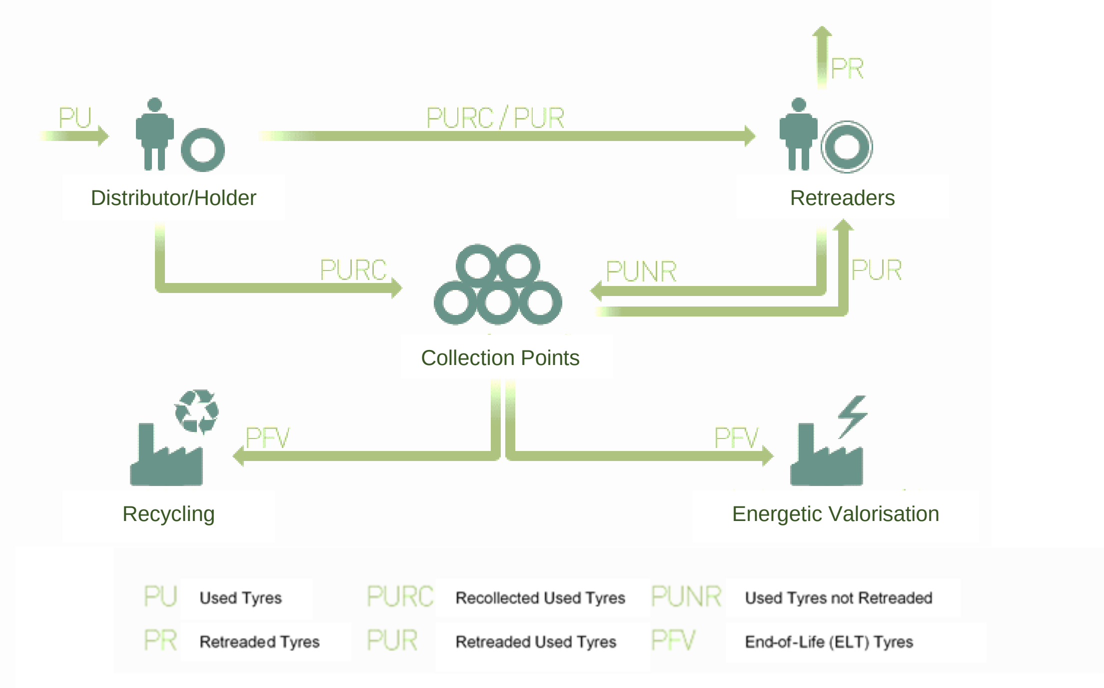

Figure 6 - SGPU model in a schematic view (Adapted from *ValorPneu*, 2020)

The SGPU model highlights the many actors who intervene in this management system and whom have different rights and responsibilities. The **Distributors** or **Holders** can either deliver the tyres in the specific centres or give them to the retreaders. The **Retreaders** can send to the **Collection Points** the tyres which have already undergone the triage of carcasses to retread, without any costs. Besides, these can also acquire carcasses to retread in the collection points. These **Collection Points** are temporary storage locations for ELT which represent an upstream "reservoir" from energy recovery agents. The collection points represent the first visible face of the SGPU model and have two main goals: (1) control and quantify all the ELT flows going towards energy recovery or other destinations and (2) provide a collection network that is adequate and uniformly distributed throughout Portugal. **Recyclers and Energy Recovery Agents** close the SGPU cycle through a financial offset and taking into consideration the legal politics. These agents receive the ELT from the **Collection Points** through the **Transportation Agents** and process them into rubber granulate which is afterward taken to the adequate recycling process or energy recovery agent. This valorisation network is mainly composed by the recycling and energy recovery operators; however, it is also possible to find operators who look for material valorisation, i.e., ELT to civil construction or maritime protection. Besides this, in the recycling process the tyre material is mostly used for rubber modified bitumen, synthetic football pitches or paving. In the Retreading process, the tyres are firstly checked to evaluate the potential to be retreaded and put again in the market as a new tyre. From this process, 40 to 50% of the tyres collected from light tyres (car tyres) are rejected whereas 20 to 30% of heavy tyres (truck tyres) are rejected. Moreover, this process is easier to perform in heavy tyres (80% of the retreaded tyres are heavy) since the market is more sceptical to absolve light tyres. These tyres that are rejected are led to reuse processes, recycling or energy recovery as it was already mentioned above. Only the reused tyres can be turned into shoe soles, however the tyres for this purpose are only valid if these have no steel in its composition. In terms of recycling, many purposes can be assigned to tyres. Recycling agents are very fond of vulcanized rubber which is one of the raw materials extracted from the tyres, but textile, steel and rubber crumb are other end products that are extracted from the tyres through recycling. *ValorPneu* recycles tyres through two main processes – Mechanical and Cryogenic. The first consists in the mechanical shredding of the tyres, fragmenting rubber in a series of shredders, removing the steel through a magnetic separation and removing the textile through density differences. In the end of this process the crumb rubber is separated according to size. The Cryogenic process focus on fragmentation of the tyre through an application to liquid nitrogen to freeze it. Firstly, the tyre goes through a mechanical grinding to be turned into small fragments that are taken to the cryogenic tunnel. After this process, steel and textile are removed through magnetic separation and suction, respectively (*ValorPneu*, n.d.). *ValorPneu* has been gathering data since the creation of the company concerning the tyres treated and its final destiny. **Figure 7** shows a representation of the distribution of tyres (in tonnes) according to its final use. It is noticed that the stockpiles or tyres ending up in landfills is practically insignificant emphasising therefore the efforts *ValorPneu* has been having in the scrap tyre market, in Portugal.

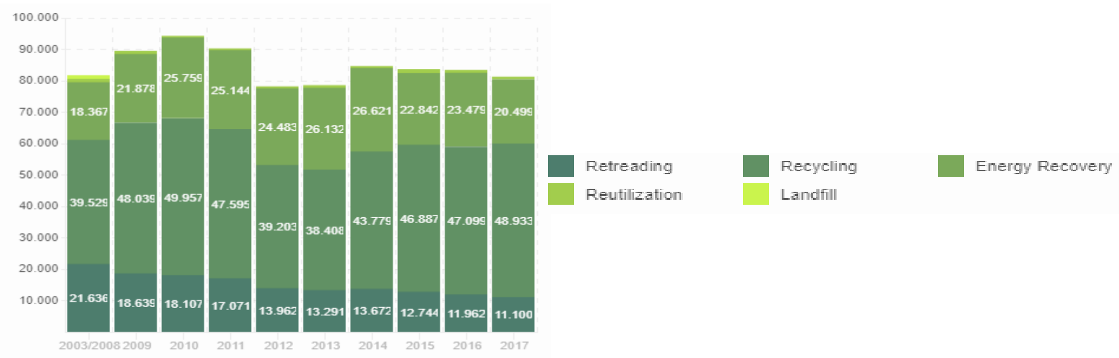

Figure 7 - Used tyres collected by the SGPU distinguished by their final destination (in ton) (Adapted from ValorPneu, 2020)

Table 3 represents the percentage of tyres collected by the model, recycled and retreaded and prepared for reuse. The percentages have been mostly decreasing since 2012, which might be an indicator to a decrease in scrap tyres in the market.

Table 3 - SGPU results and comparison throughout the years, from 2008 until 2016 (Adapted from ValorPneu, 2020)

Achieved Results	2016	2015	2014	2013	2012	2011	2010	2009	2008
Collection rate within the SGPU	104,0%	109,2%	108,6%	110,3%	120,0%	114,6%	106,0%	103,0%	106,5%
Retread + Prepare for Reuse Rate	16,1%	18,2%	18,3%	19,8%	22,4%	22,4%	20,9%	22,6%	27,0%
Recycling Rate	73,4%	78,60%	72,3%	70,7%	81,6%	81,9%	74,7%	75,3%	67,3%

2.3.4 Scrap Tyre Market and Processes

The world has already realized the tyres are a consistent issue for the human health therefore a few companies aiming at recycling scrap tyres have been arising. This is the case of Liberty Tyre Recycling, a company founded from a previous tyre processing factory, in 2000, in the USA. This company collects scrap tyres and offer remediation services also at dump sites. After collecting the tyres, these are processed and turned into raw materials that are posteriorly used as rubber goods, rubber flooring, asphalt, athletic surfaces or in playgrounds (*Liberty Tire Recycling*, n.d.).

Indosole is another company launched in 2009 in San Francisco, CA (USA) and was born out of the concept of turning tyres into shoe soles. The founder aims at producing tyre sole footwear on a world scale thus increasing the awareness of this current problem and changing the preferences of the consumers to this sustainable option. According to the company, turning a tyre into a feasible sole takes five steps. The first step consists of getting scrap from garages or tyre brokers (in Bali, Indonesia) before being dumped. Once the tyres are gathered these are shipped in trucks to the main production site. The tyres are cut to remove the its edges, in a process made by hand. Then, the soles' shapes are then cut from the tyre. According to *Indosole*, tyres provide durable, flexible and supportive soles. The third step consist of designing and bringing to life the upper part of the shoe, which are made from natural materials. Once this is concluded the two parts of the shoe are assembled through a sequence of processes: hammering, pulling, gluing, pressing and heating. Finally, the fifth step consists of adding an inside sole to the shoe (*Indsole*, n.d.).

On the scope of scrap tyres' processes, many recycling tyre models have been developed so far, such as the one by Sasikumar et al., (2010) who have developed a model applied to the remanufacture of truck tyres, by retreading the tyre. The authors state that even though recycled tyres are sold with lower prices, the quality and expected life is similar to brand new tyres. Even though there are several recycling techniques for tyres, all of these focus on the economic benefits these might bring and none of these considers any environmental impact when implemented. Therefore, Subulan et al. (2015) pointed out the need to develop an economic and environmentally friendly closed loop supply chain to achieve a sustainable development. On this scope a model aiming at maximizing the profit of the retreading operation of a reverse logistics network, considering remanufacturing and recycling, was elaborated. The author stated the lack of environmental considerations in Closed Loop Supply Chains (CLSC) is a reason for the implementation of the a methodology that quantified environmental impacts. This methodology was based on a systematic method that accomplished the subjective procedure when considering the various impact categories, thus making it better when compared to others. Moreover, it allowed a quantification of the environmental impact of a manufacturing process using only one indicator, simplifying its application and making it an advantageous option. In the study an overview over multiple recovery options was conducted and an holistic modelling approach to coordinate a system aiming at recovering the initial value of old tyres was presented. The model was based on a mixed integer programming model which prevented sensitivity analysis to be applied, therefore the Taguchi method was implemented to obtain the optimum objective values and to analyse the effects of the parameters in the objective function. To analyse the parameters effect when combined, interaction plots were implemented, and also interactive fuzzy goal programming combined with the Taguchi method were used to obtain the effects of the values of the parameters in the solution. Subulan et al. (2015) concluded the study pointing out the difficulties in assessing environmental damage within deterministic environments therefore stating the importance in considering these parameters in the study as incomplete or fuzzy.

2.4 Conclusion

Section 2 described the lethal faith plastic products are unveiling for our future. It introduced the way plastic consumption has been growing and how or what it is used for. Plastic waste management practices and consequences were also explained. Moreover, one material that can either be naturally extracted or derived from fossil fuels is introduced - rubber. Rubber has undeniable properties of resistance and flexibility and is highly used in the production of tyres. Yet, synthetic rubber is the most common type of rubber used nowadays and is also the harmful one. Tyres have a great capacity of being reused either for energy production or other applications. Use and faith of scrap tyres is also explained in detail as well as its harms for the environment if disposed illegally. The section also introduces entity that manages the scrap tyre flows and how this is achieved, in Portugal. Finally, the section concludes by introducing companies that are thriving the use of scrap tyres in marketable products.

3. State of the Art

The first section of this chapter – Section 3.1 introduces the Circular Economy concept, with different perspectives according to different authors, research on this topic, approach and its main characteristics. Also, still in this section the concept of Circular business models and strategies according to different authors is introduced. Section 3.2 presents the concept of Product Design, its phases and its interaction with the concept of Circular Economy. Section 3.3 presents the concept of Eco-Design, introducing what Eco-design is and the EU requirements for any eco product. This is followed by the tools to address Eco-design and the several practices to adopt this concept in a product or company. The last section – Section 3.4 – introduces the literature regarding business models adjusted for sustainable products.

3.1 Circular Economy

3.1.1 Circular Economy Definition

A take-make-dispose system characterizes a Linear Economy, which is what has been lived nowadays. A linear economy focusses on creating as fast as possible, as efficiently as possible and as much as possible. This economy is built on cheap energy, oils and gas and does not focus on the scarcity problem until it becomes a constraint on the system. A linear economy is a waste model, made possible by an overload of energy and materials. The urge to redesign the current business models and logistics to avoid price sensibilities and take advantage of the possibilities offered by the constant technological development have led to the concept of Circular Economy (CE) (Webster, 2013). According to *European Comission* (2015), a Circular Economy is an economy, where waste is diminished over time and products, materials and resources maintain their value if possible in the economy. The *Ellen MacArthur Foundation* (2013) describes a CE as a regenerative industrial system which replaces the "end-of-life" of the products by a regeneration of these. It focusses on a shift *"towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models"*. A more complete definition was presented by Kirchherr et al. (2018), which described a CE as an economic system based on business models that substitute the end-of-life phase by a reduction, reusage, recycling and recovery of materials used in the production, distribution and consumption process. The aim of the CE, according to the author is "*to "accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations"*. To perdure, a circular economy must be adaptive and dynamic, effective yet not too efficient or resistant to change, to avoid stagnation. A CE when dynamic emphasizes change and diversity meaning the system is resilient and redundant to change. To be able to implement a circular economy money should be compared to a flow of information that coordinates an exchange of products in an economy, reflecting the full costs of a product. Moreover, a CE can be defined by five major mantras: (1) *Decouple economic growth and development from the consumption of finite resources,* (2) *separate technical and biological* *materials keeping them at their highest value,* (3) *Effective design and use of materials to optimise their flow and maintain or increase technical and natural resource stocks,* (4) *Provide new opportunities for innovation across fields such as product design* and (5) *establishing a framework and build blocks for a resilient system able to work in the long term* (Webster, 2013). According to the author, to implement a CE it is necessary to go through four system shifts. Firstly, it is necessary to implement resource efficiency to allow the implementation of new and environmentally friendly materials and procedures, leading to a decrease in energy and waste while maintaining the quality of products. The second shift aims at changing to biomimetic models of production to reinvent ways of redesigning waste into useful items. The third shift relates to the use of current goods to provide services. Finally, the fourth shift focusses on reinvesting in natural capital (Webster, 2013). Moreover, according to a study by Lacy & Rutqvist (2015), it is also necessary to include the society in these changes and stimulate a better consumption and disposal behaviours by individuals. According to a study by the *Ellen MacArthur Foundation* (2015) there are three main principles by which a Circular Economy is believed to be based on. These principles are: (1) *Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows:* it is necessary to choose the right resources, processes and technologies that allow an environmentally friendly performance by using better resources. Plus, it is also necessary to replace the activities that compromise natural resources by others more sustainable. (2) *Optimize resource yields by circulating products, components and materials at the highest utility at all times in both technical and biological cycles:* an extension in products life cycle is necessary in a Circular Economy (Sauvé et al., 2016). To assure this it is necessary to implement techniques of remanufacturing, reuse and recycle to close the flow of materials (Geissdoerfer et al., 2018). (3) *Foster system effectiveness by revealing and designing out negative externalities:* a CE focusses on reducing the effect of negative externalities in the society, i.e., diminishing the side effects of an activity. These externalities are typically air, water or noise pollution, health effects and climate changes (*Ellen MacArthur Foundation, 2015)*

3.1.2 Circular Economy Relevant Characteristics

Circular Economy important definitions have been presented already, thus the principles of Circular Economy shall be presented. A conceptualization model of a Circular Economy, adapted from the *Ellen MacArthur Foundation (2013)* can be seen in **Figure 8**. The model starts with the extraction of biological and technical nutrients to fulfil the cycles of production of each type of nutrient.

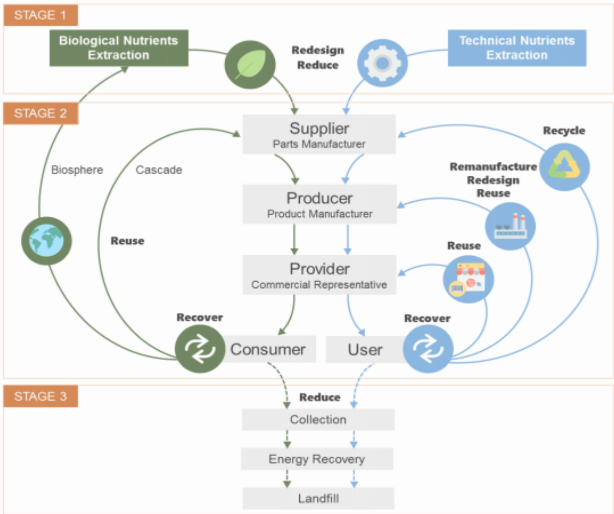

Figure 8 - Circular Economy Conceptualization model (Adapted from Ellen MacArthur Foundation (2013)

The cycle on the right corresponds to the technical nutrients whereas the cycle on the left corresponds to the biological nutrients. These nutrients are extracted from the environment by the suppliers and arranged to facilitate transportation and handling once the producer receives these. Next, the production begins, and the final product is obtained according to the specifications desired by the final customer. Yet, before reaching the market the product is firstly delivered to Providers or commercial traders (retailers, for instance). According to each nutrients the path followed is different. In the biological cycle, the final stage of the product is the consumer. In the technical cycle products are used, not consumed, thus the final stage of this product is the user. Once this process is completed and the product no longer fulfils the needs of its users or consumers it has two possible directions: recovery - stage 2 - or disposal and eventually landfilling - stage 3. In the model, only stage 2 represents the concept of Circular Economy. Yet, to achieve this, Stage 1 and 3 must be incorporated to understand the natural process by which products are going through nowadays and to understand the need for reducing these, namely the extraction of raw materials and the waste generation not to over pollute the environment (Braungart et al., 2007; Ellen Macarthur Foundation, 2013; Zhang et al., 2013; Jawahir & Bradley, 2016; Leite, 2017). The model was briefly explained; however, many more variables have impact in this model as it is also represented in it. Therefore, two concepts are introduced: (1) *Biological and Technical Cycles* and (2) *6Rs Definition*.

Biological and Technical Cycles

Depending on the type of metabolism, nutrients can be biological or technical. The first are distinguished by its decomposable characteristics. These are harmless materials and can be used again to feed biological processes (Braungart et al., 2007). Biological nutrients are materials made of plants or textiles, consumed directly or indirectly (e.g. physical degradation or abrasion) throughout its life cycle. In the technical cycle the nutrients can be mineral or synthetic materials that can perdure through multiple use cycles thus are able to be kept in a closed loop cycle with no harm to the rest (Braungart et al., 2007; Ellen Macarthur Foundation, 2013; Ghisellini et al., 2016). These nutrients are meant to bring benefits for the manufacturer and the user since the ownership of the material will always belong to the manufacturer and is lent to the customer with no liability associated (Braungart et al., 2007).

6Rs Definition

Multiple definitions of Circular Economy present the 3R framework which stands for (1) Recycle, (2) Reduce and (3) Reuse (Kirchherr et al., 2018). Later, a new dimension was added to this framework, the fourth R which was referring to Recover and meant the energy recovery from the materials incineration. To reduce pollution a green behaviour in all levels of the life cycle of a product has to be integrated to accomplish a circular economy (Kaputa et al., 2019). Therefore, Jawahir & Bradley (2016) came up with a new framework – 6R – and believe to be essential to achieve economic growth, environmental protection and societal benefits. The definitions of each letter of the 6R framework are as follow:

1. *Recycle:* process of creating new products or materials from other materials that would be considered waste (Jawahir & Bradley, 2016). This process of recuperating the materials or products is achieved without causing any harm to the environment (Ghisellini et al., 2016);
2. *Reduce:* focus on the initial phases of a products' life cycle. Reduction in the resources used for the manufacturing process, in the energy consumed and materials, and also in the emission and waste produced in the use phase are all concerns of this R (Jawahir & Bradley, 2016). This focus on minimizing three major losses: raw materials used, energy used, and waste produced by focussing on improving the efficiency of the production system (Ghisellini et al., 2016; Su et al., 2013).
3. *Reuse:* reuse of an existing product or its components to incorporate other products and components thus reducing the usage of virgin materials (Jawahir & Bradley, 2016). According to (Su et al., 2013) the goal is to use products as long as the product allows with frequent maintenance to allow this.
4. *Recover:* process of collecting used products to disassemble, sort and clean with the aim to provide further utilization of these in other life cycles (Jawahir & Bradley, 2016). This stage allows a product to be reused, remanufactures or redesign, thus this is the first step in the circular process (Leite, 2017).
5. *Redesign:* design of new products with components, materials and resources recovered from other products already at the end of their life cycle (Jawahir & Bradley, 2016). According to the *Ellen Macarthur Foundation* (2013) the processes of the circular chain can also be redesign to achieve better efficiencies throughout the production process.
6. *Remanufacture:* re-processing of existing products to restore the initial value or similar to it by reusing the most components from the previous product as possible without compromising its functionality (Jawahir & Bradley, 2016).

The 6R framework supports the CE achievements, but must be coordinated with the three main principles of CE introduced by the *Ellen MacArthur Foundation* (2015) presented in the previous section: (1) *Preserve and enhance natural capital,* (2) *Optimize resource yields* and (3) *Foster system effectiveness.* The first principle comprises the three stages of the model and is influenced by Reduction and Redesign. Reduction is related with the extraction of resources which should be decreased to assure a sustainable future and to further prevent waste discharges in landfills, also energy and emissions should too be reduced to avoid causing more harm to the environment (Sauvé et al., 2016; Ghisellini et al., 2016; Geissdoerfer et al., 2018). Considering Redesign, the processes and production activities should be redesigned to reach a balance in the renewable resource flows (*Ellen Macarthur Foundation*, 2013; Ghisellini et al., 2016; Leite, 2017). Redesigning a process involves a replacement for better technologies to increase the energetic efficiency of the current processes and reduce the dependency on fossil fuels. All connected increases the resilience of the economic systems against negative and uncontrollable oil effects (for instance increase in oil prices) (Zhijun & Nailing, 2007; Su et al., 2013; Ghisellini et al., 2016). Regarding the second principle, referring to the second stage in **Figure 8**, it mentions the distinction among the biological and technical nutrient flows. Regarding the first nutrient flow, this can be recovered and reincorporated in the processes by two different manners: return the material into the biosphere and allow it to self-restore and reuse the material for a different purpose (*Ellen Macarthur Foundation*, 2013). According to (Leite, 2017) reusing biological nutrients brings major cascading opportunities due to the easiness of handling these nutrients and turning them into different products. Regarding the technical nutrient the recovering process and consequent reintegration starts with the help of the stakeholders when the user discards it. Once it is discarded it is necessary to evaluate its condition and decide on its further destination; when the product is in a proper condition it can be reused to fulfil the previous purpose and it is sent to a commercial trader to put the product back into the market. However, when the previous conditions are not met the product is disassembled and each component is evaluated and taken to another destination. When the components are good enough to be incorporated into new products, the producer remanufactures the initial product with the older product' components. When necessary these components imply the introduction of a redesign phase to allow the incorporation of the materials into other products. In the case of the components not fitting the new products, these are taken to a recycling phase and further reincorporated into another supplier' cycle. Yet it must be considered that the recycling should be avoided if the reuse is possible (Stahel, 1997; Leite, 2017). According to Ghisellini et al. (2016) some materials may be only recyclable until a determinant point of its life. Thus, the author highlights a need for wisely selecting the materials to be introduced in the supply chain to consider these restrictions. Also, products that are unable to be composted, reused or recycled should not be chosen either by producers or users. Finally, the third principle is related to Reduce and Redesign. Redesigning a supply chain allows a reduction in the negative externalities due to a reduction in emissions. Also, extraction of resources, overproduction, overuse of fossil fuels and waste generation are major negative externalities connected to the way a supply chain is designed (Elia et al., 2017). Understanding these relations is crucial to understand the need to evoke a change in our system. The following subsection focusses on how circular business models are developed.

3.1.3 Circular Business Models

Turning a whole economy to a different paradigm, begs for a change in the decisions taken by policy makers, and an incorporation of the circular concept to the existing business models because it is necessary to change the way products are commercialized and consumed (Lewandowski, 2016; Franco, 2019). Thus, it is necessary to foster the comprehensive knowledge needed to design Circular Business Models (CBM) and understand the prerequisite this represents to a CE (Lewandowski, 2016; Bocken et al., 2016). According to Linder & Williander (2015) a circular business model is defined as one, where the idea of creation of value is held on retaining the economic value of existing products after its usage and turning into other production offerings. Above all, circular business models focus on developing sustainable solutions based on the creation of additional monetary and non-monetary value. This is only possible when three major elements are included in the organization: (1) *Sustainable Value Creation*, (2) *Pro-active Management of a more comprehensive set of stakeholders* and (3) *Long-term Perspective.* The first comprises not only the increase in value for the final customer but also the creation of private and public societal benefits. The second can be explained by an emphasis on the cooperation among stakeholders at different levels, focusing on social, environmental and economic value to align the interests of all the parties involved in the supply chain. The third specifically aims at developing solutions to reach a circular economy through the implementation of a circular value chain and a stakeholder incentive alignment. The following diagram, on **Figure 9**, represents the shift from a linear business model to a circular one, through the implementation of a sustainable business model.

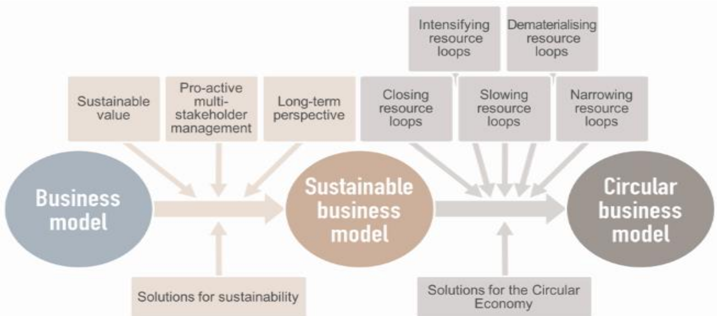

Figure 9 - Flow of strategies to implement from a traditional BM to a circular BM (Greissdoerfer et al., 2018)

Focussing on the innovation of a circular business model enhances the sustainability of the business model hence going beyond the typical focus of a sustainable business model, which is efficiency, productivity and greening the SC (N. M. P. Bocken et al., 2016; Geissdoerfer et al., 2018). To implement a CE it is necessary to follow different strategies and understand how these are important to achieve a state of circularity. These strategies are discussed in the following section.

3.1.4 Circular Economy Strategies

To achieve a CE some strategies must be applied in a value chain to promote competitiveness and prosperity. These are: (1) *Eco-Design,* (2) *Conscious Procurement,* (3) *Cleaner Production,* (4) *Sustained Lifespan* and (5) *Recovery Economy* (Leite, 2017). Yet, according to Ghisellini et al. (2016) there are two major approaches by which a nation can implement circularity, these are the top-down and the bottom-up approach. The first concerns a macro level of action, i.e., adoption of certain politics in a nation level through national legislations and politics while the second is narrower with specific policies adopted by different organisms to achieve greener objectives and push these initiatives to a macro level (Ghisellini et al., 2016; Leite, 2017). In a traditional value chain, the production phases start with the design activity followed by procurement, production, marketing and sales, usage and finally the disposal. Yet, in a modern value chain this sequence should be modified to incorporate the five mentioned strategies and achieve a greener and circular environment (Rocca, 2016). Yet, it is important to understand the number of scientific documents that refer these strategies through different nomenclatures. Therefore, seven documents were selected to analyse these strategies, with different taxonomies, through different perspectives and applied to different products or realities. These documents were selected due to the number of times these were mentioned in other articles or due to its recent publications which suggest an updated information. These articles are (*Ellen Macarthur Foundation*, 2013; Su et al., 2013; Elia et al., 2017; Geissdoerfer et al., 2018; Tam et al., 2019; Tyler & Han, 2019; Ertz et al., 2019). The first two articles are the most cited while the remaining articles were selected due to their recent publication dates. The nomenclatures used were based on the analysis by Leite (2017), yet, these differ from document to document.

