TÉCNICO LISBOA

Product Design of a Zero Waste Toothpaste Packaging

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Dissertation to Obtain the Master of Science Degree in

Industrial Engineering and Management

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July, 2021

Abstract

Since the development of the modern plastic industry, humanity have depended on plastic as an affordable, versatile and durable material. The convenience this material offer, however, let to a throw-away culture that account for the massive pollution nowadays. As for the toothpaste packaging, the small size, blended material and leftover toothpaste inside toothpaste tubes make recycling impossible. To overcome this mismanaged waste and unexploited recycling alternatives, Design for Environment has surged to develop environmentally compatible products and processes encompassing all life cycle phases, to reduce lifecycle impacts while preserving performance standards. Therefore, this research aims at filling the literature gap by developing a fully specified prototype of a zero-waste toothpaste packaging within the frames of the circular economy and eco-design to cope with the excessive volumes of plastic, by adopting a methodology centered on Slack *et al.* (2007) approach, which comprises the five pillars of product design. In this regard, a complete research on the plastic market is conducted, as well as a literature review on the circular economy, product eco-design and respective drivers and barriers. The results of the analysis enabled to select a concept that meets the majority of design requirements based on consumer research and propose a model where the toothpaste tube is a container that can be refilled with toothpaste. The viability of the proposed solution was then validated by conducting a life cycle assessment and a business evaluation, to perform both environmental and financial project appraisal that defined the starting point for launching the product.

Keywords: Eco-Design, Circular Economy, Toothpaste Packaging, Plastic, Recycling

Resumo

Desde o desenvolvimento da indústria moderna do plástico, a humanidade tem dependido deste como um material acessível, versátil e durável. Em contrapartida desta conveniência, o plástico é responsável pela poluição massiva dos dias de hoje. Quanto às embalagens de pasta de dentes, o reduzido tamanho, a mistura de materiais e os resíduos no interior da embalagem tornam a sua reciclagem impossível. Para superar a má gestão destes resíduos e alternativas de reciclagem não exploradas, o Design para o Ambiente surgiu para desenvolver produtos ambientalmente compatíveis abrangendo todas as fases do ciclo de vida. Por conseguinte, esta investigação visa desenvolver um protótipo totalmente especificado de uma embalagem de pasta de dentes dentro dos quadros da economia circular e do eco-design para lidar com os volumes excessivos de plástico, adotando uma metodologia centrada na abordagem Slack et al. (2007), que compreende os cinco pilares do design de produto. A este respeito, é realizada uma pesquisa sobre o mercado do plástico, bem como uma revisão bibliográfica sobre a economia circular, o eco-design e respetivos motores e barreiras. Os resultados da análise permitiram a seleção de um conceito que satisfaz a maioria dos requisitos de design com base na investigação do consumidor e propõe um modelo em que o tubo da pasta de dentes é um recipiente que pode ser reutilizado. A viabilidade da solução proposta foi então validada através da realização de um estudo do ciclo de vida e de uma avaliação financeira, que definiu o ponto de partida para o lançamento do produto.

Palavras-chave: Eco-Design, Economia Circular, Pasta de Dentes, Plástico, Reciclagem

Acknowledgements

At the end of this long journey, I take the opportunity to deeply thank everyone who has made it possible for me to reach this stage successfully.

First and foremost, I would like to express my sincere gratitude to my supervisor, Prof. Ana Carvalho, for her expertise, availability, and support through each step of the process. Her invaluable insights challenged me to go further at each step, but it is her constant availability and the many wise advices which I will take with me for the rest of my life.

I also wish to express my deepest gratitude to all my friends and colleagues at IST. You have made this incredible journey much easier and happier, and your good mood and sincere friendship are the best things I take from my time at IST.

Last, but surely not the least. To my parents, for their unconditional support and love throughout my life and for teaching me what really matters and to Bernardo, for his constant support, understanding and unshakeable belief in me. Without you, it would not have been possible.