Table 4 - Different taxonomies according to different authors

	Eco-Design	***Green Procurement***	***Clean Production***	***Sustained Lifespan***	***Recovery Economy***
Ellen MacArthur Foundation (2012)	- Clean and circular design - Design "waste" -Design for effectiveness and regeneration	-Material Selection and productivity	-Eco-efficiency	-Extend product longevity	-Recovery and reutilization of products and energy -Closed-loop engineering
Su et al. (2013)	-Eco-design	-Green products, consumption and purchase	-Cleaner production -Better resource allocation, utilization and productivity		-Closed loop material flow -minimize the use of virgin materials
Tam et al. (2019)	-Design out waste and pollution -Redesigning products to facilitate restorative mechanisms		-Choose alternate materials with less mass	-Recover materials and return them to productivity	-Designing for dismantling is practical and cost-effective
Elia et al. (2017)	-Eco-Design	-Sustainable sourcing	-Less pollution with cleaner material cycles -Efficient and sustainable use of resources	-Extending products lifetime	-Minimize incineration and landfill -Closed loop to recover and recycle materials
Geissdoerfer et al. (2017)			-Resource efficiency	-Durable design -Repair	-Waste prevention -Closed-loops
Tyler and Han (2019)	-Design for sustainability -Design for responsibility -Design for disassembly and disposal	-Codevelopment of circular materials - Selection of materials with low environment impacts	-Sustainable production	-Increase product longevity -Design for shared use -Customise materials to new applications	-Extended producer responsibility
Ertz et al. (2019)	-improved design for extension of lifecycle -Ensure minimal waste in design	-Use more durable parts for products	-Improved production process	-Extension of product life -Maintenance and prolonged usage -Functional life	-Close the loop by recovering a product

Eco-Design

Defined by many authors as the characteristics of a product that guarantee the sustainability of the product until the end of its useful life (Plouffe et al., 2011; Dewulf, 2013; Lindahl & Ekermann, 2013; Su et al., 2013; Ghisellini et al., 2016) . According to (Elia et al., 2017) this concept aims at developing valuable products with less materials and increase the attractiveness of recyclable and renewable assets to incorporate new products, increasing the use of these assets. Through these features, it is possible to ease the process of assuring the circularity of the materials which, according to the (*Ellen Macarthur Foundation*, 2013) is the main purpose of Eco-design.

Green Procurement

Despite being mentioned by several authors as Green Public Procurement (GPP), this is not only a public sector matter (Leite, 2017). According to Sönnichsen & Clement (2020) GPP is the search for goods, services and works that provide a minimized environmental impact throughout their life. Implementing Green Procurement in a business begs for an extensive assessment of the impacts of a product throughout its life, i.e., considering costs of acquiring raw materials, manufacturing, transporting, storing, handling, using and disposing it (Salam, 2008). According to Elia et al. (2017) sourcing in a company is an extremely important activity when incorporating a circular economy strategy. When selecting a material, it is important to understand whether this material is critic or not, i.e., if its supply is located only in one region or has few restrictions due to corporate interests, or it is a matter of national security (Ashby et al., 2012).

Cleaner Production

According to Severo et al. (2017) this concept gathers practices that assure a boost in the sustainability of the production activity of a company. Some of the practices included in assuring a cleaner production are mentioned by several authors, yet through different nomenclatures, for instance, Lieder & Rashid (2016), Winans et al. (2017) and Geissdoerfer et al. (2018) mentioned the need for assuring efficiency in the use of resources which follows the need for introducing advanced techniques and equipment and improve the use of resources expressed by Ghisellini et al. (2016) and Elia et al. (2017) mentions the need for using cleaner energy and raw materials ensuring a cleaner production process while reducing polluting emissions. According to Su et al. (2013) assuring a clean production is of extremely importance in the search for circularity since it allows a reduction in energetic emissions thus reducing negative externalities in society.

Sustained Lifespan

According to Potting et al. (2017) this is possible through reuse, repair, refurbish, remanufacture and repurpose. However, other authors (Ghisellini et al., 2016; Lieder & Rashid, 2016; Sauvé et al., 2016) suggest the longevity of a product is possible by adding robustness and quality to the product or assuring the product is easily repaired.

Recovery Economy

This is still one of the main issues of implementing circularity in the economy due to the need for capitalizing the recovery strategies of the flow of recycling materials (Elia et al., 2017; Lieder & Rashid, 2016; Winans et al., 2017). Several authors (*Ellen Macarthur Foundation*, 2013; Su et al., 2013; Lieder & Rashid, 2016; Elia et al., 2017; Geissdoerfer et al., 2018) pointed out this concept to emphasize the need of closed loop systems that start with the economic definition of these practices (reuse, remanufacture and recycle, among others). Recovery economy emerged due to the great amounts of virgin materials being used and imposing quantities of waste to the environment (Su et al., 2013; Winans et al., 2017; Geissdoerfer et al., 2018).

As is has been understood, design plays a crucial part in incorporating circularity in any product. For that reason, the subject must be properly addressed and discussed. The following chapter focus on product design and its main characteristics

3.2 Product Design

3.2.1 Product Design Definition

Design has been omnipresent since the 50s with no doubts against its importance and relevance from an economic performance to the marketing performance. Design is a global element of culture and extremely important in creating and differentiating a product thus determines every individuals' place in the society, i.e., a product is a way of communicating with others (Burdek, 2005). A good design expresses the individuality of a product, it is easy to understand and takes into consideration the product ecology, energy conservation, recyclability, durability and ergonomics (Burdek, 2005; Maiocchi, 2015). Easterday et al. (2014) states the design process follows six iterative phases: (1) *Focus the problem,* (2) *Understand the problem*, (3) *Define goals,* (4) *conceive an outlined solution*, (5) *Build a solution* and (6) *Test the solution.* The first phase is defined by the specification of product's target market, stakeholders affected, why the product was initially thought and how it should be dealt with, and the constraints and scale of it. Phase two initiates and aims at investigating the problem at hand in the scope of empirical methods and secondary sources to understand the cultural context, current solutions and design principles. The third phase is to set goals and assessments, turning an indeterminate problem to a determinate one. The fourth phase is based on the outlining of the intended design to accomplish the goals, which involves creating a non-functional, graphic representation and analyse it in terms of its feasibility. This phase is concerned with the creation of a theoretical design. The fifth phase is the prototyping of the theoretical design, followed by its evaluation. The final phase is the evaluation of the performance of the project by iterative user testing of successive versions of the design and formative evaluation to eliminate faulty designs.

Product design is related to the physical image of a product aimed at exceeding the customers' expectations. Product designers must be able to achieve an aesthetically pleasing image of the product that must perform well and endure throughout its lifetime and achieve an easy and quickly manufacture at reasonable costs. Product design has become an asset in the differentiation of a product (Homburg et al., 2015). Even so, the definition of product design is not yet well established among authors. Homburg et al. (2015) mentioned this failure and complemented it with the lack of the dimensions of product design. According to the author, the research developed, so far, is very narrow and limited, ranging from aesthetic aspect to utilitarian dimensions. Therefore, before defining the concept of product design, introduced its three dimensions: *aesthetics, functionality* and *symbolism.* These dimensions do not, individually, form a product, but the junction of the three is intrinsic to every product. Hence, according to the author, product design is a "*set of constitutive elements of a product that consumers perceive and organize as a multidimensional construct comprising the three dimensions"* indicated before. This definition of product design is valid for both visual and non-visual examination of a product. The first dimension – Aesthetics – is related to the visual image of the product (Desmet & Hekkert, 2007; Radford & Bloch, 2011). According to Reber et al. (2004) this dimension is a combination of the attributes of a product and the perception of the products' user, which goes along with the definition of product design in the scope of creating a perception of beauty to the product's holder (Leder et al., 2004; Homburg et al., 2015). The second dimension – Functionality – is related to the perception of the consumer to see the product with the ability to fulfil the consumer's needs (Boztepe, 2007; Radford & Bloch, 2011). The perception of the functionality of a product is either when the product is being consumed or used, or when the consumers see the product, which is inevitable when a consumer is buying a certain product online thus not have the possibility to use or feel somehow the product before its purchase (Radford & Bloch, 2011; Spears & Yazdanparast, 2014; Homburg et al., 2015). The third dimension – Symbolism – relies on the visual elements of a product to communicate a message and evoke associations that can be related to a place or time (Schoormans, 2005; Homburg et al., 2015).

3.2.3 Product Design Phases

Having now understood what product design is, the five stages necessary to obtain the final product with the desired features, according to Slack et al. (2007) are: (1) *Concept generation*, (2) *Concept Screening*, (3) *Preliminary Design*, (4) *Evaluation and Improvement Design* and (5) *Prototyping and final design.*

Concept Generation is the first step and stands for the transformation of the main idea into a physical product without losing its nature and necessary specifications. Creativity in this step plays a significant role thus, at this level, design requirements are more imprecise and uncertain (Huang et al., 2015). According to (Taura & Nagai, 2009) the concept generation process occurs throughout the design process thus hardening the task of capturing it in a framework of a problem-solving process. According to Unleash by Deloitte (2019) at this phase it is crucial to well-define and create a statement that properly indicates the user, the need and the insight thus increasing the specificity of the problem. This narrows down the potential solutions and assures the problem is correctly tackled with a proper solution. To facilitate this process, one of the tools used is the Problem Tree is, which according to Vesely (2008) an universal heuristic that is best utilized in the initial phases of structuring a problem when the problem is still vague and complex. It aids in the activities of identifying, prioritizing and visualizing problems and is visual represented as a tree with the causes of a problem and consequent effects. The benefits of using problem trees when identifying a problem can be summarized in three main purposes: distinguish different parts of a problem and group according to the characteristics, identify logical relations between elements and distinguish different perspectives on the problem. Moreover, Ammani et al. (2010), defends this tree diagram provides a visual map of the anatomy of a cause and effect with a better structure than any other mental map. Taking this into consideration, a problem framing tree is built based on the framework proposed by Vesely (2008), Ammani et al. (2010) and Deloitte (2019). Even though there are many tools to address this step, most of them are focussed on the exploration of important causes for such problems which is essential to help defining the area in which the designers should place focus. The exact process of concept generation is a conceptual phase thus begs for intuition and own capabilities without any other guidelines (Roofthooft, 2010).

Concept Screening is the examination of this preliminary phase of the product in terms of feasibility, acceptability and vulnerability to define whether this is a worth product in a company (Slack et al., 2007). Concept screening is also addressed as Design Concept Evaluation by other authors. According to Tiwari et al. (2016) this is one of the most important phases of the early stages of the designing process since the activity performed here impacts the later stages of the process as well as influences the success of the final design. At this phase an assessment of the overall utility of the design alternatives is made against the design objectives. Concept screening is a multi-criteria decision-making problem that is hindered by the complexity of problem solving. There are two possible approaches at this stage: numerical and non-numerical. Numerical approaches aid in qualitative and quantitative evaluation and can be in the form of an utility function or a goal programming. Yet, these have a few limitations due to the difficulty in representing intangible design criteria and factors in a quantitative manner in the initial stages of the designing process. Non-numerical methods are simpler, effective and easier. These are graphical and useful for quick selection of concepts (Tiwari et al., 2016). One of the non-numerical methods used is the Pugh chart, a methodology proved to help and facilitate the evaluation of an alternate design route (Thakker et al., 2009). This method introduced in Unleash by Deloitte (2019) is a decision-making tool that allows the comparison among different alternatives, all against an existing baseline based on range of design criteria. A Pugh chart can comprise multiple alternatives and highlight the advantages and disadvantages of each of them.

Preliminary Design uses flow charts or component structures to understand and identify, which components build up the product and how these interact (Slack et al., 2007). This stage is significantly important for the future of the design, since at this stage decisions made account for 70% of the product development costs. Even though a design process can follow different methods, the tools for this stage are still a few. It is in this phase that the main characteristics of the product are defined (such as the materials) based on the requirements defined by the developer and the design configuration is performed based on the main dimensions and components to incorporate on the product (Sebastian & Ledoux, 2009).

Design Evaluation and Improvement is highly linked with the previous since it focuses evaluating the necessity of improving the latter design before the prototype is made or tested. Many methods can be employed to perform an improvement analysis, some of these methods are related to cost efficiency and attempt to identify areas for cost improvement, others are based on the design features and try to understand what are the relevant features of the design that attempt to provide the intended benefit and evaluate whether these can be done differently (Slack et al., 2007). Regardless, according to Unleash by Deloitte (2019) a survey is a relevant tool to gather relevant information related to demographic group of the potential customer, requirements of the customer, the range of prices the customer is willing to pay and also how willing the general population is to switching from the use of previous non-sustainable versions of the product to a sustainable one. This information is necessary to better match the users' wants and needs to the product developed.

Prototyping provides the final details of the product through a range of specifications referring to the package and the process necessary to deliver the product to the customer (Slack et al., 2007). According to several authors (Moe et al., 2004; Yang, 2005; de Beer et al., 2009; Viswanathan & Linsey, 2009) it is essential to prototype when developing a product to allow designers to specify problems related to the design, facilitate the accomplishment of user needs and engineering requirements. Techniques of experimental prototyping aid in accomplishing three goals concerning the design: understanding the user context and experience, further explore the design and evaluate it, and communicate ideas (Ruvald et al., 2018). Ulrich & Eppinger (2012) defend that the decision of creating several prototypes throughout the development process must be thought through and weighted in terms of cost, time and money to build and evaluate the several prototypes. Prototyping can be done using two different technologies: *3D CAD Modelling* and *Free-From Fabrication.* 3D CAD modelling is a computer-based programme that allows to design a product with a three-dimensional visualization. This provides the ability to create a realistic assessment of the products appearance, the ability to easily change any feature of the product instantaneously, for instance, concerning the mass or volume. This technology is used to plan the final, integrated assembly and understand whether the product has geometric interferences. The free-form fabrication is the creation of physical products directly from the 3D CAD representation, and can be accomplished by a three-dimensional printer, for instance (Ulrich & Eppinger, 2012).

3.2.4 Circular Economy with Product Design

According to Sophie Thomas (Circular Economy director in RSA) waste is a flaw of design. Circular Economy and Design must be connected, yet, this connection is complex and begs for a transformation in the way designers think and develop products (Cura, 2016). Circular design must come up with products or services, which are as functional as before, with the same optimum quality materials, and providing a performance as good as otherwise, yet minimizing the negative impact throughout its useful life. The challenge rests at reducing the use of primary raw materials, keeping the products inside the closed loop (Medkova & Fifield, 2016). This challenge is overcome by a redesign of products to ease the incorporation of these again in the processing cycle. Thus, the new era' designers must consider durability, compatibility, modularity or multitasking functions (Cura, 2016; RSA, 2016). All in all, a circular product always keeps its integrity and should avoid imposing costs to the environment when it is being restored to keep the economic value (Lieder & Rashid, 2016; Hollander et al., 2017). According to N. M. P. Bocken et al. (2016), there are strategies to design a product and assure its circularity. These are divided into two major groups: i) product design strategies for slowing resource loops and ii) design strategies for closing design loops. The first is related to an extension to the useful life of products aiming at reducing the use of resources by designing products for attachment and trust, reliability and physical durability. The strategies of the first group are:

Designing for long-life products

This concerns the assurance of a longer utilization period for products. This can be possible by designing a product to be emotionally attached to its consumer by creating a long-lasting empathic relationship through "*emotional durable design"*, i.e., choosing materials to perdure without breaking down during the multiple utilizations. Additionally, designing for reliability which is related with the probability of a product failing within its expected lifecycle (Chapman, 2005; Bocken et al., 2015).

Designing for product life extension

This strategy focusses on extending the useful period of a product by the introduction of reusing strategies, maintenance techniques, repair and upgrade of a product, or any combination of these (Moreno et al., 2016). This is possible with design for standardization, creating products with interfaces designed to fit different products. Also, designing for reassembly assures the separation of a product into different components allowing it to be posteriorly assembled into other products or cycles. This latter strategy also increases the future utilization rates of a product. Designing products for future upgrading is useful in an unstable technological environment since it allows existing products to be improved in quality, value and effectiveness, delaying its obsolescence (Bocken et al., 2015). There is a logical relationship between replacement rate and two variables: product's lifetime and residence time (Franco, 2019). The first stands for the time, on average, in which a product is fully operational before reaching a failure state, which cannot be reverted (Hollander et al., 2017). As for the second, stands for the total time the product is being used (Murakami et al., 2010). Even though the replacement expected period might be long, the users still discard them previously to this date due to different trends or impulse buying that is led by a wrong judgement from users who perceive products as being outdated before its time (Franco, 2019).

The second major group of strategies for redesigning products to never leave its usage cycle, are in line with the Cradle-to-Cradle philosophy, i.e. closed loop strategies, aligned with de circular economy approach (Bocken et al., 2015).

Designing for a technological cycle

A product designed for a technological cycle is one where the its components can be recycled and turned into raw materials with high quality, allowing these to be inserted into the industrial system again. This strategy aims at reintroducing existing products into new materials or products. It is necessary to develop a continuing flow of resources into the technological cycle and assure these resources maintain properties equivalent of those in the initial material. This is assured by primary or tertiary recycling of materials since these are the only types of recycling that focus on building up a product until it is ready to be used again. Besides, this design enhances the necessity of maintaining the quality of the product or even improve it, but never diminishing it (Bocken et al., 2015; Moreno et al., 2016).

Designing for a biological cycle

This design focusses on consumption products, either consumed or worn out during its usage. This refers to products to be designed with resources captured and released to the environment without harm to it. These products are usually made out of biologically decomposing materials thus enabling a circular lifecycle (De Pauw et al., 2012; Bocken et al., 2015).

Throughout these sections, it is perceptible that circular economy and product design can be connected to develop products that have the capacity to heal the current state of the environment. These two concepts are linked via Eco-design, and this is one of the most important aspects of both product design and circular economy. Eco-design is inherent to the practices introduced previously and is important to consider its implications in the product design stages. Therefore, this concept if deeply analysed in the next section.

3.3 Eco-Design

Design for Environment, Design for Sustainability, Eco-design are all names that have been already mentioned previously. Even so, the growing concern on environment has led to an also growing amount of studies on this topic. Eco-Design drivers can be found at every sector, goals for reducing costs, improving quality, achieve environmental benefits, among others are all part of an Eco-Design perspective (Matsumoto et al., 2017). Eco-design emerged, and, according to Matsumoto et al. (2017), aims at streamlining a product in many directions. Eco-design is a reduction in environmental impact of a product throughout its lifecycle while maintaining or improving attributes like price or function. According to Favi (2013) eco-design requirements must remain cost effective because regulations on eco-design focus on achieving sustainable competitiveness by providing manufacturers with a competitive edge through the improvement of their products performance. Eco-design is an opportunity for fostering innovation in a company and allows any company to combine developments that lead to incremental innovation and/or improvement, and enhances the potential of contribution to system innovation (Brones et al., 2017). Even though there is still a deficient effective implementation of those methods in the technical departments due to the lack of allocated resources or time, lack of information on the impact on environment or lack of expert knowledge, among others (Favi et al., 2019).

3.3.1 Eco-Design Requirements in the EU

According to the EU it is mandatory for certain products to have an ecological concern when designing it. The EU calls these as *Eco-design Requirements* and are set to minimize the negative environmental impact inherent to the use, production and disposal of a product. Any product entering the EU market must obey to the rules (*European Commission*, 2019). This Directive aims at achieving a higher protection of the environment through the reduction of potential environment impacts caused mainly by energy-related products which is, eventually, advantageous for consumers. An Energy-related product is any product that needs to consume energy during its use. This Directive, by actively improving the energy and resource efficiency is contributing for an higher security in energy supply and a reduction in demand for natural resources (*European Union*, 2009). Even though these are mandatory for energy-related products, the rest of the products must also be aligned with these directives to be defined as an eco-design product. There are two different types of requirements in the Eco-design directives: *Specific Requirements* and *Generic Requirements* (*European Union*, n.d.). Regarding the *Generic Requirements,* these aim at improving the environmental performance of a product without establishing any limit value and by focussing on specific aspects of environmental concern. These are applied to all the phases of the lifecycle of a product, from the initial raw material selection to the disposal, and also when it is not possible or necessary to establish limit values for the specific product. These requirements can be divided in two types of requirements, relating to the supply of information and the manufacturing of the product:

1. *Supply of information*: the designer must deliver information to the manufacturer related with the manufacturing process, and to the treatment facilities concerning the recycling, disposal or disassembly of the product. For the consumer, the designer must inform on the relevant environment characteristics, performance, installation, use and maintenance to minimize the environmental impact (*European Union*, 2009; *European Commission*, 2019).
2. *Manufacturing activity*: the manufacturers must assess the product's lifecycle; it must be established an ecological profile of the product with mensurable physical quantities corresponding to the inputs and outputs of the lifecycle of the product. Moreover, the manufacturer must make use of the previous lifecycle assessment to identify and decide on different design solutions to improve the environmental performance. Finally, the product must be energy-efficient or recyclable *(European Union, 2009; European Commission*, 2019).

Regarding the *Specific Requirements,* these may imply a reduction in the consumption of a certain resource such as water, quantities of a given material in the product or a required value for a minimal quantity of a recycled material to be present in the product. This group of requirements is equal to the previous in what concerns the analysis done along all the stages of the life cycle of a product (*European Union*, 2009).

3.3.2 Eco-Design Tools

The Lifecycle Assessment (LCA) is considered as one of the most mature tools in eco-design and has been formalized by the *ISO 14000* (2015) series. This tool can be used in a number of different software, yet the most used one is *SimaPro* which includes a vast database with information from all over the world and multiple categories of impact and tools (Frischknecht et al., 2005; Pré Consultants, 2012; Favi, 2013). LCA can be split into four main phases: (1) *Goal and scope definition phase*, (2) *Lifecycle Inventory Analysis phase (LCI)*, (3) *Impact Assessment phase (LCIA)* and (4) *interpretation phase* (ISO, 2006). The first phase corresponds to the understanding of the product, process or activity to be evaluated the establishment of its system boundaries and desired environmental impacts to be analysed. The second phase is the consideration of all the inputs and outputs of all the activities necessary to build the product considered. Usually, the input data can be separated and analysed according to four types: processes, product stages, system description and types of waste. The processes' data is the resources and emissions used or released during the process itself. The product stages' data is the information on the processes needed for a specific products' lifecycle. The systems' data is the information that describes more complex system processes. The waste types' data is the information on emission of the different processes concerning waste management. The third phase – *Impact Assessment* (LCIA) – is where the ecological effects of using the material, water and energy are calculated. Finally, the fourth phase is the evaluation of the results from the assessment and the selection of the better performed product or process or service analysed (Favi, 2013). The assessment of the LCIA provides valuable information to make decisions on the scope of product development, improvement of production systems and product choice at the production level (Pennington et al., 2004). According to (Favi, 2013), the results of the LCIA are called eco-points which stand for a scheme that supports the LCA tools. These schemes provide a calculation of an eco-score – or single-score - attributed to each phase of the product lifecycle. There is a vast number of different schemes that help in the calculation of the eco-score – *Eco-compass, Ecoindicator-99, Recipe,* among others (Favi, 2013).

3.3.3 Eco-Design Practices

According to the ISO TR 14062 norm (2002), the integration of eco-design practice must be defined in the processes and in the development of the products and its environmental aspects should be balanced against other factors such as safety and health, cost or performance. This process must be continual and flexible, promoting innovation and environmental improvement. This norm also emphasizes relevant strategies used by organizations attempting to integrate environmental aspects into product design, such as a product life cycle analysis on the raw materials to use or multi-criteria assessment on important environmental aspects and impacts. According to the ISO TR 14062 norm (2002) there are four critical success factors when designing ecological products: (1) *Engagement and commitment for top managers*, (2) *multidisciplinary engagement*, (3) *alignment with the Plan-Do-Check-Act cycle* and (4) *use of adequate tools.* According to Johansson (2002) there are six essential elements in the development of a sustainable product: suppliers, organization in teamwork, composition of the product development team, project manager, senior manager and the final customer. The author emphasizes that the communication between these elements is one of the most important aspects to reach efficiency and efficacy in the development of a product. In another perspective. Pigosso et al. (2013) refers that these practices are activities supported by different techniques and tools with the purpose of implementing environmental concerns in the development of a product and its processes. Eco-design practices can be separated into two groups: *Management practices* and *Operational practices.* Management practices are those involved in the management of the processes and product development. Operational practices are those involved in the technical specifications of a product. The first group of practices are more generic and can be implemented in any company, such as: implement eco-design activities or create and monitor mandatory regulations on environment (Pigosso et al., 2013). The second group of practices is more specific and related to design options, such as: minimizing material content, selecting harmless and non-toxic materials and ease the upgradability and adaptability of a product (Pigosso et al., 2013). Considering these practices, it is important to take a deeper understanding of these. To understand the relevance of these when developing a sustainable product Leite (2017) gathered 9 strong practices and further elaborated on these. The practices are explained next:

1. *Substitute hazardous materials by environmentally friendly ones:* replace harming materials by materials with a better performance in providing an healthy environment; This can boost a reduction in carbon emissions and reduce the emission of other toxic materials, thus increasing sustainability of product components and the final product.
2. *Incorporate biological materials*: supported by the biodegradable condition of these materials allows these to be returned to the environment without consequences on human health. This practice helps achieving a closed loop system in a faster way.
3. *Incorporate recoverable materials:* introduce recyclable, reusable and re-manufacturable materials in the product allowing a better performance in recovering economy practices.
4. *Incorporate recovered components:* components that were used in other products can enter the lifecycle of this new product in order to reduce the amount of extracted materials, reducing the demand for raw materials thus preventing resource scarcity.
5. *Reduce materials usage:* this practice presents a challenge that must be addressed when considering the purpose of the product. This purpose must be maintained when reducing material inputs. This practice provides a reduction in demand for resources.
6. *Develop energy efficient solutions and renewable energy consumption:* boost energy efficiency in the use phase by prioritizing renewable resources. In a CE, renewable energy must be the only type of energy used to reduce the dependency on fossil energy and foster the resilience of economy on oil downturns (Ghisellini et al., 2016; Leite, 2017).
7. *Incorporate robust materials:* implementing long lasting and resilient materials, to slow down resource loops and reduce the over extraction of raw materials.
8. *Incorporate Modularity:* create products possible to be disassembled into independent modules, providing higher effectiveness and lower difficulties in recuperating products.

9. *Environmentally friendly assembly:* assemble components in such a way that facilitates disassembly and improves the durability of the product, accomplished by a placement of the components with great probability of damage inside the product and the rest in the outside area. Another option is to locate components with regular need for repair or replacement in a strategic area easier to reach.

With all the guidelines for the development of an eco-designed product, the metrics necessary to place this in the market and still guarantee its sustainability along the process must be looked. The following section elaborated on business models for sustainable products as it was mentioned before.

3.4 Business Models for Sustainable Products

To fulfil the ultimate goal of the project – the commercialization of a product – it is necessary to foster the understanding of the procedures taken to launch any product in a market. Therefore, defining and characterizing a business model is crucial and, above all, one that fits the sustainable necessities of the product is essential. Business models have been firstly introduced in 1998 by Timmers as an archetype that describes the impact and benefit of any stakeholder involved in the business, through its products, services and flow of information (Timmers, 1998). Since then, this concept has been highly referred to by many authors. One of the latest definitions given to the concept, came up in 2010 by Osterwalder et al., who have described it as the manner by which a company generates, delivers and captures value. A business model, when clearly understood provides useful insights into the alignment of strategies and actions thus fostering strategic competitiveness (Casadesus-Masanell & Ricart, 2010). Even so, to fulfil the purpose of a business model, many frameworks have been developed and these are characterized as a set of building blocks that represent the strategy by which a company commits to generate value and profit. The most well-known and applied framework is the Business Model Canvas (BMC) which was introduced by Osterwalder et al. (2010). The Business Model Canvas (BMC) is a tool highly effective for users since it is a visual representation of all the elements involved in a business model and their interactions between one another and impacts on the value creation. Due to the visual aspect of the BMC it aids in discussion and strategy decision making (Wallin & Chirumalla, 2013; Bocken et al., 2015) The development of the BMC followed design science theory and methods, highlighting the accessible and visual representation of the system to provide guidance in the creative phase of prototyping, to gather feedback and to revise the iterations on the business model (Osterwalder, 2004). This model divides a business model into nine components: customer value proposition, segments, customer relationship, channels, key resources, key activities, partners, costs and revenues (Osterwalder et al., 2010).