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List of Abbreviations

3D Three Dimensional

ABS Acrylonitrile Butadiene Styrene

ADA American Dental Association

BE Breakeven

BPA Bisphenol A

CA Customer Attributes

CAGR Compounded Average Growth Rate

CBM's Circular Business Models

CE Circular Economy

CH Switzerland Region

CM Contribution Margin

CNC Computer Numerical Control

COGS Cost of Goods Sold

CR Customer Requirements

CRM Customer Relationship Management

D4S Design for Sustainability Strategy Wheel

DCF Discounted Cash Flow

DfA Design for Assembly

DfD Design for Disassembly

DfE Design for Environment

DfL Design for Logistics

DfLC Design for Life Cycle

DfM Design for Manufacture

DfMa Design for Maintainability

DfN Design for Network

DfO Design for Obsolescence

DfP Design for Packaging

DfQ Design for Quality

DfR Design for Reliability

DfRe Design for Recycle

DfS Design for Sustainability

DfSC Design for Supply Chain

DfT Design for Transportability

DfV Design for Variety

DfX Design for X

DRs Design Requirements

EPD Ecological Product Design

EPS Expandable Polystyrene

ESW Eco-design Strategy Wheel
EU European Union
FDA Food and Drug Administration
FGS Food Grade Silicone
FU Functional Unit
GLO Global Region
GRAS Generally Recognized as Safe
HDPE High-Density Polyethylene
HoQ House of Quality
IRR Internal Rate of Return
LCA Life Cycle Assessment
LCI Life Cycle Inventory
LCIA Life Cycle Impact Assessment
LDPE Low Density Polyethylene
LLDPE Linear Low Density Polyethylene
MDPE Medium Density Polyethylene
NPV Net Present Value
NSP Net Selling Price
PBL Plastic Barrier Laminate
PC Polycarbonate
PE Polyethylene
PET Polyethylene Terephthalate
PM Pugh Matrix
PP Polypropylene
PS Polystyrene
PUR Polyurethane
PVC Polyvinyl Chloride
PVOH Polyvinyl Alcohol
PVOH Polyvinyl Alcohol
QFD Quality Function Deployment
RER European Region
RIC Resin Identification Code
RoW Rest of the World Region
SDG’s Sustainable Development Goals
SPI Society of the Plastics Industry
SS Single-Score
TDP The Disappearing Package
TR Technical Requirements
TRs Technical Requirements

UCD User-Centered Design

VC Variable Cost

VMC Variable Manufacturing Cost

VoC Voice of the Customer

1 | Introduction

1.1 | Problem Motivation

The world is currently producing more than 300 million tons of plastic every year. Although cheap, versatile, lightweight, and resistant, this unique material considered the "ubiquitous workhorse material of the modern economy" (MacArthur, 2016) has faced a remarkable global shift from durable and reusable to single-use applications. This short lifetime that led to a take-make-dispose culture coupled with mismanaged waste and unexploited recycling opportunities, led the environment to face a serious challenge that has to be acknowledged and addressed (Geyer et al., 2017; Ritchie and Roser, 2018). Plastic packaging encompasses plastics' largest application and is encountered by virtually everyone daily (MacArthur, 2017), which is reflected in the share of the waste generation it occupies. For packaging plastics, the majority of its lifetime ends within the same year they are manufactured. Particularly, the toothpaste industry alone produces more than 20 billion tubes every year that are usually made of plastic laminate and aluminium, which is cheap and convenient to use. The small size, blended material and leftover toothpaste inside toothpaste tubes make recycling almost impossible (Mazzoni, 2018). Unrecyclable packaging doesn't just end up in landfills. It can get swept into waterways, which contributes to the growing problem of plastic pollution of the world's oceans and damages marine ecosystems (Geyer *et al*., 2017).

The toothpaste is a product used every day, multiple times a day, whose tube packaging and linear process model hasn't changed in the last 50 years and therefore has to be discarded once it is empty. To cope with this mismanaged waste and unexploited recycling alternatives, Design for Environment (DfE), an inherent constituent of the Design for X (DfX) paradigm, has surged to develop environmentally compatible products and processes (Ramani *et al.*, 2010) to reduce lifecycle impacts while preserving performance standards and value for money (Holdway *et al*., 2002), while encompassing all life cycle phases from material extraction, manufacturing, transportation, usage and end-of-life (Rose, 2000). Accordingly, this research adopts the methodology proposed by Slack *et al*. (2007), which was further extended to a multi-methodology approach to integrate a more User Centered Design (UCD) approach, conducted across the five pillars of the product design process *(1) Concept Generation, (2) Concept Screening*, (3) Preliminary Design, *(4) Evaluation and Improvement design* and *(5) Prototyping and Final Design.* The aim is to develop a fully specified prototype of a zero-waste toothpaste packaging within the frames of the Circular Economy and Eco-design, having as a starting point the use of recycled plastic. The redesigned physical structure and graphic features is required to have less environmental impact without compromising usability and durability criteria, while maintaining its efficiency, pleasurable texture and hygiene standards in order to be while can be fully integrated into the new generation of toothpaste packaging.