Despite the great utility and benefits this model has brought to companies, the economic value orientation has raised some criticism (Upward, 2013; Coes, 2014). The need for implementing solutions focussed on sustainability and benefiting stakeholders while diminishing the impacts on society has begged for the development of sustainable business models (Bocken et al., 2015). A business model for sustainability has been described by Schaltegger et al. (2016) as a model that describes, analyses, manages and communicates the sustainable value proposition of a company, the creation and delivery of value and how the company commits to capture economic value while keeping natural, social and economic capital beyond the company's boundaries. On this scope, Joyce & Paquin (2016) have developed a tool that aims at supporting "*the creative exploration of sustainable business models and sustainability-oriented innovation more broadly*". The Triple Layer Business Model Canvas (TLBMC) is an extension of the previously presented BMC with two more layers that explore the environmental and social value creation. The environmental layer focus on the lifecycle perspective of the impact in the environment, while the social focus on the stakeholder management approach to explore the social impact of an organization. In the environmental layer there are nine components: functional value, the materials used, the production methods, the supplies and outsourcing activities, how the distribution is to be made, the use phase impact, the expected end-of-life for the product, the environmental impacts and the environmental benefits. In the social layer's components are: social value, employees, governance, communities impacted, the societal culture involved, the scale of outreach, end-users, the social impacts in the scope of social costs of the organization and the social benefits (Joyce & Paquin, 2016). **Figure 10** represents the TLBMC.

Figure 10 - Representation of the Three Layer Business Model Canvas (TLBMC) (Adapted from Joyce & Paquin (2016))

3.5 Conclusion

The different perspectives of CE all convey to the same goal of closing a loop of constant extraction and disposal. To make this, four main strategies were identified: (1) *Eco-design,* (2) *green procurement*, (3) *Sustained Lifespan*, (4) *Cleaner production* and (5) *Recover Economy.* To foster circularity, the changes must start from the bottom of this chain and small changes must be implemented to achieve greater goals. Product design plays a great part when developing a product and must be carefully addressed to attend all the necessities of a client and the economic constraints of the company. Eco-design was properly introduced and is crucial in changing a company's path towards circularity and is considered as necessary in several articles. Several practices and tools were explained, and how complex eco-design can be, yet necessary to foster a change in the system as it is known. And to follow this change, the necessity of rethinking a business model is evident, hence, it was presented in this final section.

4. Methodology

This chapter describes in detail the methodology to be followed throughout the master dissertation. This chapter is divided into six sections, which correspond to the six major steps to be employed. The basis of the methodology is adapted from the one proposed by Slack et al. (2007), which was further extended to a multi-methodology approach. Mingers & Brocklesby (1997) pointed out that the multi-methodologies use different methods to achieve the benefits provided by their combination. The application of different methods allows a better model validation, theory testing and a better gathering of important information to consider. Hence, in each step of the methodology proposed by Slack et al. (2007) different methodologies will be applied, following directives of different authors. **Figure 11** shows the methodology to be followed throughout the master dissertation. Each step is further explained.

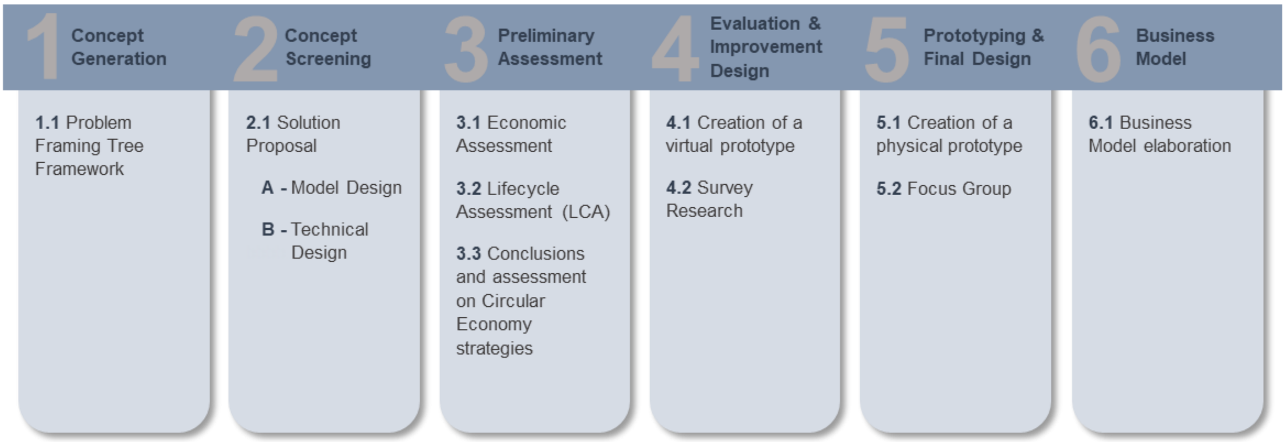

Figure 11 - Proposed Methodology

Step 1 – Concept Generation

The main goal of this phase is to clearly define and understand the problem. In this step the Problem Framing Tree Framework is applied. This tool has been used by several authors (Vesely (2008) and Ammani et al. (2010), Zimmerman (2014) and Unleash by Deloitte (2019)) due to the simplicity and objectivity it provides in correctly framing a problem. To develop the problem tree, based on the research developed and presented by Vesely (2008) and Ammani et al. (2010), Zimmerman (2014) and Unleash by Deloitte (2019), several steps will be followed.

Step I – Purpose definition: Define the purpose of the Problem tree. For this step it is necessary to clearly and specifically define the purpose of the tree.

Step II – Problem Identification: Identify major existing problems on the subject and proceed the analysis focussing on one problem at a time. The problems chosen must be formulated in a specific and comprehensible manner. If a problem is too broad or general, and it proves to be difficult to proceed with the analysis it should be eliminated.

Step III – Problem causes: Discuss causes of the problem chosen and build the tree diagram based on these. This step is carried out for all the problems identified. When a combination of causes is inherent to one effect, then these should be grouped.

Step IV – Tree Evaluation: Review the entire tree and adjust if necessary and evaluate the coherence of the whole tree.

Step V – Problem Identification: Identify the core problem. The outcome of the problem tree should be concise and comprehensible.

The Problem Tree framework is shown in **Figure 12**:

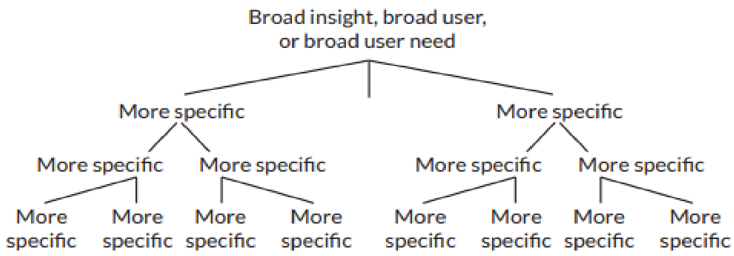

Figure 12 - Problem Tree diagram (Unleash by Deloitte (2019)

From this methodology step, after the development of the Problem Tree, a clear idea of the overall problem and how to approach it, should be presented to support a solution proposal.

Step 2 – Concept Screening

Concept Screening is the phase to conceptualize a solution to tackle the previous problems found. To initiate the solution proposal, Step 2.1 is crucial to create a baseline for a proper solution based on the problem identified in the previous phase. The solution presented should satisfy the points defined before and should as much specific as possible in terms of features and materials. To accomplish this step, the *Designing for long-life* practice, introduced by Bocken et al. (2015) should be considered, to develop an attractive and emotionally connected product. To select only one solution, among many, a multi-criteria analysis is used to evaluate the different solutions presented and decide on the most feasible one, having in consideration criteria selected. To provide an elaborated and concrete solution, an assessment over the solution characteristics must be carried out. This analysis is divided into two sub sections – A and B.

A. Model Design

In this section the selection of the best design typology is made. As suggested by Tiwari et al. (2016), a multi-criteria analysis is performed. The multi-criteria used is a non-numerical method due to its simplistic and effective characteristics pointed out by the author. Plus, to solve problems where several options are available and multi criteria are necessary to evaluate to reach a consensus, a multi-criteria analysis is crucial. The different criteria necessary to evaluate a problem and reach a solution rarely has the same relevance and thus its weight in the final solution is different. The tool Pugh Chart proposed by Thakker et al. (2009) and Deloitte (2019) will be used since it aids in evaluating design solutions against a baseline – status quo - similar product. According to the authors, to perform the Pugh Chart five steps must be followed:

Step I – Choosing Criteria: Create a list of independent evaluation design criteria (e.g. cost, durability or ease of use) which must be disposed in a left column;

Step II – Attribution of Weights: Attribute to each design criteria a weight that represent the importance of the criteria to a user. The weighting method will be determined through a multi-criteria method and will be explained in detail further ahead.

Step III – Gather Alternatives: Create a list of the different alternatives to evaluate and dispose these on the topmost row. The first option is the baseline to consider, and the respective weights for this are 0.

Step IV – Criteria Comparison: Compare the baseline and the alternatives, considering each criterion. To compare, an attribution of plus (+) signs and minus (-) signs is done if the alternative is better or worst that the baseline, respectively. In the case of the alternative and the baseline are considered equal in one criterion, the rating 0 is attributed.

Step V – Evaluation & Assessment: To obtain a numerical score, the ratings obtained in step 4 are multiplied by the weight and summed or deduced depending on the rate given.

A Pugh chart is represented in **Figure 12.**

		Status quo	Alternative A	Alternative B
Design Criteria	Weight	Details	Details	Details
Aesthetics	1	0	++	--
Durability	2	0	0	++
Cost	2	0	-	+
Ease of use	1	0	+	+++
	+	0	3	9
	0	4	1	0
	-	0	2	2
	Total	0	1	7

Figure 13 - Representation of a Pugh Chart (Unleash by Deloitte, 2019)

Despite the effectiveness of the Pugh Chart, to increase its validity a weighting method must be conjugated in step 2, in the Pugh Chart, to better attribute and decide on the weights to measure. Therefore, two different methods were considered: MACBETH method (Bana e Costa & Vansnick, 1994) and the Swing Weighting Method (Goodwin & Wright, 2014). From these two, the Swing Method was the one selected due to its quantitative-based analysis when compared to the first one – which is based on a qualitative scale, even though it provides results with less errors when compared with the second (Goodwin & Wright, 2014).

Step I – Criterion Comparison: Scoring each criterion according to the relevance of the criterion to the product. The decision maker must rank the criteria from the most important to the least and attribute to each criterion a weight under 100 points. Each criterion must weigh less than the criterion above, i.e., it can never be attributed a score higher than the one given before. The output of this step is a relevance ordinated list of criteria, from the highest to the lowest scored criteria with the correspondent weight.

Step II – Weight Generation: A normalisation of the scores is now required. This is made with the application of the following equation:

[1] $$w_i = \frac{s_i}{\sum_{i=1}^{n} s_i}, \forall i = 1,2,3,4,5$$

Where s_i is the non-normalized score attributed to each criterion i, and w_i is the normalized weight of each criterion i. The sum of the normalizations for each criterion must be equal to 1, and each value must be included in the following interval [0,1].

B. Technical Design

This section is meant to elaborate on the products' parts and composition. The technical design refers to all the features of the product that are not related to the design itself, such has the materials, components and the properties of each.

From this step, the output should be in the form of a detailed solution to be worked on in the following phases.

Step 3 – Preliminary Assessment

For the preliminary phase to initiate, all the previous phases must have been successfully completed and a solution must have been selected to be evaluated through the following phases. To initiate this phase, step 3.1 and 3.2 are essential to assess and decide on the materials to incorporate in the product. For step 3.1, an economic assessment must be done on the selected materials. This economic assessment will provide another decision variable in the selection of the materials. In the light of the ultimate goal of this dissertation it is important to address the economic strand in this analysis. To perform step 3.2 a Life Cycle Assessment (LCA) will be applied. Already presented and analysed in the Literature Review, this is one of the oldest tools used in eco-design. To perform this assessment the professional tool *SimaPro* will be used, as suggested by (Frischknecht et al., 2005; Pré Consultants, 2012; Favi, 2013). This is a software that easily runs analysis over complex lifecycles in a systematic and transparent way, grounding on the recommendations of the ISO14040 norm. This software is used in **Step 3** and provides a database – the *Ecoinvent* – which is the world's most consistent and updated source of LCI data, and provides various datasets on many industries thus aiding in increasing the accuracy in estimating relevant life cycle values and eliminating the need for over detailed life cycle assessments (SimaPro, 2020). The LCA follows four phases introduced by (ISO, 2006), the assessment steps and correspondent description are presented next.

Step I – Goal and Scope Definition: Clear definition of the purpose of the work and the future use of the results obtained. The system boundaries must be defined as well as any assumptions made to perform the analysis. The definition of the system boundaries comprises which methods – impact categories – are going to be considered, the life cycle to be studied, the physical, geographical and temporal boundaries, data limitations and quality of the data.

Step II – Lifecycle Inventory Analysis (LCI): Define the functional unit to use which will represent a calculus basis for comparing the different analysis. The functional unit should be measurable, should consider the functionality of the product according to the user's perspective, the efficacy and durability of the product, and also, must be aligned with the purpose of the study. Besides, the inputs that enter the system (raw materials, water, energy, among others) must be quantified as well as the outputs of the system (final product, water, air and earth emissions, among others). It is in this stage where all the data relevant is collected (Street et al., 2005). This step is critical to obtain a quantification of the impacts in the following phases and will be aided with the *Ecoinvent* data base, provided by *SimaPro*. This process should be accomplished by a blocks diagram where a schematic description of the problem is made, including unitary processes, mass and energy flows between processes and most relevant phases in the system. This is an iterative process, as the data is acquired it is possible to identify more limitations or data, which may require a modification in the data collection procedure (ISO, 2002). Having gathered the relevant data, a computer model must be created – in *SimaPro* -, and an analysis and reporting of the data is made. Analysing and reporting the results obtained is the final step of this phase. It is necessary to plan how the information obtained is used and select relevant data and present conclusions regarding the analysis obtained. Since the purpose of this study is only to select the most sustainable material among the alternatives, it might not be necessary to elaborate on the system inputs and outputs.

Step III – Impact Assessment (LCIA): This stage classifies, characterizes, normalizes and attributes weights to the effects of the environmental discharges inherent in the system, to understand its environmental relevance and estimate further environmental impacts. The classification of data comprises the aggregation of data into relevant categories for the analysis, and the interrelation cause-effect between emissions and impact categories must be established. For the characterization it is necessary to translate the inventory information into the impact categories, evaluate the potential impact of the impact categories and quantify the impact of each component of the LCI.

For this step, the *ReCipe* method will be used. According to Carvalho et al. (2014), the *ReCiPe* the most recommended approach because it is one of the most flexible methods since it includes three levels of outputs' aggregation. The ReCiPe, introduced by Goedkoop et al. (2013) introduces characterisation factors that are obtained through a cause-effect chain and is a combination of different methodologies in a consistent way. Thus, in this impact assessment method, 18 midpoints and 3 endpoints are considered along with normalization and weighting. The three final endpoint categories are: *damage to human health (HH), damage to ecosystem diversity (ED)* and *damage to resource availability (RA)* (Goedkoop et al., 2013).

It is necessary to compare different systems as well as environmental data relevant to decide on the materials to use (Street et al., 2005). Besides providing the environmental impacts in a uniform and quantitative way, this phase has two other main goals: increase the relevance of the inventory data by the increasing acknowledgement acquired in this phase and ease the aggregation of data to facilitate the interpretation of this and aid in the decision making (Klöpffer, 2006).

Step IV – Interpretation: Identify, verify and evaluate all the information from the previous phases. This phase aims at providing the analysis of the results with references, conclusions, limitations and recommendations on the products or materials to choose, through a transparent interpretation of the LCA. This analysis will provide a set of scenarios to improve the current system and reduce environmental charges of a certain material (ISO, 2002). In this phase a selection analysis will be performed to decide on the better material options to use in the final product. This should be the output of the phase 3.1.

Step 3.3 is a reflection over the analysis made before and studied strategies that preserve the circularity of the product. This step will gather the main conclusion from the two analysis and will encompass the fourth step of the LCA analysis. Plus, this step also aims at looking over the strategies revised in the Literature Review and critically analyse the product on the scope of these using the outputs of the previous assessments.

From the five Circular Economy' strategies formally assessed over the course of the Literature Review and presented by several authors (Ellen Macarthur Foundation, 2013; Su et al., 2013; Elia et al., 2017; Geissdoerfer et al., 2018; Tam et al., 2019; Tyler & Han, 2019; Ertz et al., 2019), three of these shall be addressed throughout the product development. These three are: *Eco-Design, Green Procurement* and *Sustained Lifespan.* Green Procurement must be addressed due to its direct connection with the decisions encompassing all the materials to be used in each component and to be analysed in the previous step in this phase. Sustained Lifespan is also liked to the search for long lasting materials and is also connected with Eco-Design on the scope of designing a product to perdure throughout many years. Finally, the Eco-Design strategy, which was highly addressed in the literature review, and whose practices – discussed also in the Literature Review – will be addressed in throughout the development of this master dissertation.

All in all, these strategies and practices will be taken into consideration throughout all the phases of conception and development, yet, this section shall provide a concise summary of how and why these are being applied.

From the accomplishment of this phase, the output will be a conceptualized product able to be evaluated by potential users.

Step 4 – Evaluation & Improvement Design

Having accomplished all the previous phases, Step 4.1 aims at creating a virtual prototype. Before proceeding to the physical prototyping phase, the creation of a virtual prototype is essential. Following the research of Ulrich & Eppinger (2012) a 3D CAD representation should be performed through a computer programme. After this virtual representation is completed, it is possible to present this conceptualization of the product to possible users. Step 4.2 aims at further investigating any need for improvement. This product is to be commercialized so that the final customer must be the centre of every phase of the innovation process, not neglecting the practices necessary to prevail the circularity and sustainability of the product. Thus, this evaluation shall be performed through a survey concerning potential users. As introduced by (Deloitte, 2019), the use of surveys allows the collection of standardized information from a large group of participants, proving to be a very cost-effective methodology. The survey will be used to gather relevant information related to demographic group of the potential customer, requirements of the customer, the range of prices the customer is willing to pay and also how willing the general population is to switch from the use of previous non-sustainable versions of the product to the sustainable developed one. This will allow to understand whether there is a need for further improvement or not, and whether the product has the capacity to perdure in the market.

As any other type of research methodology, surveys are also supported by a theoretical basis. The survey will be developed in an electronic format using the *Google Forms* platform. Based on the work by Sovacool et al. (2012) the survey should follow the four steps presented:

Step I – Designing the survey;

Step II – Testing the survey to validate its effectiveness;

Step III – Collecting data from potential users;

Step IV – Analysing the data collected.

To initiate the survey, an introductory script of the scope of the survey and project is outlined along with the structure of the survey. The survey is divided into three sections, with a total of eleven questions. The first two sections are focussed on the consumer demand patterns for the product and the product information, respectively. The last section focusses on the demographic information of the respondents.

The first section aims at understanding the current market trends and demand for similar products. This section is focussed on unveiling information on the market of summer footwear, already existent, and understand the main concerns and primary features that the consumers look for in the moment of purchase. The second section introduces the respondent to the idea for the development of the product and the business basis and questions the user on the necessity of the product in question.

The survey is mostly composed of yes/no questions and scoring questions – questions where the potential user has to evaluate in a scale from 1 to 5, different attributes (with 1 representing a low importance factor and 5 a high importance factor). The criteria used to evaluate either what a customer looks for in the process of buying a regular flip flop and a sustainable flip flop, is the same: Brand, Design, Comfort, Durability, Environmental Impact, Local Production, Social Inclusion, Recycled Material Content. It is important to understand whether these criteria differ according to the option the consumer is given to understand if the perception of the consumer differs regarding the nature of the product to buy. Before introducing the product, the user is asked to select the criteria that is more relevant when purchasing an eco-sandal – Recycled content, Local production, Social Inclusion and Environmentally Friendly Materials – to understand what is more relevant for the user. Furthermore, when the user is introduced to the product to be studied and provided with the specifications of this, the user is asked how comfortable and motivated the user would be in buying the sandal, based only on the description given. Finally, the last question on the survey presents an ecological sandal developed by *WastedShoes* (2020) and with a similar design to the sandals to develop and asks the user which price this would be willing to pay for a sustainable sandal similar to the one represented on the picture. This shall provide a broader and fairly gap between the prices that ought to be practiced, at most. Due to the image presented in this question, it is important that this question is the last one presented on the survey to dismiss the respondents of any wrongful association of the sandal in the image and the sandal in study.

Having briefly explained the content of the survey, this is fully presented next.

START

Product Development for the Scrap Tyre Industry

---Please read carefully before you start---

Thank you for your interest in answering this survey. It should take approximately 4 - 5 minutes to complete. This survey supports a Master Thesis titled "Circular Economy Solutions for the Scrap Tyre Industry" being pursued at Instituto Superior Técnico - University of Lisbon (Portugal). The present survey aims at unveiling the possibility of launching a product that combines Circular Economy and the Portuguese scrap tyre industry. All the information provided is confidential and only used for the matter of the present study. The survey is divided into three sections: 1. Consumer need; 2. Product Information; 3. Consumer data;

Thank you for your contribution.

Consumer Need

1. How often do you buy summer footwear (e.g. sandals, flip flops)? *

- I never consume summer footwear;
- Less than once a year;
- Once a year;
- Twice a year;
- 3 or more timer per year.

2. Please indicate, from 1 (least important) to 5 (most important), the importance of the following criteria when selecting a summer footwear. *

Table 5 - Criteria importance in purchasing Summer footwear

	1	2	3	4	5
Brand	○	○	○	○	○
Design	○	○	○	○	○
Price	○	○	○	○	○
Durability	○	○	○	○	○
Environmental Impact	○	○	○	○	○
Local Production	○	○	○	○	○
Social Inclusion in Production	○	○	○	○	○

3. Are you aware of any sustainable footwear alternative in the market?

- ○ Yes
- ○ No

4. What would motivate you to buy a sustainable sandal? *

- ○ Recycled Content;
- ○ Local Production;
- ○ Social Inclusion;
- ○ Environmentally Friendly Materials.

Product Information

The purpose of the developed sandal is to combine circular economy practices to develop a product made with sustainable and local materials. This product is a sandal to be manufactured by detainees from Portuguese penal institutions and composed of rubber extracted from scrap tyres, recycled rubber and jute fabric. All the materials are obtained from Portuguese suppliers.

Table 6 - Comfortability in using the product

	1	2	3	4	5	
Not Comfortable	○	○	○	○	○	**Very Comfortable**

5. Please indicate how comfortable you would be in using a sandal made from the materials described above.

6. Would you be motivated to buy the sandal described above? *

- ○ Yes
- ○ No
- ○ Maybe

6. If you were to buy a sustainable alternative to your summer footwear, how would you value the following criteria? Please indicate, from 1 (least important) to 5 (most important).

Table 7 - Criteria importance in purchasing sustainable Summer footwear

	1	2	3	4	5
Design	○	○	○	○	○
Price	○	○	○	○	○
Durability	○	○	○	○	○
Environmental Impact	○	○	○	○	○
Local Production	○	○	○	○	○
Social Inclusion in Production	○	○	○	○	○
Recycled Material Content	○	○	○	○	○

7. How much would you be willing to pay for a sustainable sandal, with the specifications described, and, with a similar design to the ones shown below?

- From 5€ to 10€
- From 10€ to 15€
- From 15€ to 20€
- From 20€ to 30€
- From 30€ to 40€
- More than 40€

Figure 14 - Similar designed eco-sandals (Source: Wastedshoes.com)

Consumer Data

8. Please state your age gap. *

- Under 18
- 18-20
- 21-25
- 26-30
- +30

9. Please indicate your gender. *

- Male
- Female
- Prefer not to say

10. Please indicate the country you are currently living at.

____

Thank you for your time and contribution.

END

For the development of the survey, most of the questions were based on the literature review of different methodologies. Hence, the following table, **Table 8**, gathers the references supporting most questions, the type of question and a brief objective of the question.

Table 8 - Survey questions' references, types and objective

Question	References	Type of Question	Objectives
Consumer Need			
1.	Hughes et al., 2016	Multiple Choice	Identifying a consumption pattern
2.	Davis, 1993; Brace, 2018	1 to 5 scale	Evaluate the value of a criterion in the purchasing activity
3.	Hughes et al., 2016	Yes/No	Are there sustainable options in the market
4.	Brace, 2018; Schrepp & Hinderks, 2014	Multiple Choice	Motivation criteria to buy sustainable sandals
Product Information			
5.	Brace, 2018; Davis, 1993; Schrepp & Hinderks, 2014	1 to 5 scale	Evaluate the respondent's comfort in using the product described
6.	Whitlark et al., 1993; Schrepp & Hinderks, 2014	Yes/No	Is there motivation to buy the product described
7.	Davis, 1993; Brace, 2018	1 to 5 scale	Evaluate the value of a criterion in the purchasing activity
8.	Whitlark et al., 1993; Schrepp & Hinderks, 2014	Multiple Choice	Identify the price range willing to be paid by the respondent
Consumer Data			
9.	Whitlark et al., 1993; Hughes et al., 2016	Multiple Choice	Identify the age gap
10.	Hughes et al., 2016	Multiple Choice	Identify the gender
11.	Hughes et al., 2016	Short Answer	Identify the country the respondent lives at

After having the survey ready, the data collection phase, follows. The surveyed sample selected shall be a convenience sample, thus not representative of any region or group, to reasonably understand the what are the potential customers' purchasing characteristics, behaviour and receptivity to the product developed. This is based on the survey distribution to different groups of people either through different social platforms (*WhatsApp, Facebook* and *LinkedIn)* or private messaging.

Step 4.1 and 4.2 will provide a clear idea of the potential of this product. The outputs from this phase should foster the final steps of the methodology.

Step 5 – Prototyping & Final Design

The final phase of the methodology is the creation of a physical prototype that incorporates all the considerations and decisions made throughout the four previous phases. The prototyping phase is for many authors one of the most important phases and therefore it should be carefully and properly addressed with the best tools. Step 5.1 is completed once the physical prototype is ready and able to be experienced by a future possible user.

Step 5.2 aims at gathering a focus group to discuss insights on the product. Having accomplished all the previous phases, the product should be ready to be formally introduced and evaluated by potential users to understand the feasibility and whether there is a need for improvement of any feature. For this step a group interview will be conducted to gather relevant opinions from the users about the product developed. The use of a focus group provides faster and cost-effective information, thus making this a better method to obtain feedback from customers. Based on the research by Wilson (2013), the focus group should be composed of three to twelve people who might actively contribute to the enhancement of the product. Adapted from the research by Krueger & Casey (2002) a focus group should follow the next steps:

Step I – Clarify the Purpose of the Study: Clearly define the purpose of the focus group, as well as the information relevant to be mentioned;

Step II – Carefully Recruit Participants: The participants to be recruited should range from different ages, sex and knowledge on the product. Besides the participants should be selected regarding their interest or characteristics that will allow them to give useful inputs;

Step III – Developing Set of Questions: Decide on the questions important to be asked during the focus group;

Step IV – Perform Focus Group Analyse Data: Decide on an approach to gather relevant information discussed during the focus group and analyse it.

Step 6 – Business Model

Afterwards, the creation of a business model, is crucial for the launch of the product in the market, and one of the goals of the present dissertation is to develop a product able to be commercialized, thus, step 6 will guide through the steps necessary to perform in the elaboration of the business model focussed on the launching of a sustainable product. The model used is the Tripled Layer Business Model Canvas, presented by Joyce & Paquin, (2016). This model has three main steps that correspond to the three layers of the model: economic, environmental and social layer.

Step I – Economic Layer: For this layer, it is necessary to define the customer value proposition, the customer segments, the customer relationships, channels to commercialize the product, key resources, key activities, partners, costs and revenues.

Step II – Environmental Layer: For this layer it is necessary to define the functional value, the materials used, the production methods, the supplies and outsourcing activities, how the distribution is to be made, the use phase impact, the expected end-of-life for the product, the environmental impacts and the environmental benefits.

Step III – Social Layer: For this layer it is necessary to define the social value, employees, governance, communities impacted, the societal culture involved, the scale of outreach, end-users, the social impacts in the scope of social costs of the organization and the social benefits.

5. Results and Discussion

This chapter is divided into five main sections each corresponding to each main step introduced in the methodology section. Section 5.1 – presents the Concept Generation phase. Section 5.2 presents the Concept Screening phase and includes two subsections where the two steps of this phase are explained. Section 5.3, Section 5.4 and Section 5.5 are the Preliminary Assessment, Evaluation & Improvement Design and Prototyping & Final Design, respectively.

5.1 Concept Generation

The first phase consists on the elaboration of a problem tree under the considerations presented by several authors in the Literature Review (Vesely, 2008; Ammani et al., 2010; Zimmerman J., 2014; Deloitte, 2019). In this section, the problem tree is presented along with relevant considerations and the important information obtained from the compilation of the tree branches.