1.2 | Dissertation Objectives

The main objective of this dissertation is to investigate the disadvantages of the toothpaste packaging and the proposal of a new packaging solution, which will not only eliminate the environmental impact that traditional toothpaste tubes cause but is also user- friendly. The research seeks to contribute to the packaging design (both primary and secondary), continuing to fulfil its role of getting products in good condition to consumers, can do so in a way that respects the environment by optimally using materials and following the appropriate processes. If, on the one hand, design is to be involved in the production process packaging, optimizing the use of materials and the production process through innovation based on sustainable development, on the other hand, it is also required that design promotes a meeting between aesthetic, practical and symbolic factors for the creation of packaging that arouses empathy in consumers, sensitizing them for a new paradigm based on ethical, social and environmental issues. Therefore, this dissertation aims at delivering (1) a characterization of the plastic market from production to consumption, (2) the state of the art on product design and development, with emphasis to DfE and respective drivers and barriers, and (3) statement of research objectives by establishing the methodology adopted during the master's dissertation development, (4) development of the integrated product design process through concept generation and screening until the proposed solution that is then *(5)* validated by conducting an environmental and financial project appraisal.

1.3 | Dissertation Outline

To conclude the first chapter of this research, the structure is now described. Chapter 2 provides a complete problem contextualization. The evolution of the plastic market is described so that the reader understands the resulting threats to the environment and the necessity of improving plastic waste management. Additionally, the plastic manufacturing landscape for the packaging industry is introduced. Since the problem has been defined, a theoretical analysis is required and is presented in Chapter 3. This chapter provides a state of the art on Circular Economy that have Circular Business Models and product design as foundations on the development of truly circular industrial systems. A broad study on the Design for X concepts is performed, where a framework categorising the different methods is presented. Lastly Design for Environment is explored, integrating its strategies, methods and tools, as well as its drivers and barriers. Chapter 4 points out research questions and the adopted methodology to complete the objectives defined in this research, which is centered across the five pillars of the product design process. The findings obtained through the research methodology are discussed in Chapter 5 that begins with the Concept Generation and recognition of what is the specific problem that requires a solution, followed by the Concept Screening stage that aims at evaluating the proposed product solutions that result from the research performed while translating customer needs into technical requirements. Chapter 5 ends with the viability assessment of the proposed toothpaste packaging solution by presenting the sustainability evaluation through a complete lifecycle assessment, and a business evaluation that defines the starting point for launching the product. Finally, to conclude the research, Chapter 6 presents a conclusion, reflection on the limitations of the study, and future work.

2 | The Plastic Market

This chapter is divided into four sections. Section 2.1 provides an overview of plastic production, consumption and plastic waste management, since its early stages up to the current “Plastic Age”. Although plastics have revolutionized the industry, they are undeniably a key environmental concern, and therefore, plastic pollution is also discussed. Section 2.2 presents the main types of plastics coupled with their industrial applications. Furthermore, in section 2.3, the manufacturing landscape for the packaging industry, and in particular for toothpaste packaging, is presented. Lastly, section 2.4 characterizes the problem, which will be the main focus of this work.