Problem Framing Tree

The process of development of the tree branches was obtained from inputs from different experts and knowledge obtained from the literature. The experts' group that provided input was composed of five people ranging from the age of 22 to 30 years old. The experts gathered in a focus group to discuss the different possible causes of the excess of scrap tyres in the world. To ease the group discussion and better explore the cause-effect underlining each statement, the 5W technique was used. The 5W technique is an iterative questioning process to answer the *What*, *When*, *Who*, *Why* and *Where* of each statement given in the group discussion. After the group discussion, the Tree was organized with causes inherent to the same problem, being organized in the same branch. The elaboration of the problem tree provided valuable insights to reach the core elements of the problem at hand. **Figure 15** shows a representation of the problem tree developed from the insights gathered.

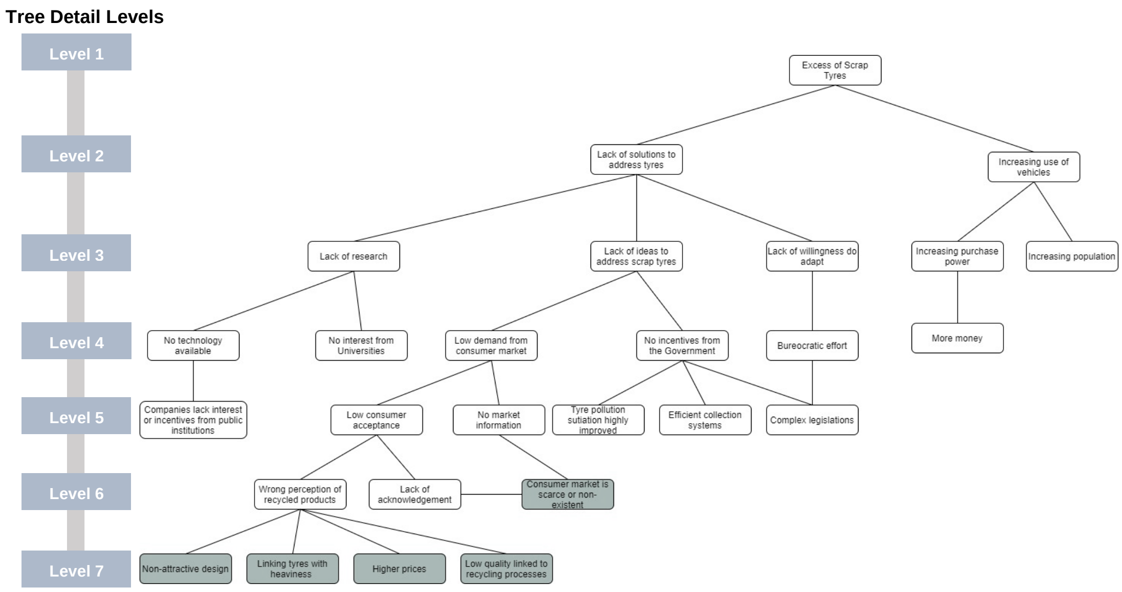

Figure 15 - Problem Tree

It is evident through the observation of **Figure 15**, that the excess of scrap tyres is highly explained by the lack of solutions to address tyres. The tree is composed of seven levels of detail, in which the first level – level 1 – corresponds to the Excess of Scrap Tyres issue. This is the superficial concern whose causes are detailed next in each level of detail.

Level 2: Emerging from the top level, two causes are identified - Lack of solutions to address tyres and an increasing use of vehicles. These two causes are the high-level causes of the excess of tyres and have different scopes of analysis.

Level 3: On this level, five causes have been identified.

i. Regarding the vehicles use, this has been caused by a growing economic power along with a growing population. As the economic power increases, the demand for self-vehicles increase as well. Tyres consumption is directly related to vehicles production, since per vehicle, it is necessary, at least, the double amount of tyres. Along with this, the growing population is also an indicator that more assets have to be produced to satisfy the also growing demand.

ii. Regarding the lack of solutions for tyres, this is being caused by an inexistence of applications for the end of life tyres, either caused by no research at this level, nor ideas to give a second life to this assets or simply no interest in adjusting to this problem.

Level 4: Overlooking at what is causing the lack of streams to provide tyres a second useful life, the lack of incentives is the main reason for this issue. With no incentives from the government there is no interest in developing any solution to tackle this problem. Without any solution that uses scrap tyres, there is no need for developing technologies to work on the tyres. As a consequence of all this, the demand from the consumer market is inexistent.

Level 5: The main reasons for not having any incentives can be explained by the progress of this sector over the past few years. The pollution issues have been highly addressed worldwide with major improvements in the collection and correct disposal of tyres. Yet, what is been hindered by this progress is that even though there are specific collection centres for this products and in theory the scrap tyres that are currently polluting ecosystems are scarce, the current solutions for the further use of scrap tyres are not sufficient for the amount of tyres reaching these centres. On a high level the scrap tyres are no longer a problem for the relevant entities, yet, looking closer over these centres, there is a major need for giving tyres a second life and ease the effort from these centres. As a consequence of this, no information regarding the consumer market for scrap tyres is known. On another perspective, this lower demand can also be caused by a lack of acceptance for products derived from old tyres.

Level 6: On the consumer level, this lack on information over the market is highly explained by the inexistence of the consumer market for scrap tyres. Even though scrap tyres are addressed for other purposes, these purposes are not considered for the consumer market. Besides, recycled products can still be seen with reluctancy regarding the safety or capacity for perduring or performing well throughout its useful life.

Level 7: On the last level of detail, the causes for this misperception over recycled products are caused either by the association of recycled products with low quality, faulty designs or higher prices practiced. These associations can emerge from a multitude of factors, such as the prices practiced by recycled items, which are usually higher than a non-recycled equivalent item. To add up, recycled items are usually perceived as not trendy or with a faulty design, and with a lower quality due to the materials composing these products, i.e., materials that have already been used previously. Finally, the stigma associated with the use of tyres to build up a product is still inherent and is mostly linked to an increased weight when compared to a similar item due to the dimension and perception of a single tyre.

Having gone over the seven levels of detail in the problem tree, the problem at hand concerns the inexistence of solutions to address scrap tyres, which is inherent to a lack of supply in the consumers' market and is supported by the lack of incentives from public institutions. To achieve the Level 1 issue on the tree, each bottom level must be addressed first. Therefore, by tackling the bottom causes in the tree – Level 7 -, it is easier to reach the upper causes. Plus, since the causes highlighted in Level 7 are more specific (less generic) should be easier to tackle. The highlighted causes can be tackled with the creation of a product to be commercialized, so that the wrongful perceptions over recycled products change. Hence, the solution should be a product that addresses all these problems. Also, by putting it to market, another cause is being tackled, in Level 6, that concerns the, so far, non-existing market. In conclusion, the solution will be developed considering the Tree' branches highlighted in green – in Level 7 and 6 of detail.

5.2 Concept Screening

Solution Proposal

A solution must be developed to tackle each of the branches selected before. For the development of this work, a private entity made a proposal to create a solution that would unveil the potential of scrap tyres. On this scope the solution of developing a footwear item made partially from scrap tyres, came up. The solution proposed is a sandal composed of three components made, preferentially, from different materials provided by companies based in Portugal and delivered to national penal institutions to be manufactured by prisoners. The sandal is composed, partially, by scrap tyres. Scrap tyres will be used to extract the outer sole of this sandal. Yet, to avoid the direct contact between the foot and the tyre, an extra midsole is necessary. This midsole will assure the necessary thickness to provide the best comfort and safety on the sandal. All in all, three components are necessary to create the sandal. The mid sole and upper fabric will be made of materials selected according to their sustainability. More information and analysis on the sustainability of the materials selected will be provided in section 3.1. To dive deeper into the specifications and design of the product proposed, two subsections are introduced ahead. The first subsection – Subsection A – refers to the model design and components, and a second subsection – Subsection B – refers to the technical design. In

Subsection A an analysis to the best possible design is made and the Pugh chart analysis is presented. In subsection B an analysis over the materials to consider is presented.

A. Model Design

The focus on Eco-design still plays an important role for the development of the product. Therefore, its practices are always intrinsic to the choices made throughout the sandal development. In the light of the Eco-Design practices, *Incorporate Modularity* was addressed in the design process. This practice was a guideline in the creation of four different designs presented (see Figure 16), which can, each, be separated into three different modules. To summarize, the guidelines considered for the designs were:

1. Possibility of separating the sandals into three components;
2. Possibility of incorporating recycled materials in each component (since these can each be prepared, independently, of the whole);
3. Having a simplistic design to aid in the process of development;
4. Being a common design sold in the markets nowadays;
5. Being equal in terms of soles, i.e., all alternatives are considered to have the same components and thickness in the soles and only differ in the fabric strap.

These four alternatives are presented in **Figure 16.**

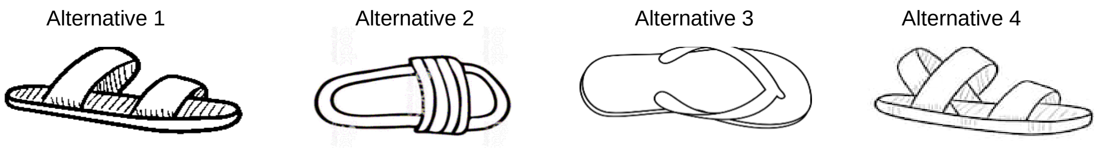

Figure 16 - Four possible designs for further selection

In order to understand, which design is the most preferable and make the best selection, a Pugh chart analysis was conducted. To develop the Pugh Chart, different evaluation design criteria were chosen. These are: Low Material Content, Adaptability, Cost, Attractiveness and Ease of manufacture. The first two criteria were selected from the eco-design practices, presented by Pigosso et al., (2013) and related to the designing options:

i) Low Material Content: refers to a minimal amount of materials when compared to the other options. This criterion is applied solely to the upper fabric, since the sole and midsole of all the alternatives is essentially the same, as it was explained before.

ii) Adaptability: related to the versatility of the sandal to be worn by everyone regardless of age or gender. This criterion evaluates each alternative in a design perspective to understand weather the sandal's design is distinctly unisex and is pleasing both for youngsters and adults.

iii) Cost: chosen to emphasize the economic pillar of sustainability and because it is a major indicator to consider in any product to be commercialized.

iv) Attractiveness: chosen since it is of great importance to increase the level of attraction of an eco-designed product to foster its utilization and its considerations over a recycled product (Homburg et al., 2015; Elia et al., 2017).

v) Ease of manufacture: selected due to an important characteristic of this product – the labour. The labour force of this product shall be the prisoners in a penal institution, whom might not be necessarily specialized for the task. Therefore, the construction of the sandal must be an easy and straight forward. The more complex the design is, the harder it is to be manufactured by non-specialized workforce.

A group of potential customers was gathered to provide inputs for this analysis. The group was composed of five people (3 female and 2 male) who were asked to contribute for this analysis by providing a rank from the least to the most important criteria and then to evaluate each alternative regarding the five criteria. The inputs obtained are presented ahead.

The next step is the attribution of weights, which are done applying the Swing Weighting Method proposed by Goodwin & Wright (2014). Before proceeding to the development of the Pugh Chart, the weights must be addressed to each criterion, according to the Swing Method. Following the procedure of the method, the criteria must be organized from the most important to the least important one. The group was asked to provide their own rank of the criteria from least relevant to the most relevant and also to provide a weight (from 0 to 100, with 100 points being the most relevant and 0 being the least relevant) to each criterion. The inputs obtained from each group member are disposed in **Table 9**.

Table 9 - Rank and weight attribution from each criterion provided by each member of the decision group

Criteria	Group Element #1		Group Element #2		Group Element #3		Group Element #4		Group Element #5		TOTAL	
	Rank	Points	Rank	Points	Rank	Points	Rank	Points	Rank	Points	Rank	Points
Adaptability	4	64	5	54	4	68	5	45	5	45	5	55
Attractiveness	5	58	4	74	5	59	4	78	4	65	4	67
Cost	2	80	3	80	2	83	3	83	3	70	3	79
Ease of Manufacture	3	65	1	90	1	90	1	92	2	75	2	82
Low Material Content	1	100	2	85	3	75	2	88	1	100	1	90

1 – Most Important Criterion 5 – Least Important Criteria

The table 9 highlights the classification attributed by each element of the group to each criterion. To elaborate the “TOTAL” column, a simple average of the inputs for each criterion was made. Regardless of all the criteria having a great level of importance for the development of the product, Low Material Content was selected by the group as the most important one to preserve the sustainability and spend as few resources as possible from nature. Ease of Manufacture and Cost also play an important role to allow the continuations of the project, due to the labour and resources available. Finally, Attractiveness and Adaptability, despite having a great importance in the product design, were considered the least important criteria in comparison to the others. Yet, this must not be neglected since these are highly important in any eco-designed product.

Having the classification and respective weights given for each criterion, a normalization of the weights was made, to be used ahead for the selection of the design alternative. **Table 10** shows a summary of each criteria's rank, points and respective weight. The normalisation of the weights was made using formula [1] presented in the methodology section – Section 4.

Table 10 - Summary of the rank, points and normalized weight from each criterion

Criteria	Rank	Points	Normalized Weight
Low Material Content	1	90	0.241
Ease of Manufacture	2	82	0.220
Cost	3	79	0.211
Attractiveness	4	67	0.180
Adaptability	5	55	0.147

Having set the weight attribution to the criteria, it is now possible to proceed with the sandal design selection. Before evaluating each design, a baseline for comparison, must be selected. The baseline is a neutral sandal design option. For this selection, each member of the decision group was asked to appoint, which design was the most common in the market. In an unanimous decision, the baseline design selected was a design like the one presented in alternative 3 but made entirely from plastic – similar to the majority of sandals available in the market nowadays.

Having the baseline set, the Pugh chart was elaborated. According to the methodology, a "+" sign attributed imply a better performance for that alternative when compared to the baseline. On the opposite, a "-" sign implies the alternative performs worse than the baseline. The inputs from the decision makers were gathered and **Table 11** presents a summary of the decisions that were collected from the decision group.

Table 11 - Pugh Chart

Design Criteria	Weight	Baseline	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Low Material Content	0.241	0	-	-	0	-
Ease of Manufacture	0.220	0	+	+	0	-
Cost	0.211	0	+	+	+	+
Attractiveness	0.180	0	-	+	+	-
Adaptability	0.147	0	-	0	0	-
Total	1	0	-0.137	0.370	0.358	-0.577

From the elaboration of the chart, the Alternative 2 is the one that gathered more points, from the overall evaluation, obtaining, therefore, the greatest sum of all. Alternative 1 and 4 obtained a negative sum, implying these would perform worse than the baseline. Overall, Alternative 2 will be considered for the following stages and its materials are discussed in the following section – Subsection B. Technical Design.

B. Technical Design

With the design selected, a range of different materials can now be selected to define the technical aspects of (*Comforting Footwear*, 2020; *Footwear Info*, 2019). The three components of the sandal will be composed of different materials, and only one of the components has already been decided on its composition. This component is the outer sole which will be made of scrap tyres. For the remaining components a deeper investigation must be made.

<u>Mid-sole:</u> The potential materials to incorporate in the mid-sole should be sustainable (to follow the *Eco-design* practices discussed) and should provide the necessary resistance and comfort. Plus, the possibility of being supplied by national suppliers should be taken into consideration. According to different sources (*Footwearinfo,* 2019; *Comforting Footwear,* 2020), rubber is the most common material used in the fabrication of shoe soles. The resistance and flexibility provided by rubber soles are highly pointed out as the differentiating factor in these types of soles. Besides these properties, rubber soles are also durable, and the low conductivity of this material makes it a safe option to be in contact with the foot surface (*Sustainable materials and components for footwear, 2016)*. Regarding these characteristics rubber is one of the selected materials. Yet, rubber soles can be divided into three different types: natural rubber, synthetic rubber and recycled rubber. The selection of rubber was made based, not only on its physical and chemical properties but also on the availability of this material in national territories to avoid any need for importing such materials. Hence, these three different rubber types will be considered for the mid-sole composition. Besides rubber, cork is also a highly used material for soles composition (*Sustainable materials and components for footwear, 2016; Footwear Info*, 2019). The elasticity provided by cork provides great comfort on the foot since it moulds to the different feet. Besides this is a material with great impact and odour resistance improving the useful life of this material and making it a good option to be analysed (*Leaf*, 2020). Cork was also selected since it is a typical Portuguese material being highly produced and used for different applications - namely soles production - nowadays.

<u>Fabric Strap:</u> Regarding the upper part of the sandal, an analysis to the most appropriate fabric to use was be performed. Three natural fibres were selected:

i. <u>Cotton:</u> highly used in the textile industry, cotton is a fibre with great strength properties due to the long cellulose chains in its composition making it highly versatile. Cotton is also produced in large scale worldwide making it easily available in all markets (*Sustainable materials and components for footwear, 2016)*;
ii. <u>Hemp:</u> Highly mentioned nowadays due to its sustainable properties, hemp fibre is beginning to be explored in the textile industry. This fibre is harsher than cotton thus making it stiffer and granting strength, durability and more UV resistant – which is a great quality to have in a

summer footwear item. This fibre is not available in Portugal, yet it can be found in Spain (*Sustainable materials and components for footwear, 2016)*;

iii. Jute: typical fibre used in Portugal. It does not require fertilizers, easing the cultivation process and making it economically viable. It is used in footwear items due to its strength and low extensibility, making it more advantageous when compared to cotton (*Sustainable materials and components for footwear, 2016)*.

The materials selected will be analysed - in Section 3 – in terms of sustainability. To summarize the potential materials selected, **Table 12** presents the final materials considered for the midsole and for fabric strap.

Table 12 - Materials to select for the different components of the sandal

Midsole Materials	Fabric Strap Materials
Cork	Jute
Synthetic Rubber	Organic Cotton
Recycled Rubber	Hemp
Natural rubber	

In the light of the *Eco-design* practices, the maximization of the production efficiency and minimization of the resources used in the sandals is a priority. Hence, to minimize the use of resources and maximise the potential use of the sandal, grouping sandal sizes is a priority. Similarly, to the system already used by *Havaianas* (2019), each sandal shall be made to fit two feet sizes, i.e., grouping two shoe sizes in the same sandal. **Table 13** presents how the size grouping will be performed. The *length (cm)* refers to the dimension of the sole of a sandal, from the one edge to the opposite other.

Table 13 - Sandal size distribution (Adapted from Havaianas (2019))

Length (cm)	European Size
21.5 - 22.5	35/36
23 - 24	37/38
24 - 25	39/40
25.5 - 26.5	41/42
27 - 28	43/44
28 - 29	45/46

Having selected one design and different possible materials, it is necessary, now, to evaluate each of those materials and decide which materials are the best options. To do this, in the next section – Section 5.3 – a life cycle analysis of each material will be conducted.

5.3 Preliminary Assessment

With the design selected, the materials to use must be selected. In this section, an evaluation to the materials considered previously is presented. This section is divided into three main subsections. Subsection 5.3.1 is an economic approach to the comparison of the materials. Subsection 5.3.2 is an analysis over the lifecycle of each material. Subsection 5.3.3 is the interpretation phase of the LCA Analysis along with the main conclusions from the section. Plus, an overview over the Circular Economy strategies incorporated so far, is presented. In the end of this section the materials to use in the midsole and fabric strap are selected.

5.3.1 Economic Analysis

In any product development process, costs play a great part in the decision making of every activity. Therefore, it is crucial to provide an economic analysis to aid in the decision process for the selection of the materials. For this analysis, an economic evaluation was performed to compare each material in an economic perspective along with an assessment over the suppliers of the different materials. Preference was given to Portuguese suppliers to give emphasis to the social component in recurring to local production. However, for some materials, it was not possible to find a Portuguese provider. **Table 14** shows the cost of acquisition obtained per each material along with the supplier and supplier location.

Table 14 - Prices and suppliers of the different materials

Material	Cost	Supplier	Supplier Location
Jute	5,90 € / m2	Mundo dos Tecidos (consulted in September 2020)	Portugal
Organic Cotton	7,90 € / m2	Mundo dos Tecidos (consulted in September 2020)	Portugal
Hemp	7,63 € / m2	Hemp Fabric Lab (consulted in September 2020)	India
Natural Rubber	4,41 € / m2	Thames Supplies Valley (consulted in September 2020)	United Kingdom
Synthetic Rubber (TR)	3,20 € / sole	Bolflex (consulted in September 2020)	Portugal
Cork	5,36 € / m2	BricoButikk (consulted in September 2020)	Portugal
Recycled rubber	3,45 € / sole	Bolflex (consulted in September 2020)	Portugal

The materials displayed first in the table are the possible materials to use in the fabric strap. All the prices obtained were in Euros and the materials were all sold in m2. All the materials have similar prices, yet organic cotton is the most expensive fabric with an overall higher cost than the other two fabrics. Jute presents the lowest price and is supplied from a Portuguese supplier whereas hemp was only possible to be sourced from India thus implying an extra cost for the transportation until reaching Portugal. This cost is not only economic but also environmental due to the high emissions inherent to the transportation modes necessary. From this analysis, Jute seems to be the fairest option to use so far, yet, an environmental analysis still must be done to have a better selection basis.

For the mid sole materials, three of those are obtained from Portuguese suppliers, only natural rubber could not be found in any Portuguese manufacturer. Plus, all the materials are sold with 4mm thickness. Natural rubber was only found in a English brand sold by 19,69£ per 5 m2. At the current exchange rate (consulted on 6th of September 2020) of 1,12€/£, this would translate into a price of 22,05€ per 5 square meters of natural rubber slab (with 4mm thickness), i.e. 4,41€ per square meter of natural rubber slab. Cork slabs were also sold in a 15 square meter wide slab (80,17€/15 square meter) which translates into 5,36€/m2.

To compare these four materials, it is necessary to understand how many soles can be obtained with one square meter of slab. Considering the data in table 13 (Section 5.2), each sole has a maximum length of approximately 32cm (corresponding to a size 48) and a corresponding maximum width of approximately 12cm (*Havaianas*, 2019). Obtaining a rough area per sole of around 0,04m2. To take into consideration necessary margins for the cutting process and eventual material losses during the transformation process, an area of 0,05m2 per sole shall be considered. This translates into a fit of 20 soles per square meter. Looking at data in Table 14, a natural rubber sole would be obtained by 0,22€ per sole and a cork sole per 0,27€.

Natural rubber proves to be the cheapest material, yet, being supplied by an English supplier implies transportation costs (economic and environmental) higher than any of the other three materials, therefore cork would be a better option. However, it must be taken into account that both natural rubber and cork are being sold in slabs, whereas synthetic and recycled rubber are being sold in transformed soles. This results in a trade-off on whether to acquire the materials already ready for incorporation (yet, more expensive) or acquire the materials with a necessity for transformation. This last option would imply a need for a bigger labour force and acquiring the necessary cutting and finishing tools or machinery.

To aid in the decision process and given the trade-offs found, the next section will analyse the lifecycle of each material to provide more variables for the decision making of the final materials.

5.3.2 Life Cycle Assessment

This subsection is divided into three steps – Goal and Purpose Definition, Life Cycle Inventory Analysis and Impact Assessment Phase (LCIA). By applying this analysis, a sustainability assessment of each material will be obtained along with the respective single score to provide a fair basis for comparing the seven materials.

Step 1 – Goal and Purpose Definition

The goal of this analysis is to select different materials under the LCA scope. The results obtained from this assessment shall be used to support the decision making over the available options and provide basis for the selection of the materials to be incorporated in the design, to develop in further sections.

The scope of this study is to design a product; thus, the current lifecycle analysis will only emphasize the preliminary data of each material to be discussed. The geographical boundary is Portugal – since we are producing the sandal in Portugal and the materials should be obtained by Portuguese suppliers - and the temporal boundary is subject to the product's useful life – which will highly depend on the use of each consumer, yet the average flipflop lifespan is 2 years (Yasukawa & Page, 2020), therefore no less than this would be considered. The physical boundary is the *Cradle-to-Gate,* which only covers the production and extraction of each material. On this extent, the processes and activities that are inherent to the production of the sandal were not considered, nor the transportation of the materials to the production site. Only the materials' extraction and production on site was considered to allow a fairest comparison between the different materials and to simplify the analysis, since this is a preliminary selection. Plus, the materials are meant to be further recycled, therefore, there is no need to consider right away the end of life of these. So far, the design to be elaborated is a preliminary one, thus it is not necessary to perform a more detailed analysis. This would not justify the intense time and data it would imply, only for the comparison of the materials. Therefore, this boundary will provide a simplistic analysis where the materials' production information proves to be more relevant and efficiently used. Plus, the information extracted from the software will encompass the impacts inherent to each product and not each product's component, thus turning this analysis more objective and time efficient. To illustrate this boundary, **Figure 17** shows a representation of what is included in this analysis.

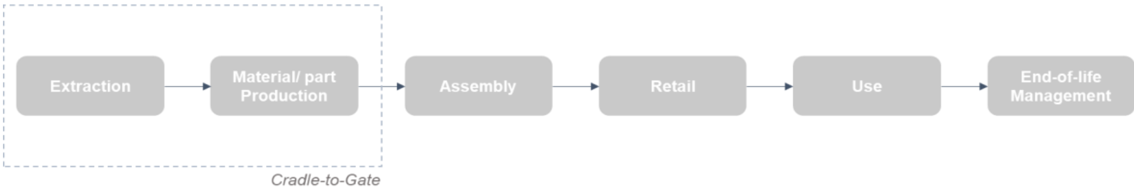

Figure 17 - Cradle-to-Gate boundary representation

Step 2 – Lifecycle Inventory Analysis

As it was already introduced, the software to used was *SimaPro* and the correspondent data base used was *EcoInvent Database.* For the study of the different materials, a functional unit was defined. For the sandal production, regardless of the material to use, the quantity to implement in each sandal is the same, i.e., in the midsole, for instance, the quantity of material for the final design shall not vary depending on the material to use. Yet, before making this assumption the density of the materials should be roughly the same per component, i.e., the density of the fabric materials should be close to one another and the density of the midsole materials as well. For the textile materials this value is essentially the same, ranging from 1,25 to 1,50 g/cm3 – maximum of 17% difference between the materials (Hasan & Alam, 2020). For the midsole materials, according to a study by Lopes et al. (2015), which conducted an experiment on the mechanical properties of different rubber types (including natural, recycled and synthetic rubber) concluded that the densities of the different variations of rubber do not vary substantially, with the means of each rubber type ranging from 1,05g/cm3 to 1,17g/cm3 – maximum 10% difference between the three materials. While cork density can range from 0,45g/cm3 to 1,20g/cm3 (*Amorim*, 2016; *Amorim*, 2017). Even though there is a slight difference between the ranges of density of rubber and cork – with 2,5% to 57% difference between the material - , since this is a preliminary analysis (and there is no certainty on the amount of materials to use in each sandal) meant to compare each material, the same quantity of material will be considered for the analysis.

Therefore, the functional unit to use will be an arbitrary mass value. The FU selected was 1kg of material. To proceed with a fair comparison, only the fibre production of the different fabric materials was considered due to the *Ecoinvent* limitations regarding some types of textiles. The materials used for the analysis are displayed in the following **Table 15** - with the fabric materials displayed first and followed by the sole materials - along with its *SimaPro* references.

Table 15 - Materials and correspondent SimaPro references

Material	Reference
Organic Cotton	Fibre, cotton, organic {PT}| market for fibre, cotton, organic | Cut-off, U
Jute	Fibre, jute {PT}| market for fibre, jute | Cut-off, U
Hemp	-
Synthetic Rubber	Synthetic rubber {PT} | Production | Cut-Off, U
Recycled Rubber	Waste Rubber, unspecified {PT} | treatment of, municipal incineration | Cut-Off, U
Natural Rubber	Seal, natural rubber based {DE} | Production | Cut-Off, U
Cork	Cork Slab {PT} | Production | Cut-Off, U

Regarding the materials to compare, these were already divided into fabric and sole. Yet, to the fabric comparison, the hemp fabric was not available on the *Ecoinvent* data base, therefore, to proceed with the comparison, the data was obtained from an existing study. This study was conducted by Van Eynde (2015) – *Comparative Life Cycle Assessment of hemp and cotton fibres used in Chinese Textile manufacturing* – and presents the impacts inherent to the fibre production for the hemp fabric. The goal and scope of the study are aligned with the goal and scope of the present analysis. Plus, both the Functional Unit and the physical boundary of the study is the same as the one chosen for this analysis. Therefore, it is possible to make a direct comparison between both the results of this paper and the results of the present analysis. More details, materials' references and results of this study are presented in **Appendix A**. According to Carvalho et al. (2014) the *ReCipe* method is the most used method by the *European Commission*, therefore, this was the method used to conduct the analysis made.

Step 3 – Impact Assessment Phase (LCIA)

Before introducing the comparison charts it is important to note that, the characterization data is always the best method to compare, since it provides the exact values for the impact of the material in the different categories. The characterization values have the lowest uncertainty, yet, to allow a fair comparison, all the values would have to be aligned. Plus, to make a decision on the best material, all the trade-offs would have to be eliminated. Yet, since this is not possible with the materials chosen, a normalization of the values must be performed. Following this normalization, the *Single Scores* of each material must be extracted to compare each material through this metric. The characterized values are used to highlight the performance of the different materials with their real emissions' values. The normalized values usually have a higher degree of uncertainty than the characterized values, however, since the goal is to select the best material, it is necessary to use normalized values as a comparison basis to extract a *single score* for each material. Based on the study by Van Eynde (2015) the normalized values for Hemp are presented in table, **Table 16**. It is important to note that the study only mentions the most significant emissions' categories. These categories and correspondent values are displayed in the following table, along with the organic cotton and jute values for the same categories (obtained from the *SimaPro* software).

Table 16 - Normalized values per impact category for jute, organic cotton and hemp fibre

Impact Category	Fibre, jute {GLO}| market for fibre, jute | Cut-off, U	Fibre, cotton, organic {GLO}| market for fibre, cotton, organic | Cut-off, U	Fibre, hemp *
Global warming	8 375,98	5 340,00	7 741,46
Terrestrial acidification	0,70	0,79	1,48
Freshwater eutrophication	0,00	0,01	0,00
Marine eutrophication	0,02	0,11	0,08
Terrestrial ecotoxicity	3 757,85	1 106,47	0,41
Freshwater ecotoxicity	0,10	0,09	0,04
Marine ecotoxicity	0,10	0,10	0,01
Human carcinogenic toxicity	0,09	0,00	0,45

Highlighted in green are the values that show the best performance for the given category. It is possible to note that hemp performs better in four categories, whereas the performance of jute and cotton is better in two and three categories, respectively. Yet, all the values for each material are relatively low and close to each other, thus the trade-offs are evident, despite of the total values. **Figure 18** highlights the differences Table 16. It is possible to notice the orange bars that stand out in the chart. Organic cotton is the material that appears to cause more damage in Global Warming, Terrestrial Ecotoxicity, Freshwater Ecotoxicity and Marine Ecotoxicity as it was already seen through the data available in Table 16. Jute and hemp seem to have a lower impact when compared to cotton, yet these vary among one another. For instance, in Human Carcinogenic hemp proves to have a higher impact and both jute and cotton present a lower impact, as it is evident by the bars in the chart in **Figure 18**. Regarding Marine and Freshwater Ecotoxicity, and Freshwater Eutrophication, jute is more harmful than hemp fibre while in Global Warming and Terrestrial Acidification hemp proves to cause more hazard than jute.

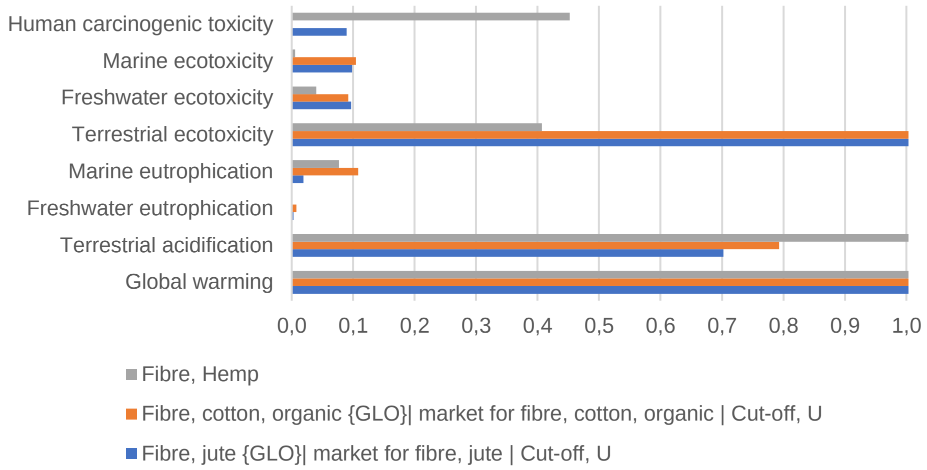

Figure 18 – Midpoint comparison of normalized values per impact category for jute, organic cotton and hemp fibre

Regarding the analysis made, it is hard to decide whether on jute or hemp fibre due to the evident trade-offs from the very distinct impacts from each fibre in the different categories. Therefore, it is necessary to compare the materials' S*ingle Scores.* This information is provided in **Table 17**.

Table 17- Single scores for jute, organic cotton and hemp fibre

Material	Single Score
Organic Cotton	114
Jute	40,4
Hemp	4 744*

Single scores provide a valuable comparison basis for selecting one material. Regarding these, Jute is the best material with a Single score of less than half the amount of the Organic Cotton's single score. It was not possible to obtain a weighted single score for hemp. The single score provided results from the sum of the normalised impacts for the categories provided. However, when comparing this material with Jute, even though it performs better in more categories, in the ones where its performance is poorer, it is evident that the difference between this and Jute is significant. More details on this analysis are provided in **Appendix B**.

Having completed the fabric material comparison, the comparison for the sole material follows. The comparison will be performed on Recycled Rubber, Cork, Synthetic Rubber and Natural Rubber. All the materials were available in the *SimaPro* software and were modified to fit to the Portuguese electricity medium voltage data. Only Natural rubber does not include any electricity consumption for its production, according to the *Simapro* software. Recycled Rubber goes by the name of Waste Rubber since it represents a flow of rubber waste from another rubber process. To highlight the environmental impact between each material, **Table 18** shows the characterized values for the most impactful categories and for the four different materials. The characterized values are disposed to extensively highlight the environmental impact of each midpoint category according to each type of material. Plus, highlighted in green, are the materials that perform better in the correspondent category and thus present the lowest value for the given category. Through this comparison it is more evident the low impact, when compared to the other materials, that recycled rubber presents with a better performance is almost all of the impact categories. Only Natural Rubber and Cork also present a better performance than the rest, in two categories each. In the light of this comparison, synthetic rubber is the least preferable option. From the analysis of the characterized values it is evident that there are still some trade-offs in a few categories, even though on the global Waste rubber seems to behave better.

Table 18 - Midpoint comparison between 1kg of Recycled rubber, Cork, Synthetic Rubber and Natural Rubber

Impact category	Unit	Seal, natural rubber based {DE}	Synthetic rubber {PT}	Cork slab {PT}	Waste rubber, unspecified {PT}
Global warming	kg CO2 eq	1,64	2,21	1,19	3,13
Ionizing radiation	kBq Co-60 eq	0,06	0,18	0,04	0,00
Ozone formation, Human health	kg NOx eq	0,05	0,01	0,00	0,00
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,07	0,01	0,00	0,00
Terrestrial ecotoxicity	kg 1,4-DCB	1,84	3,23	2,91	0,08
Freshwater ecotoxicity	kg 1,4-DCB	0,02	0,05	0,01	0,05
Marine ecotoxicity	kg 1,4-DCB	0,02	0,08	0,02	0,08
Human carcinogenic toxicity	kg 1,4-DCB	0,03	0,06	0,04	0,00
Human non-carcinogenic toxicity	kg 1,4-DCB	0,54	2,14	0,56	2,10
Land use	m2a crop eq	0,01	0,07	5,06	0,00
Fossil resource scarcity	kg oil eq	1,53	1,59	0,39	0,01

To ease the visualization of the different impacts presented in the Table 18, a midpoint comparison chart was elaborated with the normalized values for the most impactful categories and is presented in **Figure 19.**

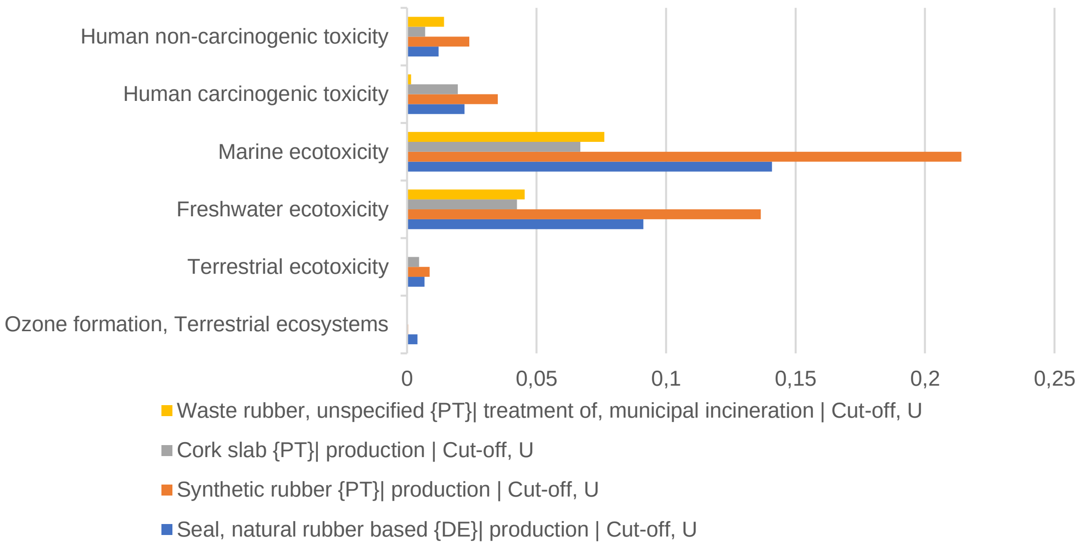

Figure 19 - Midpoint comparison between 1kg of Recycled rubber, Cork, Synthetic Rubber and Natural Rubber

Figure 19 represents the most relevant midpoint categories – categories with higher impacts for all the materials - of environmental impact in the production of the materials. The two materials with the highest impact in most of the categories is both natural and synthetic rubber (blue and orange bars, respectively), with the synthetic rubber having the greatest impact in all the categories presented in the chart, apart from Ozone Formations, Terrestrial Ecosystems which present scarce values and in which natural rubber has the worst environmental performance. For recycled rubber and cork, these have similar impacts in all the categories, despite Human non-carcinogenic and Terrestrial Ecotoxicity where recycled rubber presents relatively low impacts when compared to the remaining materials. Even though, synthetic rubber and natural rubber are not sustainable options to consider for further analysis, there is still a tie between recycled rubber and cork. To uncover this tie, it is important to introduce the single scores of each material to have a better decision basis. **Table 19** indicates the single score of each material.

Table 19 - Single scores for jute, organic cotton and hemp fibre

Material	Single Score
Natural Rubber	69,6
Synthetic Rubber	93,6
Recycled Rubber	63,4
Cork	74,3

The Single Scores are relatively close to one another except for synthetic rubber, which presents a much higher single score. Cork and Natural rubber both present lower single scores, yet, recycled rubber is still the material with the lowest value, thus representing the best sustainable option among the other materials. More details on this analysis can be found in **Appendix B**.

5.3.3 LCA Interpretation

In this subsection the last step of the LCA analysis – Interpretation Phase – is included, to complement the conclusions reached from the analysis. An overview over the Circular Economy strategies that are being considered so far is also presented. Before highlighting the main conclusions from the previous analysis is it important to name the two main limitations that might compromise the results obtained. Firstly, due to the lack of hemp fibre in the database, it was necessary to obtain the data for this material from an external study, and that data could have been calculated differently or different assumption might have been considered, which could diverge from the assumption made for this analysis. To overcome this limitation, the insertion of the hemp fibre in the software would be necessary, meaning all the lifecycle activities from seed acquisition to fibre threading would have to be mapped and the impacts of each activity needed to be calculated. Secondly, it was considered the same density for all materials which can result in different values for the impact categories. This would be overcome by measuring the mass of each component if the final product, with the different materials. That is, for instance, creating four midsoles made from all the four possible materials, weighting these and making an analysis based on this weight, where the functional unit would be the 1 sandal midsole. The same process would be carried for the fabric strap. However, at this stage of development it not yet possible to make this analysis since the product has not yet been developed. Despite these limitations, with the results and economic data obtained it is possible to draw conclusions for the materials.

For the textile strap, jute was the material with the lowest price and has the possibility of being supplied by Portuguese brands which is an advantage compared to hemp, for instance. Jute was also the material with the lowest single score, even though in a few categories' hemp proved to be less pollutant. For these reasons, jute is the selected material to be used in the fabric strap in the sandal. Being a typical Portuguese material, used for many applications in the past, it makes it a good option to highlight the Portuguese nature on the essence of the sandal.

For the midsole, the most sustainable material is recycled rubber and the worst is synthetic rubber. Synthetic rubber was cheaper than recycled rubber, yet, in the light of the Eco-design practices, namely, *Replace hazardous materials by environmentally friendly ones,* synthetic rubber will not be selected due to its worst impact on the environment. Between cork and natural rubber – whose prices were only obtained per square meter, and not soles – cork proves to be more damaging to the environment and more expensive than the natural rubber. Hence, cork is also excluded from the analysis. Now, it is necessary to choose between natural rubber and recycled rubber. Despite having the lowest environmental impact, recycled rubber's price was relatively higher than the natural rubber one (recycled rubber sole sold by 3,45€ whilst one square meter of natural rubber was sold by 4,41€ - about 0,22€ per sole). Even though the difference is significant, this latter one would be imported from UK implying an extra cost and environmental impact. Plus, since this material is sold in slabs and not soles would impose more activities in the processing of the sandal. All in all, and considering, the Eco-design practices mentioned before and also *Incorporating modularity* and promoting an *environmentally friendly assembly* the use of recycled rubber soles will ease the process of assembly with the promotion of the use of an environmentally friendly material. Besides the use of independent components that, assembled together, create a sandal, goes straight towards the *incorporating modularity* practice.

Having all the materials selected, **Table 20** highlights the eco-design strategies that are being followed in the development of this sandal and summarizes how this is being achieved. This is an important step to emphasize the focus of this project in obtaining a product that thrives circularity in the market, especially in the Portuguese market.

Table 20 - Single scores for jute, organic cotton and hemp fibre

Circular Economy Strategies	Solution Proposal
Eco-Design	The focus on Eco-Design is brought up throughout the analysis, to aid in the decisions made. Both recycled rubber and jute are selected in the light of 3 of the eco-design practices discussed.
Green Procurement	The search and selection of the final materials is based on the economic evaluation made and the supplier locations and emissions of each material. It is being considered both prices practiced, location of suppliers, and nationality of these. The focus on favouring Portuguese typical materials and suppliers meant to emphasize the Portuguese economy and use national materials in spite of imported ones. Thus, highlighting the potential of the national products and materials.
Recovery Economy	Reusing scrap tyres and recycled rubber will favour the potential of incorporating these materials in existing products, replacing harmful ones and closing the loop of these products' life. Putting this product in the market will highlight the capacity of producing environmentally friendly products with the same utility of the existing non-sustainable ones. Creating a direct substitute of a harmful product will give way for more of this product to be produced and will foster the circularity in the Portuguese market.

Having completed the materials analysis and selection, the product can be materialized, and a prototype can be created with the materials selected. The following sections focus on the development of the prototypes and the gathering of market information ang guidelines for the implementation of the product in the market.

5.4 Evaluation & Improvement Design

In this section the outputs obtained in the previous analyses will be used for the progression of the development of a prototype. This section is divided in two subsections. Subsection 5.4.1 will introduce the virtual prototype and all the guidelines for its development. In subsection 5.4.2 the results obtained from the market research are analysed in the scope of the necessary features to incorporate before launching the product.

5.4.1 Creation of a Virtual Prototype

From the previous sections it was defined that the sandal will be composed of three independent components. Each assembled in a one-strap design and each composed by a different material. These materials have already been decided and, so, in this subsection the assembly process is introduced. As a reminder, the design is a major task for the product development and plays a crucial role in the conceptualization process. On this scope, a virtual design must be developed to idealize how the product will look like. The software used to develop the virtual design was *Rhinocerus 3D*, a software that provided 3D modelling tools for design. The sandal design and its three components are displayed in **Figure 20**.

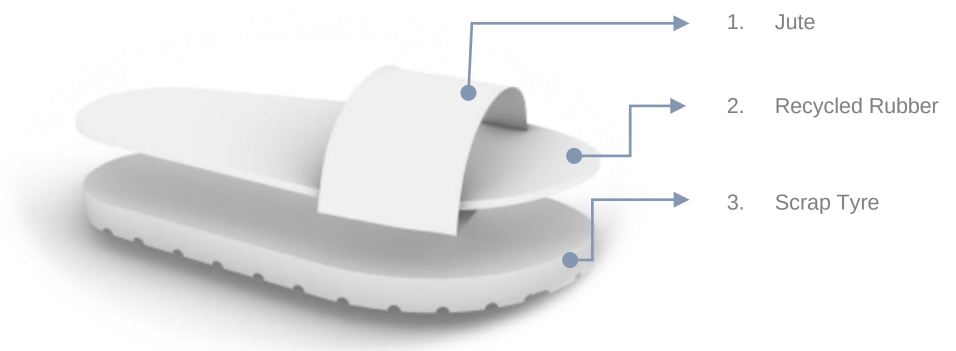

Figure 20 - Exploded View of the components to be incorporated in the sandal

Figure 20 highlights a basic design of the components that will be part of the sandal. This is an approximate design of the design selected in Section 5.2 – A and will be a guideline for the development of the physical one.

The preparation and assembly of the three components should be made through a few independent activities. Therefore, to better comprehend the activities necessary to achieve the final product **Figure 21** shows a process flow chart with what needs to be followed to prepare and combine each part.

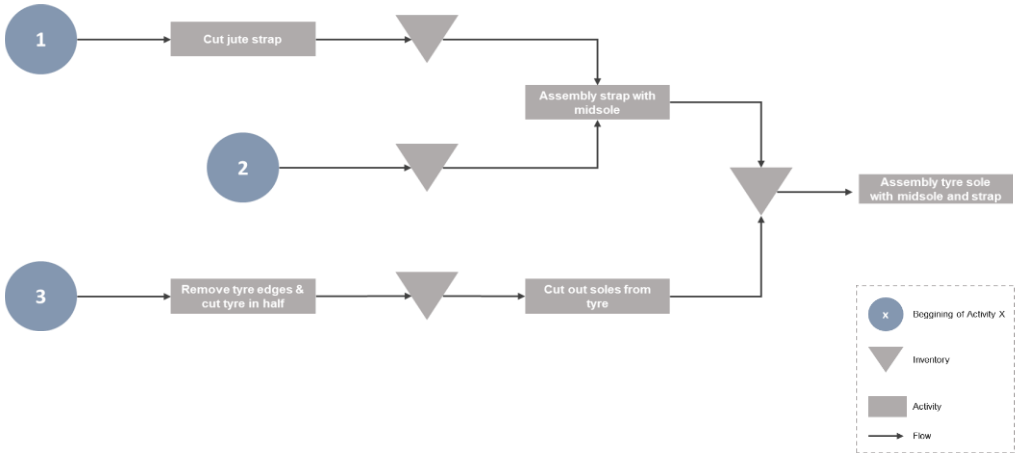

Figure 21 - Process Flow Chart of the activities that complete the sandal

Following the steps introduced in the process flow chart, activity one is the preparation of the jute strap. The jute fabric must be cut in straps according to the size of the sandal. Note that all the components' dimensions will vary according to the sandal size. From this activity, an inventory of fabric straps is created with the straps separated by sandal size. Activity two regards the preparation of the midsole. Since this will be obtained already in the sole format, there will be no need for further processing in these. Note that the midsole is added to better accommodate the foot (hence, increasing the comfort) and to provide a better and softer surface. With the midsole and the fabric strap ready, these two can be assembled, creating the upper part of the sandal. Besides, this midsole will also increase the robustness of the sandal and resistance, by allowing the strap to be held within the outer sole and the midsole. Plus, this process increases the resistance of the sandal and avoids the strap to be easily removed during use. Activity three refers to the tyre preparation and processing. The tyre should be delivered fully. Once it reaches the production centre, the tyre edges must be removed, and the tyre cut in half. With this activity finished, the tyre must, then, be cut into the soles' sizes. To conclude the process of development of the sandal, the three components must be assembled. For both assemblies – jute strap with midsole, and tyre sole with jute strap and midsole -, the parts must be pressed together with an gluing agent. As it is observed in Figure 21, all the activities are independent of each other and can be initiated at the same time, as long as there are enough resources – labour – to complete each activity. Evidently, only the assembly activities are dependent from the inventory of the parts.

This modular design is important to increase the circularity of the products by easing the process of disassembly and recycling of the individual parts for the same product or for other purposes. Plus, since the product is to be manufactured by non-specialized labour it is important to provide an easy-to-assemble product that could be put together by any person regardless of age or gender.

Having the basic design set, the parts idealized, and the processing flow explained, an upgrade on the design shall be made to correctly represent how the product should look like after the assembly if the parts. As decided before, the materials to incorporate are scrap tyres, recycled rubber and jute fabric. Through the *Rhino 3D* software, it was possible to obtain materials with the similar colours and contours as the real components, which allowed to obtain a close to real representation of the final design. This representation is presented in **Figure 22**.

Figure 22 - Virtual prototype of the assembled sandal

As it is perceptible through the design the bottom part represents the tyre surface and in-between the two soles, the fabric is held. The figure represents the basic colours of the sandal, without any colouring of any component – the tyre is typically black, and the jute fabric typically presents a brownish colour -, except the recycle rubber surface which can be obtained in any colour. To highlight the extent of colour variations able to fit in the sandal – weather by colouring the tyre, the fabric strap or the midsole - two more sandals were designed, only with a colour variation from this basic one presented. **Figure 23** presents these two alternative options to highlight this diversity.

Figure 23 - Basic design with two more alternatives with a colour variation

In Figure 23 the design on the left represents the basic design presented previously already, along with two different options on the right. The sandal on the middle is a brownish version with the tyre sole painted in brown and the mid-sole with a mixture of white and brown. The sandal on the left is a beige version with the tyre painted in a dirty-white colour and the mid-sole in a mixture of different variations of white. To recall, these variations only highlight the diversification possible to get from this design only by colouring the parts. Plus, it is important that the design is not subject to only one gender and can be versatile and diversified.

Having the virtual prototype ready, a representation of the final design is already possible to see. Yet, before beginning the physical prototype processing, an analysis on the market was performed to understand whether there was a need to modify the design and rearrange the process or whether the product would not fit to the current market. Recall that the survey must be done at this stage to avoid wasting time and resources producing a product that could be turned down by the consumers. Therefore, it is necessary to make clear the necessity – or not - of this product in the market, so that the processing can be initialized.

5.4.2 Survey Research

Following the proposed methodology, a survey was designed and presented to several potential consumers. The survey responses were gathered online, and a total of 127 responses were obtained. Before analysing the results and major conclusions it is important to note that the sample of analysis is a random convenience sample hence, it is not representative of any region or group. Even though the demography information is only requested in the last section of the survey, it is important to analyse this information first to learn more about this convenience sample before introducing the answers from the two initial sections. **Figure 24** highlights the age, gender and region of the respondents.

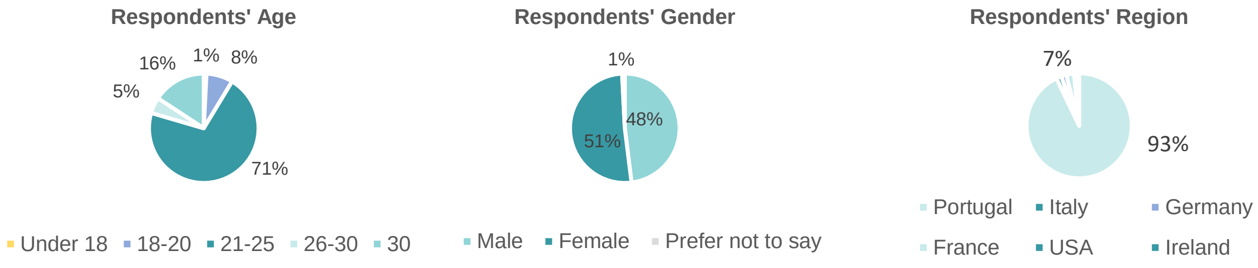

Figure 24 - Age, gender and region of the survey respondents

Analysing the distribution charts presented in Figure 24, it reflects that the majority of the inquired belongs to the 21-25 (71%) age gap, are mostly female (51%) and are currently living in Portugal (93%). Hence, with a fairly distributed sample – roughly the same proportion of female and male respondents – and mostly Portuguese, this sample is representative of the target market.

Regarding now the first section of the survey, which focussed on analysing the consumer market of summer footwear, the chart in **Figure 25** represents the tendency the respondents have to buy summer footwear.

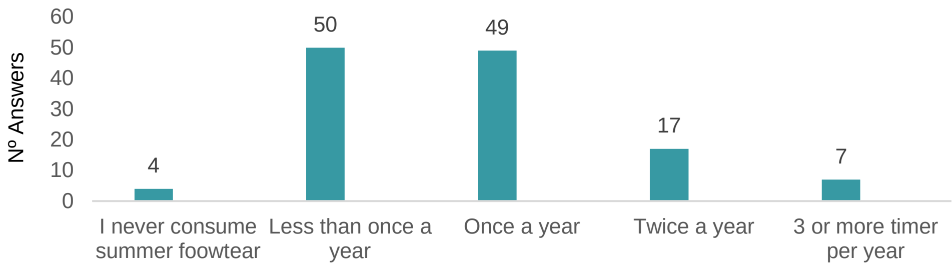

Figure 25 - Average purchase frequency for summer footwear

Most respondents stated to purchase less than once a year summer footwear. Yet, only 4 people mentioned never buying summer footwear, which means the rest of the respondents (73) purchase summer footwear at least once a year. Considering all the responses, there is an obvious tendency for buying summer footwear at least once a year, thus confirming the needed demand for producing this type of products.

Analysing the characteristics more important when buying a sustainable item and whether the respondent is aware of any sustainable alternative in the market, the responses obtained are presented in the following charts, in **Figure 26**.

Most of the respondents does not acknowledge any sustainable alternative in the market, which begs the need for the scrap tyre sandal to be developed. Plus, most concern more about the existence of environmentally friendly materials rather than social inclusion or local production.

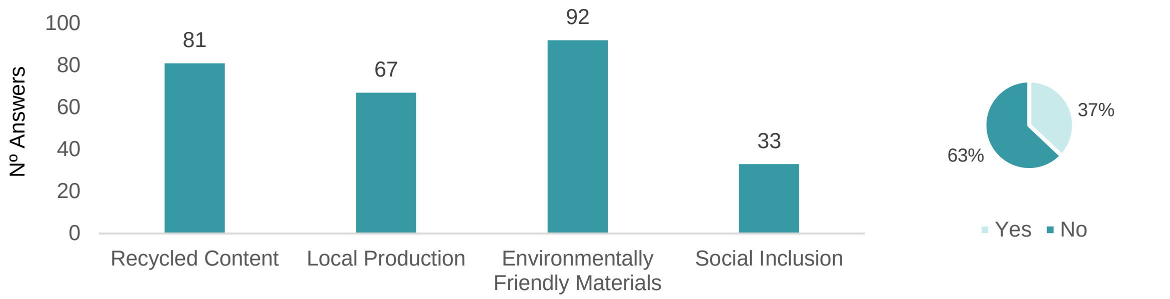

Figure 27 - Most relevant characteristics when buying a sustainable item and knowledge of any sustainable alternative in the summer footwear market

Recycled content was also pointed out as the most relevant in the decision process of buying sustainable. With this information, the need for the product designed is clear. The lack of sustainable alternatives in the market, or at least known sustainable alternatives, gives space for fostering the production of these to put it in market. Highlighted also by this question is the need for emphasizing the use of sustainable materials in the production of the sandal since it is what the sample market is mostly concerned about when looking for sustainable products.