2.1 | The Plastic Age

2.1.1 | Plastic Production and Consumption

The development of modern plastic industry started its expansion in the first 50 years of the twentieth century (Andrady and Neal, 2009), through the production of the first synthetic plastic in 1907 (Ritchie and Roser, 2018). Plastics consist of a wide range of synthetic or semi-synthetic materials, produced by polymerization. Characterized by their malleability and plasticity during manufacture, plastics can easily be moulded, cast, pressed or extruded into complex shapes (Plastics Europe, 2017). On behalf of its versatility, high resource efficiency, lightweight, low cost and resistance (Plastics Europe, 2017; UNEP, 2018), “plastics have become the ubiquitous workhorse material of the modern economy” (MacArthur, 2016) for various commodity items in multiple key sectors, as a source of innovation, sustainability and welfare (Plastics Europe, 2018). Plastic packaged food extends the life of perishable food, ensuring food safety and reducing wastage; due to their light weight, reduces fuel consumption in vehicles and consequently carbon dioxide emissions; saves energy when applied as insulation material; facilitates clean drinking water supply; and enables medical innovation in surgical equipment by combining with Three Dimensional (3D) printing and biocompatible plastic materials (Andrady and Neal, 2009; COM, 2018). As represented in **Figure 1**, production of plastics worldwide has increased two hundred times from 1.5 million tonnes per year in 1950 to an estimated 348 million tonnes by 2017 (Plastics Europe, 2018), predicted to double within 20 years and nearly quadruple by 2050 (MacArthur, 2017), if current trends remain unchanged.

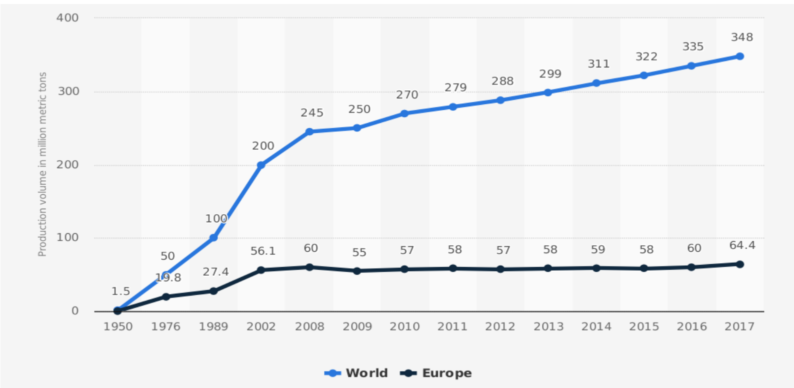


Figure 1 - Production of plastics worldwide from 1950 to 2018 in million metric tons (Statista, 2019)

Cumulatively, it was estimated that by 2015 the total amount of plastic ever manufactured in the word transcended 7.8 billion tonnes, from which nearly half has been made since 2000 (Geyer *et al.*, 2017). Today half of the world’s plastics are produced in Asia. China alone is the largest producer, accounting for 30% of the global production volume, followed by NAFTA (18%) and Europe (17%) (Plastics Europe, 2019). Although plastics production in the European Union (EU) has been stable in recent years, its share of the global market is falling as production grows in other parts of the world (COM, 2018).

Driven mainly by the packaging industry, in the past half-century the rate of plastic production has broadly outweighed that of any other material, accelerated by a global shift towards single use plastics (UNEP, 2018). In addition, the industrial use sector and polymer type also undergone a significant shift as a consequence of the different product lifetimes (Geyer *et al*., 2017). By comparing both graphic representations presented in **Figure 2**, the plastic waste generation by industry sector is not directly reflected by the primary plastic production, since this is also influenced by the lifetime of the end product (Ritchie and Roser, 2018). The majority of the packaging plastics lifetime ends within the same year they are manufactured, while plastics used in building and construction hold lifetime means of over 30 years. To this extent, those currently entering the waste generation, were produced decades earlier when production volumes were inferior.