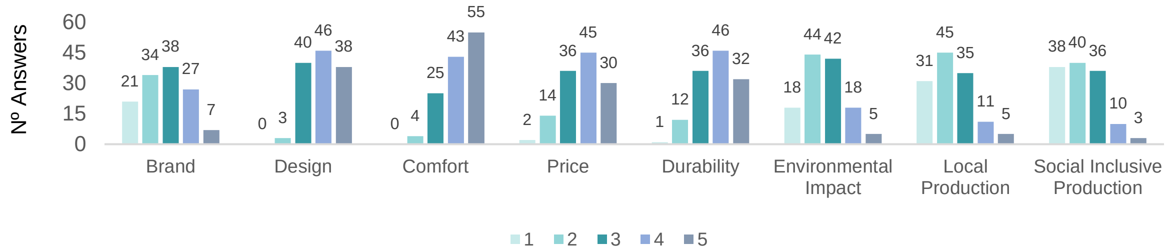

Figure 26 - Relevance (1 for the least and 5 for the most relevant) of the different criteria when buying regular footwear

Figure 27 underlines the relevance each criterion has when purchasing a regular summer footwear. Looking deeper into the responses, design, comfort, price and durability are the attributes more highlighted as important, whereas local production and social inclusion are the ones referred with less importance. This means, an appealing design and comfort is essential to please the customers. No conclusions on the importance of sustainability can be drawn since these answers are referring to regular non-sustainable footwear. For sustainable footwear, the answers given are presented ahead.

Considering the responses given in the third section, in which the product designed was introduced, to evaluate the responses to from the surveyed sample, **Figure 27** refer to the responses given when asked about how comfort the respondent would be in using the described sandal (chart on the left), whether the respondent would be motivated to buy the sandal (chart on the right) and the price range this would be willing to pay for the described product (**Figure 28**).

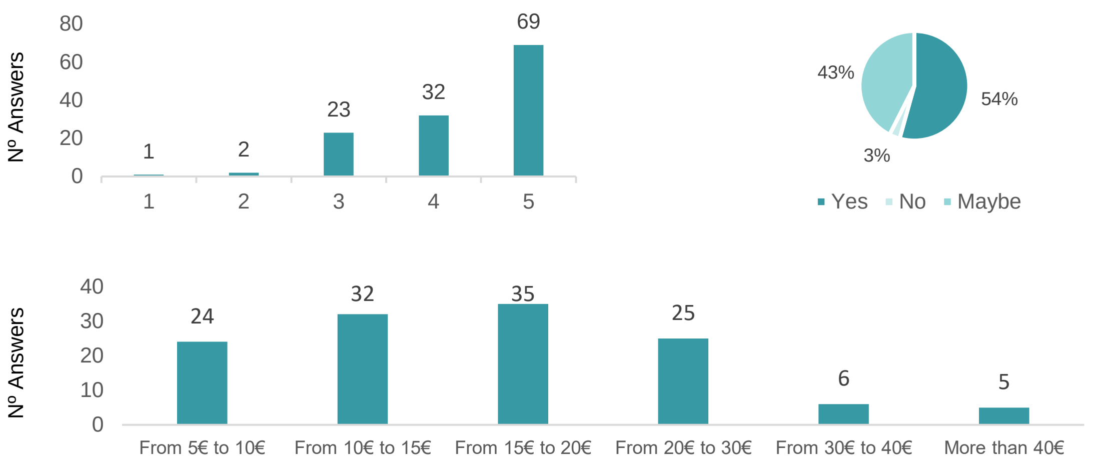

Figure 28 - Comfortability in using the sandal (on the left), interest in buying (on the right) and price range willing the respondent would be to pay (below)

Nearly 55% of the respondents voted with 5 points regarding the comfortability in using the described sandal, with only 2% of the respondents attributing between 1 and 2 points in this question. This proves the good receptivity of the product in the market, despite of the different products that compose the sandal. On this scope 54% of the respondents stated to be motived to buy the sandal against 3% which stated the opposite. This means, more than half the sample analysed would be interest in acquiring the product only based on the description of this. This, once again, suggests the good receptivity for this product and the need for putting it in the market.

Regarding the price range, there was not a concise opinion, yet, most (35) voted on a price range between 15-20€ and another great number of respondents (32) pointed a price between 10-15€. To obtain a concise average price, a weighted average, considering the average price in each interval (considers 40€ in the "More than 40€" option), was made. From this calculation it was obtained an average price of 17€. This is a good metric to define the maximum target price to be practiced by the product. Hence, the costs of producing one pair of sandals must be less than 17€ to compensate the production it and to justify the launch of the product.

Finally, the last chart to present refers to the relevance attributed to different criteria when buying a sustainable footwear item.

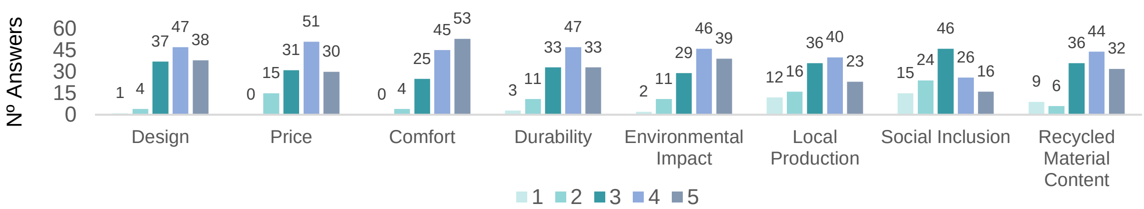

Figure 29 - relevance of different criteria when buying a sustainable footwear item

Regarding the answers provided before to the same question, yet considering the regular non-sustainable summer footwear, a different set of responses was given. It is clear, the relevance of the concern for environment, local production, social inclusion and recycled materials, has slightly increased and, for instance, design has slightly flattened. For the design, comfort and durability, the answers given were barely the same. This is important to understand that these last attributes are relevant regardless of the nature of the footwear production. However, design is seen with less importance, and the care for sustainability is emphasized. Durability, for instance, is assured through the resistant materials thar are being incorporated in the sandal, while comfort is also being assured with the midsole that provides a softer surface to place the foot. The importance given to the sustainability and environmental criteria is important to establish how the product should be communicated to the consumer. When implying that it is of an environmentally friendly nature, the characteristics that make this product sustainable must not be neglected. Hence, the LCA results should be explained along with the production characteristics, the drive for including unfavoured groups in the production process and the guidelines used for the selection of the different materials. Plus, the reality of the current tyre pollution in the environment and how this product is tackling this pollution streams must also be presented to the consumer.

To deepen the analysis made to the survey responses, these answers were crossed between different questions to provide a more detailed analysis regarding the inquirers' preferences. The most relevant observations and data gathered is presented as follows:

- Almost 80% of women reported buying sandals at least once a year while for men, only 39% stated to buy at least once with only 3% buying twice or 3 times; Hence, the women market seems to be larger than men's enhancing the need for a more diverse offer for female buyers than men. Translating this into numbers, the production of female sizes and designs should be at least twice the amount of male production.
- Regarding the price, most men revealed to pay from 10€ to 15€ while for women this price was higher (from 15€ to 20€). Besides, in men, around 55% choose to pay from 5€ to 15€. In women almost 40% stated to be willing to pay more than 20€. While in men this value was only for 11%. Again, with the average price held in the 17€, this seems a good metric since the intervals of price ranges for men and women are not very distant.
- Regarding the attributes more important when buying sustainable, men claimed to concern more about the recycled content while women worry more about the environmentally friendly material. Both genders claim Social Inclusion as the least important criterion. This begs the need for emphasizing the selection and analysis process of the materials that make the sandal. As seen before, this is a critical message to be communicated to the consumer when launching the product.
- Design proved to be more important to women than to men with the double the amount of women selecting 5 points than men; on the opposite side, durability is far more important to men than to women, also with 50% more men attributing 5 point to this criterion than women. To better satisfy the female market demand, in the long term, focus should be placed in creating a wider range of different sandals (with different color or design variations) focused on this market. While for men, there is no need for creating different models even because this market seems to have a lower purchasing frequency. However, focus should be placed

in communicating and proving the durability of the product with the materials specifications and test to the behavior of the sandal in different scenarios.

- When comparing the criteria evaluation either for regular summer footwear or sustainable, price revealed to be less important when buying sustainable, while environmental impact, local production, social inclusion and recycled content scored more. Thus, highlining the concern for the environment when the consumer is aware the product to buy is sustainable.

To summarize, the market is receptive to the product, justifying the intention of creating it. With this cleared out, the physical prototype will be developed, and its process of development is explained in the following section.

5.5 Prototyping and Final Design

All the details, design and processing guidelines of the sandal have already been defined; hence, it is possible to produce the sandal with the indications given and based on the virtual prototype. This chapter is divided into two subsections. Subsection 5.5.1 will guide through the creation of the physical prototype and the insights obtained from the focus group created. Subsection 5.5.2 will present the business plan necessary to launch the product in the market.

5.5.1 Creation of a Physical Prototype

To develop a physical prototype, all the guidelines presented previously in the virtual prototype section, were followed. The process initiated with the preparation of the tyre. An old tyre was collected from a local repair shop and the edges were easily cut using a simple domestic cutter. Yet, to cut open the tyre in half, the cutter proved to be insufficient due to the aluminium mesh that is embedded in the tyre. Therefore, it was necessary to cut the tyre with a saw. After this process, the tyre was ready to be modelled into the shape of a shoe. The mould was made using an old sandal (size 38) and was directly sketched onto the tyre surface, using a chalk stick. Since the tyre had to be cut in the specific sole format, it was not possible to do this using a saw, therefore, another tool had to be used. After many attempts to cut the tyre with different tools, the best tool proved to be a regular domestic grinding wheel. Even though it was possible to cut the tyre in the desired shape, it was an hard task and the sole did not come out with a clean edge surface afterwards. Due to the use of a domestic grinding wheel, several aluminium threads from the aluminium mash were sticking out of the sole thus, potentially causing harm when manoeuvring the sandal.

With the tyre sole ready, preparing the jute strap was the task that followed. To work on the jute fabric, several straps were cut in different sizes and sewed together in an attempt to increase the stability of the strap. For the physical prototype it was not possible to obtain the recycled rubber soles, nevertheless, a recycled rubber slab was used. To cut this slab into the sole format, a regular domestic scissors was used. Finally, the three components were assembled as it was explained before and regular glue was used to join the three components. The sandal was held in a press machine for 12h to assure its assembly. This first attempt to create the physical prototype and its different activities were photographed through the process and the following **Figure 30** presents the result obtained. Additional photographic details of the sandal development process is presented in **Figure 37 - 40** in **appendix C.**

Figure 30 - First physical prototype developed

From the development of the first prototype, a few difficulties were faced along the way. Cutting the tyre with a domestic grinding wheel was a hard process due to the size of the wheel used and possibly due to the lack of technique in using this tool. Hence, a better option should be adopted. Regarding the fabric strap, underlying only in one layer of jute to make a steady strap was immediately unpractical, therefore a few layers of jute were used in an attempt of providing stability and consistency to the strap. Yet, this was also not efficient and still no stability was provided. Plus, a lot of fabric was being used in this process, neglecting right away the focus in minimizing the materials used. For this reason, a different technique had to be used. On the overall, it was hard to make the sandal adjust perfectly to the foot due to the difficulties found in placing the strap with the right width (not too large nor too tight). This was also an important pain point considered.

To improve the previous prototype and ease the development process, more attempts were made. Another shoe size 38 and 42 were used to create more moulds. The moulds were design in the tyre and cut, again. This time a professional grinding wheel was used. This new tool eased the process and highly improved the soles' surface. A cleaner surface was obtained with a better finishing, a cleaner cut and cleaner edges with hardly any thread sticking out of the sole. Two of the soles were painted in white, using a regular ink spray. This was meant to highlight the versatility of the sandal and create different options to present in the focus group as well.

In an attempt to improve the stability of the strap and avoid the use of extra layers of jute (even because it proved inefficient) the same spray used to paint the tyres was used to paint the jute straps to potentially improve its stability when assembled in the sandal. This process was successful and gave the strap a better consistency and increased the comfort when using the sandal. With these different techniques, two of the difficulties found before were rectified. Even so, the struggle to find the right width in the strap was still an issue. To get around this difficulty, one of the sandals was made with an open strap able to be adjusted to the user's foot. Yet, this adjustment slightly changed the design initially proposed. Despite of this change in design, this option was easily assembled and proved to be easily manufactured for anyone with no expertise.

These two extra prototypes are shown in **Figure 31**. Additional photographic details and its manufacturing activities were photographed and are presented in **Figure A-Z** in **appendix C.**

 

Figure 31 - Two alternative and improved physical prototypes

Having done different attempts of physical prototypes, a few insights were gathered along the way in what it is necessary to guide the production of these in a small/medium scale, initially. The process of extracting the soles from the tyres is probably the most demanding task, hence, a professional grinding wheel must be used, and this should be performed by someone with experience in manoeuvring this tool. The remaining tasks do not require any expertise. To make the process more efficient and automate the assembly line, each task should be allocated to different people. Exact moulds of soles and straps must be used to avoid any differences in the models, and, for the soles' moulds, these should be made from the midsoles format, to assure both soles will fit each other.

To evaluate the physical prototype developed, a focus group was elaborated, and its main insights obtained are presented next.

5.5.2 Focus Group

A focus group was elaborated on the 13th of October at 19:00h in Lisbon with a group of 3 people. This group of people was selected having in mind that most of the answers obtained from the survey were from people ranging from 21-25 years old. Therefore, it was important that the participants of the focus group fit in this criterion to have consistency between the answers provided in the survey with the insights from the focus group. The group was composed of potential customers ranging from 21-23 years old and the activity lasted for 30 minutes. The activity was divided in three different parts. The first part was the presentation of the physical prototype and introduction of all the scope, materials and goal of the project. In the second part the group was given the sandals developed to touch, try on and use for a while to experience the product during the time of use. Finally, in the third part some questions about the product were made and feedback regarding the use of the product was obtained. The questions and a summary of the answers/feedback give are organised as follows:

1. *What are the first impressions you have when you see the sandal? And how do you feel?*

The group mentioned a feeling of curiosity about the sandal due to the different materials composing it. Plus, a desire to hold it and feel it was stated, derived also to the different materials. The design was also pointed as attractive and original leading to a desire to try and touch the product.

2. What was the first thing you thought about when you hold the sandal?

The group was unanimous about this question, stating that the product's weight is the first thing noticed when holding the sandal. The sandal was heavier than expected which was immediately pointed out as a negative point in the customer experience. Regardless of weight, the midsole was identified as a soft surface thus bringing comfort feelings when touching it. Moreover, the sandal edges were also pointed out due to the aluminium threads sticking out of the sole which caused discomfort when touching it.

3. How does it feel in your feet when trying the sandal?

Even though the sandal was comfortable, the weight was causing a negative impact in the user experience since it proved to be harder to hold the foot up. Also, the prototype with the open jute strap was more comfortable for all elements of the group since it was possible to adjust the strap to the feet avoiding any discomfort caused by wider or tighter straps as it is found in some sandals. Consequently, the prototype with the closed strap was less preferred due to the strap size which was not adjusted to the feet thus leading to an unpleasant feeling of "not belonging". The potential customers also pointed out that when looking for a shoe they would rather not have a feeling of misplacement when walking and preferred a shoe that would make them forget about even wearing it, which was not being transmitted by the sandal due, mainly, to its weight on the feet.

4. What would you improve about the sandal?

In a more structured and straight-to-the-point way, the group organized the improvement points from the most emergent to the least relevant, in the following order:

i. Sole weight must be addressed to provide a better user experience;
ii. For the closed strap design, the strap should have a better adjustment to the feet;
iii. Aluminium threads should be removed or addressed to avoid any harm when holding the sandal.

5. What are the positive points you identify on the sandal and that would make you buy it?

The group was unanimous about the most important aspect, which would make them pay more attention to the product and would have more impact in the decision making of buying the product or not. This was the idea around the product development and all the current concerns it is addressing, either environmental or social. It was stated that these would make them more eager to buy the product. Plus, the open strap design was mentioned as an innovative and disruptive one, thus adjusting to every kind of foot. The materials composing the sandal were addressed as positive points due to the lack of anything alike in the markets, and the tyre sole was highly praised by all the members due to the footprint on the bottom of the sandal - the tyre marks - which made them have the sensation of wearing the tyre and really addressing the problem of scrap tyres excess. Apart from the functional aspects, the white design was also preferred (in comparison with the black one) and the midsole was also praised due to the colours and design.

6. Would you buy this product?

The answer was also unanimous with all the elements stating they would buy the product. Besides, the ideals around the product development would make the elements more eager to pay more for this sandal than they would pay for a similar one without the environmental or social aspects involved in the development.

7. Do you have anything else you would like to add?

No further answers were given to this question.

Regarding the answers obtained from the focus group, it is essential to improve the design by addressing the main pain points given:

i. Reduce the product weight;

ii. Preference for the open strap design;

iii. Eliminate the aluminium threads from the sole.

Most of these recommendations focus on the design of the product. Considering the survey answers, the design is an important attribute in the process of acquiring any sandal (whether sustainable or not), hence, these recommendations/pain points must be incorporated before handing it for market preparation and production. The next section introduces the business model which guides how the product is to be launched and produced in a market scale.

5.6 Business Model Elaboration

The triple layer business model canvas was the model chosen to create the sandal's business model. The three layers are disposed bellow in **Table 21, 23** and **24,** and the detailed information is presented below each table.

Table 21 - First layer of the business model canvas

Partners	Activities	Value Proposition	Customer Relationship	Customer Segments
Local Penal Institutions in Lisbon area *ValorPneu*	Collection Production Marketing Distribution	Beach sandal made entirely with sustainable materials from Portuguese suppliers and manufactured in local penal facilities	Local Communities support National materials and production	Portuguese communities
	Resources		**Channels**	
	Workforce Facilities for production		Website and online purchase Local shops	
Costs			**Revenues**	
Materials' acquisition	Labour	Distribution Marketing	Sandals' sales	

<u>Partners:</u> *ValorPneu* is the entity that will provide the scrap tyres for the development of the soles. Additionally, an agreement with Portuguese penal institutions will be established to enable the production of these in the facilities of each institution.

Activities: There are four main activities inherent to the development process. Initially it is necessary to collect the tyres from the collection centres and deliver in the specific institutions where the production will take place. From the production to the distribution it is necessary to establish a connection with the customers and market, therefore, a marketing strategy must be aligned. For the marketing strategy, a focus on the materials selected and environmental concern must be communicated, as it was pointed out by the survey responses.

Resources: Include all the labour available in the detention centres along with the facility in which the production will take place and the machinery/tools that are necessary to produce the sandals.

Customer Relationship: This will thrive from the emphasis in the national production and materials. Plus, as it was highlighted by the survey made, the potential customers value the use of recycled and environmentally friendly materials. Hence, it is important to establish the position of the product in prioritizing the use of these materials along with an inclusive workforce.

Channels: This product will be launched in the online market initially to diminish distributions costs and maximize market coverage as possible with the minimum costs. On a long-term analysis, the distribution of these must be made also to local shops.

Costs and Revenues: Here, it is necessary to look over the production process. The costs considered refer to the labour wages, the midsole acquisition and jute strap. The machinery/tools necessary for the production of the sandal are not being considered since these costs represent a necessary investment for the production of the product. Plus, it is being considered that the scrap tyres will be provided without any costs. To understand how many sandals must be sold to cover the costs incurred a breakeven analysis was made to understand how many sandals must be sold to obtain revenue. The price selected for the pair of sandals is 17€ (8,50€ per single sandal) which was the most preferred price obtained from the survey responses. Plus, it is considered a strap with 20cm long and 5cm wide, and the Portuguese minimum wage for the workers (635€/month). The following table highlights the costs inherent to the production that were gathered throughout the project and the breakeven point.

Table 22 - Breakeven analysis

Description	**Cost**
Recycled rubber midsole	3,45€
Jute strap (20x5cm)	0,06€
Wage (3 workers considered)	635€ x 3 = 1 905€
Sandal	8,50€
Breakeven Point (#sandals)	382 sandals (191 pairs)

From the analysis made, it is necessary to sell a minimum of 191 pairs of sandals per month to obtain revenue. This is an high-level analysis, only to provide a rough estimation of the dimension of the necessary production. This analysis is a guideline for the development of this business model.

Table 23 - Second layer of the business model canvas

Supplies & Out-sourcing	Production	Functional Value	End-of-life	Use Phase
Scrap Tyres from *ValorPneu* Production site and labor at penal institutions Distribution	Transform tyres into soles Cut jute fabric into straps	One pair of sandals consumed by customer in a year	Disassembly and recycling of the sandal materials	There is no environmental impact in the use phase
	Materials		**Distribution**	
	Scrap Tyres Recycled Rubber soles Jute straps		Outsourcing	
Environmental Impacts			**Environmental Benefits**	
All the environment impacts are inherent to the production and distribution phases			Reuse of scrap tyres and recycled rubber	

Suppliers & Outsourcing: Scrap tyres are directly supplied by *ValorPneu* and the remaining materials will be acquired from national providers. The production and distribution are fully outsourced since the production will be made by prisoners entirely and the distribution should also be made by an external company to ease the process and decrease costs of distribution across the country.

Production and Materials: The production consists of extracting the soles from the scrap tyres, preparing the strap for the sandals and assembling all the components together. The materials necessary are the components of the sandal (tyres, recycled rubber soles and jute) and the tools necessary to work on the materials and prepare these (e.g. cutter, grinding wheel, glue, scissors).

End-of-life: In the light of the Eco-design practices, the modularity is incorporated in the sandal to allow it to be easily disassembled when in the end of useful life. This will make the sandal easily recycled by removing each component of the sandal and reusing these when possible or recycling to incorporate other products. It must be assured the used sandals can be collected for further recycling of its parts. This collection shall be made possible in penal institutions or in specified centres to be further forwarded to the production sites.

Distribution: Since the distribution shall be obtained through an external company, little is possible to influence the distribution means. However, when selecting a distribution company, sustainability is always a concern.

Environmental impacts and benefits: Even though the materials selected were all in the light of its sustainability, the production, transformation and distribution of these always result in environmental impacts. Despite, the focus in minimizing those impacts is always a concern of the company, as such, little environmental impacts are linked to the production. Only the distribution will have an higher impact on the environment. Regarding the environmental benefits, these are addressed to the use of scrap tyres, recycled rubber soles. The use of this materials is providing an alternative way of giving use to discarded products, thus, fostering circularity.

Table 24 - Third layer of the business model canvas

<table>
<tr><th>Local Communitites</th><th>Governance</th><th>Social Value</th><th>Societal Culture</th><th>End-User</th></tr>
<tr><td rowspan="3">Evolving national suppliers and local workforce in the production activities</td><td>Transparency in decision making
Cooperative governance</td><td rowspan="3">Providing value from mutual beneficial relationships with national companies and institutions

Fostering circularity in national markets</td><td>Culture of environmental responsibility and inclusive society</td><td rowspan="3">Meeting user need in terms of environmental and community benefits</td></tr>
<tr><th>Employees</th><th>Scale of Outreach</th></tr>
<tr><td>Detainees in penal institutions</td><td>Growing selling margins and market coverage, nationally</td></tr>
<tr><th colspan="2">Social Impacts</th><th colspan="3">Social Benefits</th></tr>
<tr><td colspan="2">-</td><td colspan="3">Community engagement and possible economic benefits for the country by unveiling the potential of local suppliers and communities</td></tr>
</table>

Governance: Related with the bureaucratic part of the selling of the sandals. Since this is a product made for local communities with local products, providing transparency in the production and decisions taken for delivering this product is the fairest way of providing the product. Besides, due to the different entities involved in the production of these and the partnerships with the different companies providing the resources necessary, this governance shall be a cooperative one, so that the different entities' goals are all achieved.

Social Value: Pioneering circular products in the national markets is a milestone of the company and will make way for other companies to thrive in this market. Plus, by creating partnerships with different national companies that will play a part in the sandal production will benefit all.

Scale of Outreach: On the long term the expansion for other markets is essential to foster any company, thus this is of great importance in the development of this company. Yet, this expansion must not neglect the values of sustainability and environmental concern of the company.

Social Impacts: No negative social impacts are considered since no social costs are being imposed on the society by developing this product, since the environmental costs are being highly minimized. Plus, no harm is linked to the use of this product.

6. Conclusion

The world has reached a point that the actions taken today will impact the current generations living in our planet. The way the current resources on the planet are used today will decide the future of the younger generations and the generations to come. For that reason, now, more than ever, it is so urgent to address the current situation of our planet. Despite having the scrap tyre issue being tackled and improving day by day, a long effort still remains undone, and the current plastic being used to produce shoes must be replaced by other alternative materials.

In this dissertation the scrap tyre market is studied and a solution to address this issue is presented. This solution takes advantage of the most sustainable materials and combines also the existing wastage of materials in the world, namely, scrap tyres and rubber. Scrap tyres are currently collected by a specialized entity in each country. The Portuguese entity that addresses all the steps in the scrap tyre value chain from collection to, either, recycling, energetic vaporization or requalification to incorporate in the market again, are addressed by *ValorPneu.* Most scrap tyres, that are not qualified to be returned to the market, are now being recycled for other purposes. However, with the growing automobile industry, the number of tyres increases likewise, and the current solutions are not enough to address all the tyres reaching the collection points. To support the attainment of developing a solution to allocate the potential of the excess of scrap tyres, an exhaustive literature review has been elaborated. The Literature review showed that the circular economy is the ideal approach to address the disposal of plastic materials and close the loop of over extraction and disposal. Many authors have suggested different approaches to incorporate circular economy, yet these all converge to the same principles. From these many different principles Eco-design is addressed as one major practice to incorporate circular economy within an industry. Even though the literature basis in this field is far from being insufficient, many authors state there is still a scant level of implementation of eco-design in the industry. This skepticism in adopting new principles is manly pointed out by the lack of knowledge and non-willingness to adapt to new processes. Even so, the benefits of implementing eco-design are undeniable thus, this practice is a necessity to extend the usage period of products and decrease the burden on the natural resources. Plus, the implementation of Eco-design can bring major economic benefits to an industry that is currently being hindered by the easiness of acquiring and extracting resources from the environment. Therefore, the goal of this project is to use the eco-design to build up a product from existing resources that at the same time is viable to be placed in the market.

To develop the solution, different steps were followed according to the methodology studied in the Literature Review. The development of a solution was parted in six sub steps and gathered different analysis and the application of different methodologies within each step. For step (1), a decision tree was elaborated to highlight the need for the proposed solution, based on the causes that are currently hindering the problem of excess of scrap tyres and lack of solutions to address these. Step (2) provided a detailed description of the solution proposed. This solution was as sustainable modular sandal ease to be manufactured without necessity to resort to industrial machinery or specialized labor, made not only from scrap tyres but also from other sustainable materials. This sandal is intended to be manufactured by detainees in penal institutions. Step (2) comprised also an analysis over the most adequate design that sustains the eco-design principles. For the further development of the proposed solution, step (3) followed with an analysis to different alternative materials to provide scientific basis for the selection of those materials to incorporate the three modules that compose the sandal. The materials selected assured the preservation of the sustainability of the sandal and were also selected regarding the economic viability of acquiring each material. Moreover, a concern for preferring national suppliers also impacted in the selection. The material selected, apart from scrap tyres, were jute fabric and recycled rubber slabs. With all the theoretical basis specified, step (4) initialized with a development of a virtual design to guide the creation of the sandal and to virtually materialize the conceptualization of the solution. Several attempts were created, and different color ranges were designed to highlight the variability and adaptability provided by the design. With the conceptualized sandal, a survey was developed to study the feasibility of launching the product to the market and to study the acceptability this would have, by a convenience sample randomly selected. The survey study comprised 127 answers, mainly 21-25 years old Portuguese. The survey enlightened a need for the product in the market and a sound acceptability and interest for this sandal that praises sustainability, social inclusion and recyclable materials.

The fifth step materialized all the insights and studies made on the different dimensions of the sandal. From different and numerous attempts, a physical prototype was created, and a focus group was gathered to obtain more feedback and relevant insights given from the utilization of the product itself. Finally, in step (6) a business model was elaborated with all the different activities and extents necessary to launch the product, along with guidelines to improve the feasibility of this.

Throughout the different phases of development, and introspection over the Circular Economy strategies and eco design practices is made and the practices implemented are analyzed to assure these are being addressed and not to undermine the main goals of this dissertation – provide a solution that preserves circular economy and incorporated eco design practices in its development.

All in all, one of the main objectives of this dissertation was to develop a sustainable and environmentally friendly design that would promote circular economy practices and combine these with eco-design strategies. This dissertations' goal was accomplished and all the necessary guidelines to make further research were outlined. To provide a marketable product still further work must be done. This remaining work can be summarized into two parts.

First it is necessary to address the main pain points obtained from the focus group and from the insights gathered throughout the development of the product. These pain points concern improvements to be done in the design and concern the way the product modules are being addressed. To finalize these points, expertise from the shoe manufacturing industry would be the best approach, and regarding Portugal's vast history in the shoe market, this ought not to be a bottleneck in the accomplishment of these final details. The second part is to facilitate partnerships with key entities to make the production possible with the projected materials and take advantage, in the best way, of the labor force from Portuguese penal institutions.

All in all, collaboration is key for change, and a social collaboration is necessary. Using the resources at hand and making the most with what there is in excess at the world is necessary to achieve equilibrium among all actors. Besides, the accomplishment of this project would bring a breakthrough for Portugal, in terms of sustainable and circular growth along with business opportunities for all parties involved.

7. References

Ammani, A., Auta, S., & Aliyu, J. (2010). Challenges to Sustainability: Applying the Problem Tree Analysis Methodology to the ADP System in Nigeria. *Journal of Agricultural Extension*, *14*(2), 35–45. https://doi.org/10.4314/jae.v14i2.64122

Amorim. (2016). *Amorim: The future is our present*. https://amorimcorkcomposites.com/media/2948/the-future-is-our-present_amorim_lr.pdf

Ashby, A., Leat, M., & Hudson-Smith, M. (2012). Making connections: A review of supply chain management and sustainability literature. *Supply Chain Management*, *17*(5), 497–516. https://doi.org/10.1108/13598541211258573

Bana e Costa, C., & Vansnick, J. (1994). *MACBETH — An interactive path towards the construction of cardinal value functions*. https://www.sciencedirect.com/science/article/abs/pii/0969601694900108

Bocken, A. N. M. P., Bakker, C., & Pauw, I. De. (2015). *Product design and business model strategies for a circular economy ! April*, 12–14.

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Boztepe, S. (2007). *User Value : Competing Theories and Models*. *1*(2), 55–63.

Brace, I. (2018). *uestionnaire Design: How To Plan, Structure And Write Survey Material for Effective Market Research*. https://www.researchgate.net/publication/258969177_Questionnaire_Design_How_To_Plan_Structure_And_Write_Survey_Material_for_Effective_Market_Research

Braungart, M., McDonough, W., & Bollinger, A. (2007). Cradle-to-cradle design: creating healthy emissions - a strategy for eco-effective product and system design. *Journal of Cleaner Production*, *15*(13–14), 1337–1348. https://doi.org/10.1016/j.jclepro.2006.08.003

Brones, F. A., Carvalho, M. M. de, & Zancul, E. de S. (2017). Reviews, action and learning on change management for ecodesign transition. *Journal of Cleaner Production*, *142*, 8–22. https://doi.org/10.1016/j.jclepro.2016.09.009

Burdek, B. (2005). *Design: History, Theory and Practice of Product Design*. https://books.google.pt/books?id=VszO_kZl4bUC&printsec=frontcover&hl=pt-PT

Carvalho, A., Mimoso, A. F., Mendes, A. N., & Matos, H. A. (2014). From a literature review to a framework for environmental process impact assessment index. *Journal of Cleaner Production*, *64*, 36–62. https://doi.org/10.1016/j.jclepro.2013.08.010

Casadesus-Masanell, R., & Ricart, J. E. (2010). From strategy to business models and onto tactics. *Long Range Planning*, *43*(2–3), 195–215. https://doi.org/10.1016/j.lrp.2010.01.004

Casey, R. A. K. & M. A. (2002). *Focus Groups. A Practical Guide for Applied Research*. https://www.qualitative-research.net/index.php/fqs/article/view/791/1718

Chapman, J. (2005). *Emotionally Durable Design: Objects, Experiences and Emphaty*. https://books.google.pt/books?id=VszO_kZl4bUC&printsec=frontcover&hl=pt-PT

Chaturvedi, B., & Handa, R. (2017). *A Report by Chintan Circulating Tyres in the Economy*. https://www.chintan-india.org/sites/default/files/2019-09/Tyres Report_Final.pdf

Coes, B. (2014). CRITICALLY ASSESSING THE STRENGTHS AND LIMITATIONS OF THE Master thesis Business Administration. *University of Twente*, 1 to 99

Comforting Footwear. (2020). https://comfortingfootwear.com/different-sole-classifications-and-characteristics-that-make-them-unique/

Cura, K. (2016). *Lahti Cleantech Annual Review 2016*.

Davis. (1993). User acceptance of information technology: system characteristics, user perceptions and behavioral impacts. In *International Journal of Science Education* (Vol. 41, Issue 18). https://doi.org/10.1080/09500693.2019.1693081

de Beer, D. J., Campbell, R. I., Truscott, M., Barnad, L. J., & Booysen, G. J. (2009). Client-centred design evolution via functional prototyping. *International Journal of Product Development*, *8*(1), 22–41. https://doi.org/10.1504/IJPD.2009.023747

De Pauw, I. C., Karana, E., & Kandachar, P. V. (2012). Nature-inspired design strategies in sustainable product development: A case-study of student projects. *Proceedings of International Design Conference, DESIGN*, *DS 70*, 787–796.

Deloitte. (2019). *UNLEASH Innovation Process*.

Desmet, P., & Hekkert, P. (2007). *Framework of Product Experience*. *April 2007*.

Dewulf, K. (2013). Sustainable Product Innovation: The importance of front-end stage in the innovation process. *Intech*. https://doi.org/10.1016/j.colsurfa.2011.12.014

Easterday, M. W., Lewis, D. R., & Gerber, E. M. (2014). Design-based research process: Problems, phases, and applications. *Proceedings of International Conference of the Learning Sciences, ICLS* , *1*(January), 317–324.

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, *142*, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196

Ellen Macarthur Foundation. (2013). Towards the Circular Economy Vol 1. In *Economic and business rationale for an accelerated transition* (Vol. 40, Issue 2). https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

Ellen MacArthur Foundation. (2015). Towards a Circular Economy: Business Rationale for an Accelerated Transition. *Ellen MacArthur Foundation (EMF)*, 20. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/TCE_Ellen-MacArthur-Foundation_26-Nov-2015.pdf

Engel, H., Stuchtey, M., & Vanthougnout, H. (2016). *Managing waste in emerging markets*. https://www.mckinsey.com/business-functions/sustainability/our-insights/managing-waste-in-emerging-markets#

Ertz, M., Leblanc-proulx, S., Sarigöllü, E., & Morin, V. (2019). Resources , Conservation & Recycling Advancing quantitative rigor in the circular economy literature : New methodology for product lifetime extension business models. *Resources, Conservation & Recycling*, *150*(October 2018), 104437. https://doi.org/10.1016/j.resconrec.2019.104437

European Comission. (2015). Closing the loop - An EU action plan for the Circular Economy. In *Communication from the comission to the european parliament, the council, the european economic and social committee and the committee of the regions*. https://doi.org/10.1016/0022-4073(67)90036-2

European Commission. (2018a). A European Strategy for Plastics. *European Comission*, *July*, 24. https://doi.org/10.1021/acs.est.7b02368

European Commission. (2018b). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee snd the Committee of the Regions: A European Strategy for Plastics in a Circular Economy. *COM(2018) 28 Final*, *SWD(2018)*(1), 1–18. https://doi.org/10.1021/acs.est.7b02368

European Commission. (2019). *Commission Regulation (EU) 2019/424*. *2019*(March), 46–66.

European Union. (n.d.). *Ecodesign Requirements*. http://europa.eu/about-eu/eu-history/index_en.htm

European Union. (2009). Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 - Establishing a framework for setting ecodesign requirements for energy-related products. *Official Journal of the European Union*. https://doi.org/10.1016/j.cirp.2012.03.121

Evans, R. (2006). *The Composition of a Tyre : Typical Components*. *November 2005*.

Favi, C. (2013). Toward eco-design: an integrated lifecycle engineering system to develop sustainable mechatronic products and services. *Phd Dissertation, Università Politecnica Delle Marche*.

FAVI, C., MARCONI, M., & GERMANI, M. (2019). Teaching eco-design by using LCA analysis of company ' s product Teaching by study using LCA analysis of company ' s product portfolio : the case of Italian manufacturing firm portfolio : the case a study of an Italian manufact. *Procedia CIRP*, *80*, 452–457. https://doi.org/10.1016/j.procir.2019.01.032

Footwear Info. (2019). http://footwearinfo.tech/construction/

Franco, M. A. (2019). A system dynamics approach to product design and business model strategies for the circular economy. *Journal of Cleaner Production*, *241*, 118327. https://doi.org/10.1016/j.jclepro.2019.118327

Frischknecht, R., Jungbluth, N., Althaus, H. J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., & Spielmann, M. (2005). The ecoinvent database: Overview and methodological framework. *International Journal of Life Cycle Assessment*, *10*(1), 3–9. https://doi.org/10.1065/lca2004.10.181.1

Geissdoerfer, M., Morioka, S. N., de Carvalho, M. M., & Evans, S. (2018). Business models and supply chains for the circular economy. *Journal of Cleaner Production*, *190*, 712–721. https://doi.org/10.1016/j.jclepro.2018.04.159

Gent, A. (2016). Rubber - Chemical Compound. *Encyclipaedia Britannica*. https://www.britannica.com/science/rubber-chemical-compound

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). *Production , use , and fate of all plastics ever made*. *July*, 25–29.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*(January), 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Goedkoop, M. J., Heijungs, R., Huijbregts, M. A. J., Schryver, A. De, Struijs, J., & van Zelm, R. (2013). Category indicators at the midpoint and the endpoint level ReCiPe 2008. *ResearchGate*, *June 2016*, 126. https://doi.org/10.2307/40184439

Goldstein Research. (2020). *Global Tire REcycling MArket Analysis 2025: Opportunity, Demand,* *Growth and Forecast 2017-2025*. https://www.goldsteinresearch.com/report/global-tire-recycling-industry-market-trends-analysis

Goodwin, P., & Wright, G. (2014). *Decision Analysis for Management Judgment*. https://books.google.pt/books?id=VszO_kZl4bUC&printsec=frontcover&hl=pt-PT

Hasan, S. T., & Alam, M. (2020). *A complete comparison between JUTTON & COTTON-increase jute dependency instead of cotton*. 106–110. https://doi.org/10.15406/jteft.2020.06.00238

Havaianas. (2020). https://www.havaianas-store.com/pt/perfect-size/size-guide.html

highlights of the 8th scrap tire recycling conference in south carolina. (2019). https://weibold.com/highlights-of-the-8th-scrap-tire-recycling-conference-in-south-carolina

Hollander, M. C. Den, Bakker, C. A., & Hultink, E. J. (2017). *Product Design in a Circular Economy Development of a Typology of Key Concepts and Terms*. *21*(3). https://doi.org/10.1111/jiec.12610

Homburg, C., Schwemmle, M., & Kuehnl, C. (2015). New product design: Concept, measurement, and consequences. *Journal of Marketing*, *79*(3), 41–56. https://doi.org/10.1509/jm.14.0199

Huang, Y., Leu, M. C., Mazumder, J., & Donmez, A. (2015). Additive manufacturing: Current state, future potential, gaps and needs, and recommendations. *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, *137*(1), 1–10. https://doi.org/10.1115/1.4028725

Hughes, J. L., Camden, A. A., & Yangchen, T. (2016). Rethinking and Updating Demographic Questions: Guidance to Improve Descriptions of Research Samples. *Psi Chi Journal of Psychological Research*, *21*(3), 138–151. https://doi.org/10.24839/2164-8204.jn21.3.138

Indsole. (n.d.). https://indosole.com/

ISO. (2002). *Technical Report Iso / Tr 14062*. *2001*.

ISO. (2006). *ISO 14040:2006 - Environmental MAnagement - Lifecycle Assessment - Principles and framework*. https://www.iso.org/obp/ui/#iso:std:iso:24415:-1:ed-1:v1:en

ISO. (2015). *ISO 14000 Series*. https://www.iso.org/iso-14001-environmental-management.html

Jawahir, I. S., & Bradley, R. (2016). Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing. *Procedia CIRP*, *40*, 103–108. https://doi.org/10.1016/j.procir.2016.01.067

Johansson, G. (2002). Success factors for integration of ecodesign in product development. *Environmental Management and Health*, *13*(1), 98–107. https://doi.org/10.1108/09566160210417868

Joyce, A., & Paquin, R. L. (2016). The triple layered business model canvas: A tool to design more sustainable business models. *Journal of Cleaner Production*, *135*(June), 1474–1486. https://doi.org/10.1016/j.jclepro.2016.06.067

Kaputa, V., Triznova, M., & Matová, H. (2019). Responsible consumer in the context of Circular Economy. *Digitalisation and Circular Economy: Forestry and Forestry Based Industry Implications*, *1*.

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., & Hekkert, M. (2018). Barriers to the Circular Economy: Evidence From the European Union (EU). *Ecological Economics*, *150*(January 2019), 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028

Klöpffer, W. (2006). The role of SETAC in the development of LCA. *International Journal of Life Cycle Assessment*, *11*(SPEC. ISS. 1), 116–122. https://doi.org/10.1065/lca2006.04.019

Lacy, P., & Rutqvist, J. (2015). Waste to Wealth: Creating Advantage in a Circular Economy. *Accenture Strategy*, 293. https://doi.org/10.1057/9781137530707

Leaf. (2020). https://www.leaf.tv/articles/the-advantages-of-cork-sole-shoes/

Leder, H., Belke, B., Oeberst, A., & Augustin, D. (2004). *A model of aesthetic appreciation and aesthetic judgments*. 489–508.

Leite, C. (2017). *Framework for Environmental Practices in Frugal Innovation*. *February*, 1–43.

Lewandowski, M. (2016). Designing the business models for circular economy-towards the conceptual framework. *Sustainability (Switzerland)*, *8*(1), 1–28. https://doi.org/10.3390/su8010043

Liberty Tire Recycling. (n.d.). https://libertytire.com/

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, *115*, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042

Lindahl, M., & Ekermann, S. (2013). Structure for categorization of EcoDesign methods and tools. *Re-Engineering Manufacturing for Sustainability - Proceedings of the 20th CIRP International Conference on Life Cycle Engineering*, 117–122. https://doi.org/10.1007/978-981-4451-48-2_19

Linder, M., & Williander, M. (2015). *Circular Business Model Innovation: Inherent Uncertainties*. *196*(September 2015), 182–196. https://doi.org/10.1002/bse.1906

Lopes, D., Ferreira, M. J., Russo, R., & Dias, J. M. (2015). Natural and synthetic rubber/waste - Ethylene-Vinyl Acetate composites for sustainable application in the footwear industry. *Journal of Cleaner Production*, *92*, 230–236. https://doi.org/10.1016/j.jclepro.2014.12.063

Maiocchi, M. (2015). *The Neuroscientific basis of successful design: how emotions and perceptions matter*. https://books.google.pt/books?id=VszO_kZl4bUC&printsec=frontcover&hl=pt-PT

Matsumoto, M., Masui, K., Fukushige, S., & Kondoh, S. (2017). *Sustainability Through Innovation in Product Life Cycle Design*.

Mckinsey&Company. (2016). The Circular Economy: Moving from theory to practice. *McKinsey Center for Business and Environement*, *1*(1), 322–331.

Medkova, K., & Fifield, B. (2016). Circular Design - Design for Circular Economy. *Lahti Cleantech Annual Review 2016*, *February*, 32–47.

Mingers, J., & Brocklesby, J. (1997). Multimethodology: Towards a framework for mixing methodologies. *Omega*, *25*(5), 489–509. https://doi.org/10.1016/S0305-0483(97)00018-2

Moe, R. E., Jensen, D. D., & Wood, K. L. (2004). Prototype partitioning based on requirement flexibility. *Proceedings of the ASME Design Engineering Technical Conference*, *3*, 65–77. https://doi.org/10.1115/detc2004-57221

Moreno, M., De los Rios, C., Rowe, Z., & Charnley, F. (2016). A conceptual framework for circular design. *Sustainability (Switzerland)*, *8*(9). https://doi.org/10.3390/su8090937

Murakami, S., Oguchi, M., Tasaki, T., Daigo, I., & Hashimoto, S. (2010). Lifespan of commodities, part I: The creation of a database and its review. *Journal of Industrial Ecology*, *14*(4), 598–

612. https://doi.org/10.1111/j.1530-9290.2010.00250.x

Ophardt, C. (2019). Natural and Synthetic Rubbers. In *Map: Organic Chemistry (Smith)*. https://chem.libretexts.org/Bookshelves/Organic_Chemistry/Map%3A_Organic_Chemistry_(Smith)/Chapter_31%3A_Synthetic_Polymers/31.5%3A_Natural_and_Synthetic_Rubbers

Origins, C. (2017). *Cork Solutions & Manufacturing Processes*. https://amorimcorkcomposites.com/media/2914/171124_acc_book_cork_solutions_and_processes_long_digital_web.pdf

Osterwalder, A. (2004). *THE BUSINESS MODEL ONTOLOGY A PROPOSITION IN A DESIGN SCIENCE APPROACH*.

Osterwalder, A., Pigneur, Y., Smith, A., & Movement, T. (2010). Business Model Generation: book reviw. *Business Model Generation*, *5*(7), 288. http://www.amazon.com/Business-Model-Generation-Visionaries-Challengers/dp/0470876417

Paul Timmers. (1998). *Business Models for Electronic Markets, Electronic Markets*. https://www.tandfonline.com/doi/abs/10.1080/10196789800000016

Pennington, D. W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., & Rebitzer, G. (2004). Life cycle assessment Part 2: Current impact assessment practice. *Environment International*, *30*(5), 721–739. https://doi.org/10.1016/j.envint.2003.12.009

Pigosso, D. C. A., Rozenfeld, H., & McAloone, T. C. (2013). Ecodesign maturity model: A management framework to support ecodesign implementation into manufacturing companies. *Journal of Cleaner Production*, *59*, 160–173. https://doi.org/10.1016/j.jclepro.2013.06.040

Plouffe, S., Lanoie, P., Berneman, C., & Vernier, M. (2011). *Economic bene fi ts tied to ecodesign q*. *19*. https://doi.org/10.1016/j.jclepro.2010.12.003

Portugal, C. (2016). Sustainable Materials and Components for Footwear. *CTCP Portugal*, 6–26. https://www.solidaridadnetwork.org/leather

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). Circular Economy: Measuring innovation in the product chain - Policy report. *PBL Netherlands Environmental Assessment Agency*, *2544*, 42.

Pré Consultants. (2012). *Sustainability software for fact-based decisions*. https://www.pre-sustainability.com/sustainability-consulting/sustainable-practices/custom-sustainability-software#SimaPro/

Radford, S. K., & Bloch, P. H. (2011). *Linking Innovation to Design : Consumer Responses to Visual Product Newness **. *28*, 208–220.

Reber, R., Schwarz, N., & Winkielman, P. (2004). *Processing Fluency and Aesthetic Pleasure : Is Beauty in the Perceiver ' s Processing Experience ? Processing Fluency and Aesthetic Pleasure : Is Beauty in the Perceiver ' s Processing Experience ? May 2014*. https://doi.org/10.1207/s15327957pspr0804

Reschner, K. (2003). Scrap Tire Recycling. *Waste Management World*, 1–16. http://www.waste-management-world.com/articles/2003/07/scrap-tyre-recycling.html

Ritchie, H., & Roser, M. (2018). Plastic-Pollution. *Our World in Data*. https://ourworldindata.org/plastic-pollution

Rocca, F. C. (2016). *Supply Chain Management for Frugal Innovation Products*. *June*.

Roofthooft, W. (2010). Customer equity: A creative tool for SMEs in the services industry: How small and medium enterprises can win the battle for innovation. *Service Business*, *4*(1), 37–48. https://doi.org/10.1007/s11628-009-0082-6

Root, T. (2019). Tires: The plastic polluter you never thought about. *Environment - The Story of PLastic*. https://www.nationalgeographic.com/environment/2019/09/tires-unseen-plastic-polluter/

RSA. (2016). *Designing for a circular economy: Lessons from The Great Recovery 2012 – 2016*. *March*.

RubberCal. (n.d.). *Types of Synthetic Rubber: Santroprene and Styrene-Butadiene*. https://www.rubbercal.com/sheet-rubber/types-of-synthetic-rubber/

Ruvald, R., Frank, M., Johansson, C., & Larsson, T. (2018). Data Mining through Early Experience Prototyping -A step towards Data Driven Product Service System Design. *IFAC-PapersOnLine*, *51*(11), 1095–1100. https://doi.org/10.1016/j.ifacol.2018.08.458

Salam, M. A. (2008). An empirical investigation of the determinants of adoption of green procurement for successful green supply Chain management. *Proceedings of the 4th IEEE International Conference on Management of Innovation and Technology, ICMIT*, 1038–1043. https://doi.org/10.1109/ICMIT.2008.4654511

Sasikumar, P., Kannan, G., & Haq, A. N. (2010). *A multi-echelon reverse logistics network design for product recovery — a case of truck tire remanufacturing*. 1223–1234. https://doi.org/10.1007/s00170-009-2470-4

Sauvé, S., Bernard, S., & Sloan, P. (2016). Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. *Environmental Development*, *17*, 48–56. https://doi.org/10.1016/j.envdev.2015.09.002

Schaltegger, S., Maas, K., & Crutzen, N. (2016). *Advancing the integration of corporate sustainability measurement, management and reporting*. https://www.sciencedirect.com/science/article/abs/pii/S0959652616306746

Schoormans, J. P. L. (2005). *The Different Roles of Product Appearance in Consumer Choice*. *December 2004*. https://doi.org/10.1111/j.0737-6782.2005.00103.x

Schrepp, M., & Hinderks, A. (2014). *Design, User Experience, and Usability. Theories, Methods, and Tools for Designing the User Experience*. *8517*(January 2015). https://doi.org/10.1007/978-3-319-07668-3

Science Matters: The case of Plastics. (n.d.). History and Future of Plastics. https://www.sciencehistory.org/the-history-and-future-of-plastics

Scott, E. (2015). *End-of-life Tyre REPORT, European Tyre & Rubber Manufacturers Association, 2015*. 36. http://www.etrma.org/library-2

Sebastian, P., & Ledoux, Y. (2009). Decision support systems in preliminary design. *International Journal on Interactive Design and Manufacturing*, *3*(4), 223–226. https://doi.org/10.1007/s12008-009-0077-5

Severo, E. A., Guimarães, J. C. F. de, & Dorion, E. C. H. (2017). Cleaner production and environmental management as sustainable product innovation antecedents: A survey in Brazilian industries. *Journal of Cleaner Production*, *142*(September), 87–97. https://doi.org/10.1016/j.jclepro.2016.06.090

SimaPro. (n.d.). *Ecoinvent LCI database*. https://simapro.com/databases/ecoinvent/

Slack, N., Brandon-jones, A., & Johnston, R. (2007). Operations management. In *Handbook of Global Supply Chain Management*. https://doi.org/10.4135/9781412976169.n10

Smalley, M. (2018). Road Ahead for Scrap Tire Recycling. *Recycling Today*. https://www.recyclingtoday.com/article/road-ahead-for-scrap-tire-recycling/

Sönnichsen, S. D., & Clement, J. (2020). Review of green and sustainable public procurement: Towards circular public procurement. *Journal of Cleaner Production*, *245*. https://doi.org/10.1016/j.jclepro.2019.118901

Sovacool, B. K., Valentine, S. V., Jain Bambawale, M., Brown, M. A., de Fátima Cardoso, T., Nurbek, S., Suleimenova, G., Li, J., Xu, Y., Jain, A., Alhajji, A. F., & Zubiri, A. (2012). Exploring propositions about perceptions of energy security: An international survey. *Environmental Science and Policy*, *16*, 44–64. https://doi.org/10.1016/j.envsci.2011.10.009

Spears, N., & Yazdanparast, A. (2014). ScienceDirect. *Journal of Consumer Psychology*, 1–10. https://doi.org/10.1016/j.jcps.2014.01.003

Stahel, W. R. (1997). The service economy: "Wealth without resource consumption"? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *355*(1728), 1309–1319. https://doi.org/10.1098/rsta.1997.0058

Street, D. S., Adamson, P., Yo, Y., & Hoy, S. (2005). Final report Final report. *The National Audit of Violence (2003 - 2005)*, *May*, 1–74. https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=LIFE08_ENV_E_000126_FTR.pdf

Su, B., Heshmati, A., Geng, Y., & Yu, X. (2013). A review of the circular economy in China: Moving from rhetoric to implementation. *Journal of Cleaner Production*, *42*, 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020

Subulan, K., Tas, A. S., & Baykasog, A. (2015). *Designing an environmentally conscious tire closed-loop supply chain network with multiple recovery options using interactive fuzzy goal programming* (Vol. 39). https://doi.org/10.1016/j.apm.2014.11.004

Tam, E., Soulliere, K., & Sawyer-beaulieu, S. (2019). Resources , Conservation & Recycling Managing complex products to support the circular economy. *Resources, Conservation & Recycling*, *145*(November 2018), 124–125. https://doi.org/10.1016/j.resconrec.2018.12.030

Taura, T., & Nagai, Y. (2009). Design Creativity: Integration of Design Insight and Design Outrsight. *Japanese Society for the Science of Design*, *16*.

Thakker, A., Jarvis, J., Buggy, M., & Sahed, A. (2009). 3DCAD conceptual design of the next-generation impulse turbine using the Pugh decision-matrix. *Materials and Design*, *30*(7), 2676–2684. https://doi.org/10.1016/j.matdes.2008.10.011

Tiwari, V., Jain, P. K., & Tandon, P. (2016). Product design concept evaluation using rough sets and VIKOR method. *Advanced Engineering Informatics*, *30*(1), 16–25. https://doi.org/10.1016/j.aei.2015.11.005

Tyler, D. J., & Han, S. L. (2019). *Designing Products for the Circular Economy*. 93–116. https://doi.org/10.1007/978-3-030-15483-7

Ulrich, K., & Eppinger, S. (2012). Product design and development. In *Biosensors and Bioelectronics* (Vol. 7, Issue 2). https://doi.org/10.1016/0956-5663(92)90013-D

United Nations Environment Programme. (2018). *Single-use plastics: A roadmap for sustainability | UN Environment*. https://www.unenvironment.org/resources/report/single-use-plastics-roadmap-sustainability

United States Environemntal Protection Agency, Solid Waste and Emergency Response, & Policy, P. and E. (1991). *Markets for Scrap Tires*. https://archive.epa.gov/epawaste/conserve/materials/tires/web/pdf/tires.pdf

Upward, A. (2013). *Towards an Ontology and Canvas for Strongly Sustainable Business Models: A Systemic Design Science Exploration*. *August*, 1–1138. http://yorkspace.library.yorku.ca/xmlui/handle/10315/20777

ValorPneu. (n.d.). *ValorPneu Sistema SGPU*. https://www.valorpneu.pt/sistema-sgpu/

Van Eynde, H. (2015). *Comparative Life Cycle Assessment of hemp and cotton fibres used in Chinese textile manufacturing*. 158. https://www.scriptiebank.be/sites/default/files/VanEyndeHannes_KUL_Eindwerk.pdf

Verheye, W. (2010). Growth and Production of Rubber. *Land Use, Land Cover and Soil Sciences*, 295–300. https://biblio.ugent.be/publication/1009121/file/6718218

Vesely, A. (2008). Problem Tree: A Problem Structuring Heuristic. *Central European Journal of Public Policy*, *2*(2), 68–80. http://www.cejpp.eu/index.php/ojs/article/view/24/20

Viswanathan, V. K., & Linsey, J. S. (2009). Enhancing student innovation: Physical models in the idea generation process. *Proceedings - Frontiers in Education Conference, FIE*, *November*. https://doi.org/10.1109/FIE.2009.5350810

Wallin J., Chirumalla K., T. A. (2013). *Developing PSS Concepts from Traditional Product Sales Situation: The Use of Business Model Canvas*. https://link.springer.com/chapter/10.1007/978-3-642-30820-8_23

WastedShoes. (2020). https://wastedshoes.com/es/

Webb, H. (2012). *Biodegradation of poly(ethylene terephthalate) by marine bacteria, and strategies for its enhancement Submitted* (Issue May). https://researchbank.swinburne.edu.au/file/d006bb4d-4487-4623-9b69-199a23951255/1/Hayden Webb Thesis.pdf

Webster, K. (2013). What might we say about a circular economy? Some temptations to avoid if possible. *World Futures: Journal of General Evolution*, *69*(7–8), 542–554. https://doi.org/10.1080/02604027.2013.835977

Whitlark, D., Geurts, M., & Swenson, M. (1993). *New product forecasting with a purchase intention survey*. https://www.researchgate.net/publication/313636439_New_product_forecasting_with_a_purchase_intention_survey

Wilson, V. (2013). *Focus Groups: a useful qualitative method for educational research?* https://bera-journals.onlinelibrary.wiley.com/doi/abs/10.1080/0141192970230207

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, *68*(October 2015), 825–833. https://doi.org/10.1016/j.rser.2016.09.123

Yang, M. C. (2005). A study of prototypes, design activity, and design outcome. *Design Studies*, *26*(6), 649–669. https://doi.org/10.1016/j.destud.2005.04.005

Yasukawa, O Page, T. (2020). *Cnn*, *2019*(March), 199. https://iris.wpro.who.int/bitstream/handle/10665.1/7977/9789290615323_eng.pdf%0Ahttps://promundoglobal.org/covid-19-demands-that-we-pay-attention-to-who-does-the-care-work-and-how-we-support-them/%0Ahttps://centreforfeministforeignpolicy.org/feminist-reso

Zhijun, F., & Nailing, Y. (2007). Putting a circular economy into practice in China. *Sustainability Science*, *2*(1), 95–101. https://doi.org/10.1007/s11625-006-0018-1

Zimmerman J., F. J. (2014). *Research Through Design in HCI*. https://link.springer.com/chapter/10.1007/978-1-4939-0378-8_8#citeas

Appendix A – Hemp Fabric LCA

For the selection of fabric materials for the sandal development, hemp was chosen as one of the materials to analyse and compare in terms of sustainability. Due to the lack of hemp available in the *EcoInvent* database, a comparative study was selected to provide the necessary inputs to compare this material with the other fabrics chosen. This study was elaborated by Van Eynde (2015) and is detailed in this appendix. The goal of the study is to compare the environmental performance of hemp and cotton and understand whether hemp fibre is more sustainable than the use of cotton fibre in the textile industry and for different applications. This study does not include the use and disposal phases thus, it is assumed as relatively close for both products. The geographical boundary of this study is limited to China due to the great exploration of hemp fabric in this territory. The functional unit used is 1kg of woven fabric ready to be dyed and further processed, in China. In this study, different scenarios are elaborated to provide more insightful data related to the use of hemp fabric. Two fibre production scenarios are presented - CP and GAP. The latest corresponds to the Good Agricultural Practices' scenario, while CP scenario is relative to the Common Practices scenario. The latest is the one considered for the current dissertation. Four fabric production scenarios are also selected – A, B, C and R. Scenario R corresponds to the baseline scenario in which only cotton is considered to allow a benchmarking comparison with the three hemp scenarios. Scenario A is the preparation of a fabric composed of a combination of 55% of hemp and 45% of cotton. Scenario B and C both include fabrics composed only by hemp, with the difference in the preparation method, yet, for scenario B a slightly different functional unit is used due to technological limitations. Due to this variations, Scenario C data is presented in this appendix since it is the only scenario that considers 100% of hemp fibre fabric and the functional unit is also equal to the one selected for the comparison of the material sin this dissertation.. However, for scope of this dissertation only the fibres of each material are being compared, therefore, the final output of this study – the fabric – shall not be used. The relevant data obtained from the study corresponds to the output emissions derived from the fibre production solely. The following illustration highlights the system boundaries for this LCA along with all the activities inherent to the composition of the fabrics for the four scenarios. For the development of the life cycle assessment *SimaPro* is used, more specifically, the *Recipe* method is used. Since the goal of the study is to compare in what conditions hemp is more beneficial than cotton, only midpoint categories are considered. The fibre production is addressed as the Subsystem 1B in **Figure 32**. To address the fibre production, several inputs are considered: use of pesticides, fertilizers, irrigation processes in the cultivating fields, seed production, plastic mulch, on-farm fuel use and energy used in the ginning and scutching activity. Consequently, the outputs from these activities were calculated and the correspondent emissions are gathered in the different impact categories, presented in **Table 25**. Yet, before presenting the final results for the fibre production, the activities included in the fabric production are also presented, which correspond to the activities that follow the subsystem 1.B in Figure 32.

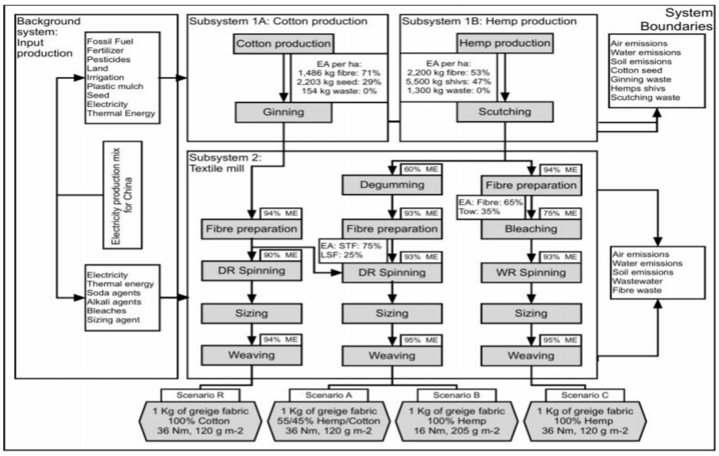

Figure 32 - Scenario A, B, C and R activities and boundaries (Eynde, 2015)

In this study not all the impact categories are discriminated, therefore the results presented only comprise the categories presented in the study which correspond to the most impactful ones. Even though the normalization values for the impactful categories are presented, this are highlighted in a comparison chart with the four scenarios, and the normalized values are not presented separately. Therefore, a single score could not be obtained from the study nor the normalization values for the impact categories. **Table 25** presents the characterization values from the main impact categories along with the impacts from each activity inherent in the fibre production activity, relative to the subsystem 1.B. The impact categories presented are Climate Change (CC), Terrestrial Acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Human toxicity (HT), Particulate matter formation (PMF), Terrestrial Ecotoxicity (TET), Freshwater ecotoxicity (FET) and Marine ecotoxicity (MET). The results only cover the fibre production of hemp for the further processing into fabric. The results presented in **Table 25** correspond to the fibre production activity. From the comparison of both cotton and hemp fibre production, the study reveals that the hemp fibre production is more environmental beneficial than the cotton fabric production, in the CP scenario. From the study, in scenario C, it was obtained that the most impact from the hemp fabric production is derived the fibre production activity, yet, the bleaching activity presents lower impacts than the other scenarios. The study concludes that the use of hemp is not so beneficial in fabrics when compared to the use of cotton, mostly due to the technology and machinery available in China, which is one of the main hemp fabric producers. Even though adding a percentage of hemp fabric in the textile industry could reduce the impact on certain environmental categories, it would increase the impact in other categories.

Table 25 - Characterization values for the hemp fabric (Eynde, 2015)

Impact category	Unit	Total	Fertilizer production	Fertilizer emissions	Pesticide production	Pesticide emissions	Hempseed	Fuel use	Scutching	Retting emissions
CC	kg CO_2-eq	0.969230243	0.219230348	0.403325182	0.004881627	0	0.032935189	0.05185111	0.224844461	0.032162327
		100%	23%	42%	1%	0%	3%	5%	23%	3%
TA	kg SO_2-eq	0.036019679	0.001703916	0.029883881	0.000156001	0	0.001542046	6.08946E-05	0.001978934	0.000694006
		100%	5%	83%	0%	0%	4%	0%	5%	2%
FE	kg P-eq	0.000183396	7.76841E-05	6.76545E-05	1.51268E-06	0	7.14085E-06	4.28868E-07	2.89752E-05	0
		100%	42%	37%	1%	0%	4%	0%	16%	0%
ME	kg N-eq	0.016690809	7.14955E-05	0.01578241	2.12623E-06	0	0.000768841	1.31597E-06	3.42826E-05	3.03382E-05
		100%	0%	95%	0%	0%	5%	0%	0%	0%
HT	kg 1,4-DB-eq	0.163381438	0.107378705	0.019234534	0.001831498	0.000677201	0.006291676	0.000643877	0.027323946	0
		100%	66%	12%	1%	0%	4%	0%	17%	0%
PMF	kg PM_{10}-eq	0.005899269	0.000573976	0.004293434	3.51353E-05	0	0.000238528	1.70936E-05	0.000615502	0.0001256
		100%	10%	73%	1%	0%	4%	0%	10%	2%
TET	kg 1,4-DB-eq	0.000392729	6.26869E-05	-2.68685E-05	8.63521E-07	0.00033256	1.79618E-05	1.2213E-06	4.30391E-06	0
		100%	16%	-7%	0%	85%	5%	0%	1%	0%
FET	kg 1,4-DB-eq	0.032647738	0.002904104	-4.46857E-06	0.000226475	0.027447176	0.001483199	1.76976E-05	0.000573554	0
		100%	9%	0%	1%	84%	5%	0%	2%	0%
MET	kg 1,4-DB-eq	0.005484846	0.002810302	-2.42153E-06	4.77599E-05	0.00178718	0.000227316	4.55754E-05	0.000569134	0
		100%	51%	0%	1%	33%	4%	1%	10%	0%

Appendix B – Life Cycle Assessment Results

In this appendix further data and analysis is presented regarding the comparison and selection of the different materials in *Simapro.*

Fabric Materials Analysis

The analysis made to the different fabric materials to incorporate in the sandal is presented. All the materials are compared in the level of its fibre production since this was the only material available for both jute and organic cotton in *SimaPro.* Regarding the hemp fibre, its data was collected from an independent study made by Van Eynde (2015) and presented in Appendix A. As it was already mentioned, the functional unit for this study is 1kg of material.

Table 26 presents the characterized values for all the impact categories for both jute fibre and organic cotton fibre.

Table 26 - Characterized values per impact category for jute and organic cotton fibre

Impact Category	Unit	Fibre, jute {GLO}| market for fibre, jute | Cut-off, U	Fibre, cotton, organic {GLO}| market for fibre, cotton, organic | Cut-off, U
Global Warming	kg CO2 eq	1,05	0,67
Stratospheric Ozone Depletion	kg CFC11 eq	0,00	0,00
Ionizing Radiation	kBq Co-60 eq	0,01	0,00
Ozone Formation, Human Health	kg NOx eq	0,00	0,00
Fine Particulate Matter Formation	kg PM2.5 eq	0,00	0,00
Ozone Formation, Terrestrial Ecosystems	kg NOx eq	0,00	0,00
Terrestrial Acidification	kg SO2 eq	0,02	0,02
Freshwater Eutrophication	kg P eq	0,00	0,01
Marine Eutrophication	kg N eq	0,00	0,02
Terrestrial Ecotoxicity	kg 1,4-DCB	3,63	1,07
Freshwater Ecotoxicity	kg 1,4-DCB	0,08	0,07
Marine Ecotoxicity	kg 1,4-DCB	0,10	0,10
Human Carcinogenic Toxicity	kg 1,4-DCB	0,03	0,00
Human Non-Carcinogenic Toxicity	kg 1,4-DCB	-6,23	-0,48
Land Use	m2a crop eq	1,85	13,86
Mineral Resource Scarcity	kg Cu eq	0,01	0,00
Fossil Resource Scarcity	kg oil eq	0,14	0,02
Water Consumption	m3	0,44	0,00

From the table 26, it is possible to observe different trade-offs in several categories. Jute has the best performance in four of the eighteen categories whereas organic cotton performs better in eight categories. Even though cotton seems to have the best performance overall, some categories where this material performs worse than jute have severe differences, which is the case of Human Toxicity and Land use, for instance. Due to the lack of hemp fibre available in the *EcoInvent* database, the environmental impacts from hemp fibre production were obtained from the study mentioned before and presented in Appendix A. Only the emissions from the most relevant impact categories were provided. Therefore, these categories are presented in **Table 27** along with the emissions from the three materials.

Table 27 - Characterized values per impact category for jute, organic cotton and hemp fibre

Impact Category	Unit	Fibre, jute {GLO}| market for fibre, jute | Cut-off, U	Fibre, cotton, organic {GLO}| market for fibre, cotton, organic | Cut-off, U	Fibre, hemp *
Global warming	kg CO2 eq	1,05	0,67	0,97
Terrestrial acidification	kg SO2 eq	0,02	0,02	0,04
Freshwater eutrophication	kg P eq	0,00	0,01	0,00
Marine eutrophication	kg N eq	0,00	0,02	0,02
Terrestrial ecotoxicity	kg 1,4-DCB	3,63	1,07	0,00
Freshwater ecotoxicity	kg 1,4-DCB	0,08	0,07	0,03
Marine ecotoxicity	kg 1,4-DCB	0,10	0,10	0,01
Human carcinogenic toxicity	kg 1,4-DCB	0,03	0,00	0,16

From table 27 it is clear that there are a few trade-offs between different categories. For instance, in regard to Global warming, organic cotton presents the lowest emission value, whereas for the category of freshwater Eutrophication this material seems to be the most pollutant even though this value is scarce. In the categories of Marine and Freshwater Eutrophication, jute fibre is the least pollutant with no emissions, yet with the highest value for Terrestrial Ecotoxicity. Hemp, on the other hand, seems to have the best performance on this category, which is also true for the categories of Marine Ecotoxicity and Freshwater Ecotoxicity. All in all, the three materials seem to have a lot of trade-offs with Jute having the best performance in two of the eight categories, organic cotton in also two and hemp in three. To have a better perception these values were reflected on a chart. Yet, a normalization was elaborated to have a better reflection over the relevance of each category on the all. Also, faced with the inexistence of the single score of the hemp fibre, the normalization should aid in the perception of each category on the whole. To obtain the normalization values, a normalization factor had to be calculated from the following formula: $Normalization\ value = \frac{Caracterization\ value}{normalization\ factor}$. From the characterized values from the organic cotton and jute fibre it was possible to get the normalization factor. The normalized values of the three materials along with the normalization factor used is presented in **Table 28**.

Table 28 - Normalized values per impact category for jute, organic cotton and hemp fibre

Impact Category	Normalization Factor	Fibre, jute {GLO}| market for fibre, jute | Cut-off, U	Fibre, cotton, organic {GLO}| market for fibre, cotton, organic | Cut-off, U	Fibre, hemp *
Global warming	7987,22	8375,98	5340,00	7741,46
Terrestrial acidification	40,98	0,70	0,79	1,48
Freshwater eutrophication	0,65	0,00	0,01	0,00
Marine eutrophication	4,61	0,02	0,11	0,08
Terrestrial ecotoxicity	1036,27	3757,85	1106,47	0,41
Freshwater ecotoxicity	1,23	0,10	0,09	0,04
Marine ecotoxicity	1,03	0,10	0,10	0,01
Human carcinogenic toxicity	2,77	0,09	0,00	0,45
Total		12 134,8	6 447,6	7 743,9

From the table 28, it seems that organic cotton is the most sustainable material, with the least total value, yet in this table only the impact categories provided in the hemp fibre study are mentioned. Therefore, jute and organic cotton can not be compared with the values. From the *Simapro,* the single scores correctly pondered and weighted by the software were 40,4 for Jute fibre and 114 for organic cotton. Therefore, Jute proves to be the best environmental performer. To support the reading of the analysis in table 34, a chart was developed with the normalized values for the three materials. **Figure 33** highlights the differences between one another in the eight categories provided in the hemp fibre study.

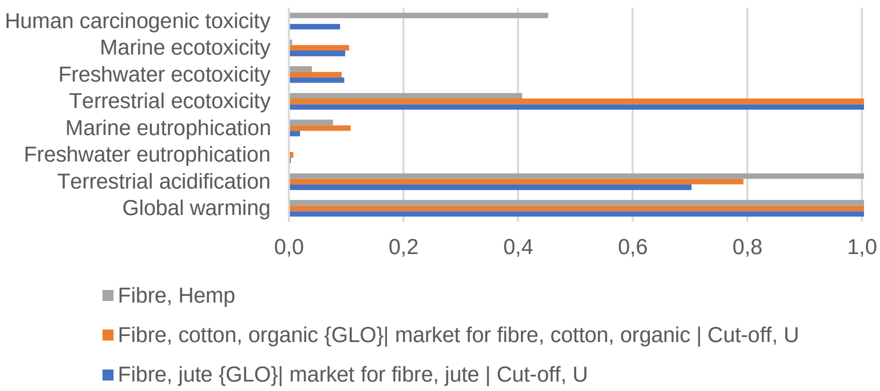

Figure 33 - Midpoint comparison of normalized values per impact category for jute, organic cotton and hemp fibre

The endpoint comparison of both organic cotton and jute was also elaborated to highlight the jute performance with all the categories when compared with the organic cotton. The chart highlighting this is presented in **Figure 34**.

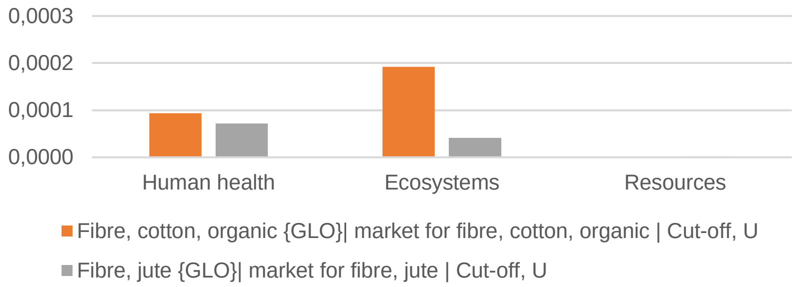

Figure 34 - Endpoint comparison of normalized values per impact category for jute and organic cotton fibre

From figure 34 it is highlighted the impact of cotton fibre production both in Human Health and Ecosystems when compared to jute. Even though the Resources impact category values are too low, the organic cotton performs better in this category with a lower impact when compared to the Jute (3,41E-07 unit in cotton and 1,54E-06 unit in jute). Yet, in both human health and ecosystems impact category is evident that the production of 1kg of organic cotton fibre has a greater impact in these when compared to the production of 1 kg of jute fibre. Therefore, from the comparison of the two, the jute is preferential to be used. All in all, cotton fibre seems to have the worst values for emissions in most categories. Having this analysis concluded, the analysis made for the sole materials is introduced next.

Sole Materials Analysis

All the materials selected for the sole were available in the *EcoInvent* database. Besides, all the materials were modified to fit to the Portuguese electricity medium voltage data. Only Natural rubber does not present the Portuguese electricity values since this material does not include any electricity consumption for its production, according to the *Simapro* software. Plus, Recycled Rubber goes by the name of Waste Rubber since it represents a flow of rubber waste from another rubber process. **Table 29** presents the characterized values for the four materials.

Table 29 - Characterized values per impact category for natural, synthetic, waste rubber and cork

Impact category	Unit	Seal, natural rubber based {DE}|	Synthetic rubber {PT}|	Cork slab {PT}|	Waste rubber, unspecified {PT}|
Global warming	kg CO2 eq	1,64	2,21	1,19	3,13
Stratospheric ozone depletion	kg CFC11 eq	0,00	0,00	0,00	0,00
Ionizing radiation	kBq Co-60 eq	0,06	0,18	0,04	0,00
Ozone formation, Human health	kg NOx eq	0,05	0,01	0,00	0,00
Fine particulate matter formation	kg PM2.5 eq	0,00	0,00	0,00	0,00
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,07	0,01	0,00	0,00
Terrestrial acidification	kg SO2 eq	0,01	0,01	0,01	0,00
Freshwater eutrophication	kg P eq	0,00	0,00	0,00	0,00
Marine eutrophication	kg N eq	0,00	0,00	0,00	0,00
Terrestrial ecotoxicity	kg 1,4-DCB	1,84	3,23	2,91	0,08
Freshwater ecotoxicity	kg 1,4-DCB	0,02	0,05	0,01	0,05
Marine ecotoxicity	kg 1,4-DCB	0,02	0,08	0,02	0,08
Human carcinogenic toxicity	kg 1,4-DCB	0,03	0,06	0,04	0,00
Human non-carcinogenic toxicity	kg 1,4-DCB	0,54	2,14	0,56	2,10
Land use	m2a crop eq	0,01	0,07	5,06	0,00
Mineral resource scarcity	kg Cu eq	0,00	0,08	0,00	0,00
Fossil resource scarcity	kg oil eq	1,53	1,59	0,39	0,01
Water consumption	m3	0,02	0,04	0,02	0,00

To ease the comparison between the categories in Table 29, a chart was elaborated with the most significant impact categories.

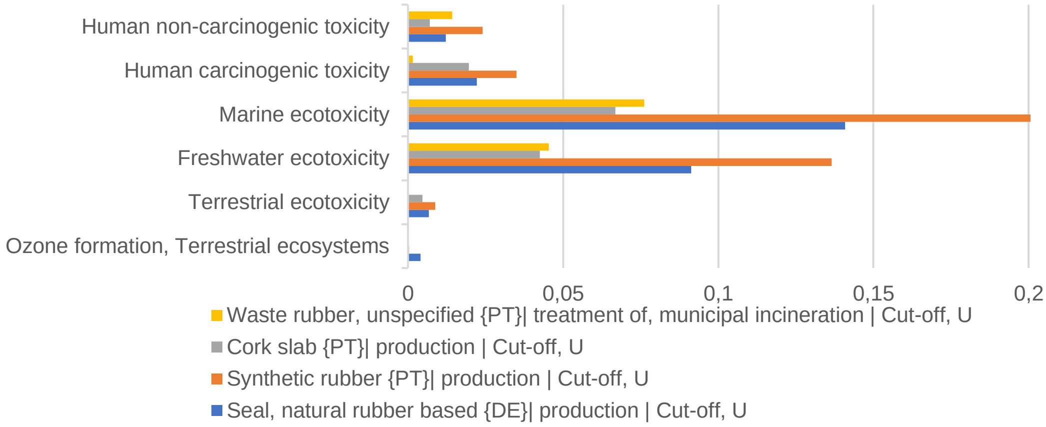

Figure 35 - Midpoint comparison between 1kg of Natural Rubber, Recycled Rubber, Synthetic Rubber and Cork

Figure 35 represents the most relevant midpoint categories of environmental impact of the production of the four materials. The two materials with the highest impact in most of the categories is both natural and synthetic rubber (blue and orange bars, respectively), with the synthetic rubber having the greatest impact in all the categories presented in the chart, apart from

Ozone Formations, Terrestrial Ecosystems which present scarce values and in which natural rubber has the worst environmental performance. Regarding recycled rubber and cork, these have similar impacts in all the categories, despite Human non-carcinogenic and Terrestrial Ecotoxicity where recycled rubber presents relatively low impacts when compared to the remaining materials. Even though, synthetic rubber and natural rubber are not sustainable options to consider for further analysis, there is still a tie between recycled rubber and cork.

To provide a straighter forward comparison, the next chart, in **Figure 36** highlights the endpoint comparison of the four materials.

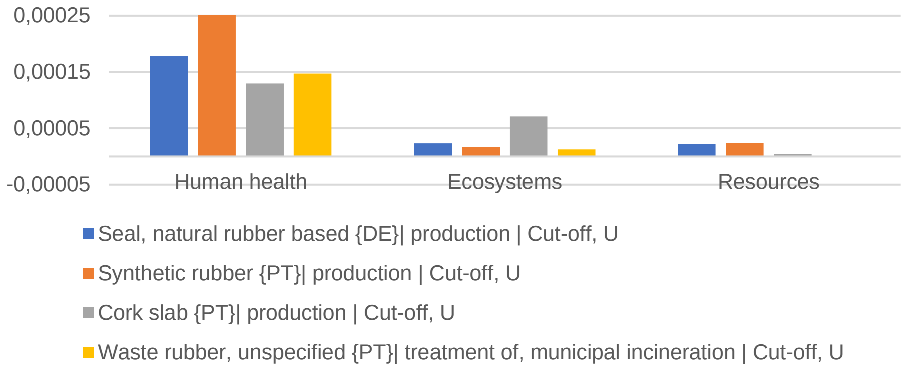

Figure 36 - Endpoint comparison between 1kg of Natural Rubber, Recycled Rubber, Synthetic Rubber and Cork

Figure 36 highlights the endpoint comparison of the four materials in the three impact categories. From this analysis it is clear that both cork and recycled rubber have an overall lower impact compared to the other materials with a lower impact both in Resources and Human Health. However, cork is still the greatest pollutant for the ecosystems, compared to the other materials, even though the values for this category are overall still low. Regarding Recycled Rubber, this performs great in all the categories despite still presenting a slightly higher impact in Human Health when compared to cork. All in all, Recycled Rubber is still the least pollutant in the remaining two impact categories and, in Ecosystems, the difference between this and Cork is still significant thus neglecting its worst performance (when compared to Cork) in Human Health.

The single scores were necessary to provide a better basis for decision. The single scores for the four materials were: Natural Rubber – 69,6 -, Synthetic Rubber – 93,6 –, Cork – 74,3 – and Recycled Rubber – 63,4. Therefore, Recycled rubber is the most sustainable material regarding the categories analysed.

Appendix C – Sandal Photographic Memory

This appendix gathers a photographic memory of the different phases of development of the sandal. The first section of footage shows the initial stage of preparing the tyre. Once received, the edges were removed with a cutter as it is represented in **Figure 37**.

Process Phase 1 – Removing the Tyre Edges

Figure 37 - First process phase – Removing the tyre edges

Process Phase 2 – Opening up the tyre

After removing the tyre edges, it was necessary to cut the tyre in half to allow the sole shapes to be designed and cut, afterwards, in the tyre surface. An initial attempt to make this with the cutter end up failing due to the aluminum mash in between the tyre surfaces. Therefore, a saw was used. It was possible to cut the tyre in half, with the saw, yet this procedure was not the most time efficient nor the most accurate. Therefore, to remove the soles from the tyre another method had to be used. No footage was taken from this phase.

Process Phase 3 – Designing and cutting tyre soles

To overcome the aluminium mash, a grinding wheel was used, as it is observed in the following Figure. The first sole was cur with a domestic grinding wheel, and it required quite some time to obtain the sole since it was harder to manoeuvre the grinding wheel and cut through the aluminium mash. After completing this process and obtaining the first tyre sole an improvement on the cutting method had to be done. The domestic grinding wheel was not the best tool since it did not provide the cleanest cut and due to that many aluminium threads were sticking off the sole. Therefore, it was necessary to resort to a professional grinding wheel, as it is observed in the last two pictures in **Figure 38**. This method was a better approach and was also more time efficient allowing several soles to be cut in a short time. The edges of the sole were also better cut, and a clear improvement was achieved. Yet, even if scarce, some aluminium threads were sticking out from the sole, which could imply a need for restructuring the sole.

Figure 38 - Third process phase – Cutting soles from tyre

Process Phase 4 – Cutting waste rubber slabs

The recycled rubber slabs were cut with a regular scissors. The slabs are shown in **Figure 39**.

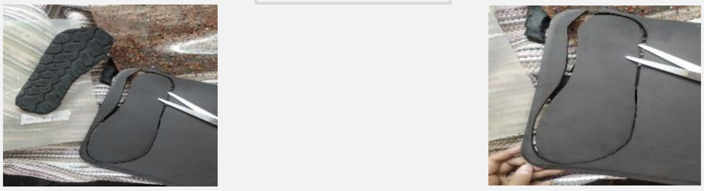

Figure 39 - Fourth process phase – Cutting waste rubber slabs

Process Phase 5 – Preparing jute strap

There is no photographic register of this phase. The jute was cut in different sizes and the width of the strap was selected based on the width of similar traps in regular sandals. Different attempts to obtain the best strap size were made. The first strap cut was sewed with another strap in an attempt to provide a better structure, consistency and a more stable strap to add in the sandal. This was an unfortunate attempt and the strap did not succeed. Provided that, another attempt to provide more stability in the strap was made. This time, the strap was painted using a regular ink spray. This attempt was successful, and the following straps cut also went through this process before creating the sandal.

Process Phase 6 – Assembly

The assembly weas made with the three modules at the same time. No other option was possible. Glue was the element to assemble the parts. After gluing the three parts together, the sandal was placed in a press for 12 hours. This first attempt was successful, and it was possible to try the sandal a wear it. Yet, this first sandal was made with the first attempt of jute strap made, therefore, a need for improvement was evident. For the second attempt, the sandal tyre was painted with a white ink spray and another recycled rubber slab was used, this time with a different pattern as well. For this attempt, the jute strap used was the one that was also painted with the white ink spray. This attempt was also successful, and a sandal was made. Yet, the strap was loose, thus giving a rather uncomfortable feeling when using. Finally, another attempt was made, this time to overcome the loose feeling of the strap, an open strap was glued (instead of a closed one). This strap was open so that the user could tie the strap and adjust if to the feet, thus, providing more comfort and avoiding any loose or tight strap. Different attempts were made in-between these three versions. Yet, did not succeeded somehow and were not registered, for that reason. **Figure 40** show the three final versions obtained.

Figure 40 - Sixth process phase – Final Prototype