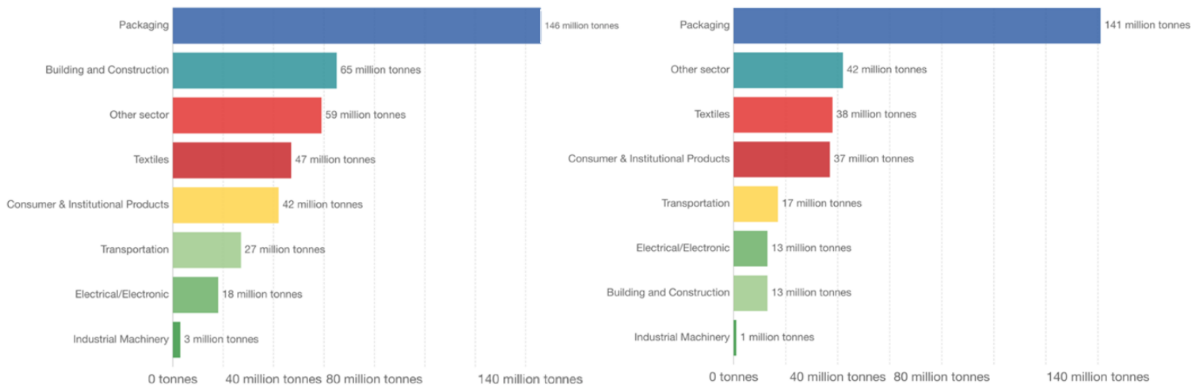


Figure 2 - Primary global plastic production and global plastic waste generation by industrial sector in 2015 (from left to right) (Ritchie and Roser, 2018)

The left side of **Figure 2** reveals that globally 42% of the plastic polymers produced in 2015 were used for packaging, followed by the building and construction sector comprising 19% of production. The former also generated the most waste (54%), reflecting its short lifetime, in contrast with the 5% plastic waste from the latter, as shown on the right of **Figure 2**. Roughly 75% of all plastic produced by the end of 2015, was converted into waste in the same year (Geyer *et al*., 2017). As a consequence, plastics production has grown remarkably over the last 60 years. Nevertheless, several environmental problems arise from their current levels of consumption and disposal (Hopewell *et al*, 2009), as the next sections will illustrate.

2.1.2 | Plastic Waste Management

Numerous are the challenges relating to littering and the end-of-life methods for plastic waste, comprehended in three main waste management strategies. These are recycling, landfilling and thermal destruction through incineration.

According to Jambeck *et al.* (2015), “We will not reach a global “peak waste” before 2100”, as humanity’s waste is expected to continue growing associated with increased population and increased per capita consumption coupled with economic growth. In addition, plastics life expectancy in the environment is not yet certainly known since it has only been mass-produced for about 60 years. The fact that most plastics are not biodegradable, coupled with their extreme durability, means that most of today's manufactured polymers will prevail in the environment for at least decades, if not centuries (Hopewell *et al*., 2009). Each year, the EU generates approximately 29.1 million tonnes of post-consumer plastic waste, from which less than 32.5% is collected for recycling. Of this share, 19% is captivated to be treated in countries outside the EU, where less tight environmental standards and cheaper processing fees are applied. Simultaneously, there has been a decrease in landfill and a growth in energy recovery over the past decade, although rates remain high at 24.9 and 42.6%, respectively. (Plastics Europe, 2019; COM, 2018).

Every plastic ever produced must be disposed of, therefore recycling delays this fate. It only reduces overall waste if and to the extent it displaces primary production. However, there are main issues when comparing recycled products to their unrecycled counterpart. Due to the diversity of raw materials and contamination of polymer types, the recycling process gets costly and generates materials of limited technical value (Geyer *et al*., 2017). As a consequence, the demand for recycled plastics accounts for only 6% of the total plastics demand in Europe (COM, 2018), implying substantial losses for the economy as well as for the environment. The second waste treatment method involves thermal destruction of the material, being in some cases viable to recover energy from the incineration process. Although reducing the need for landfills, this process can release hazardous substances into the atmosphere and therefore should be executed out under controlled and regulated conditions (Hopewell *et al*., 2009; Ritchie and Roser, 2018). Finally, plastics can be discarded. Since none of the conventionally used plastics are biodegradable, they widely pile up in landfills or in the natural environment (Geyer *et al*., 2017). In this context, there has been an increasing concern associated with the natural environment contamination. According to researchers, between 1.5 to 4% of global plastic production entering the marine environment every year, which corresponds to 5–13 million tonnes of plastic (Geyer *et al*., 2017). The main components of terrestrial and marine plastic litter are films (dominated by LDPE), which are the easiest items to escape containment transported by wind, alongside with disposed fishing equipment and food and beverage packaging (Hopewell *et al*., 2009). **Figure 3** illustrates global plastic production and its course to its ultimate fate from 1950 to 2015.

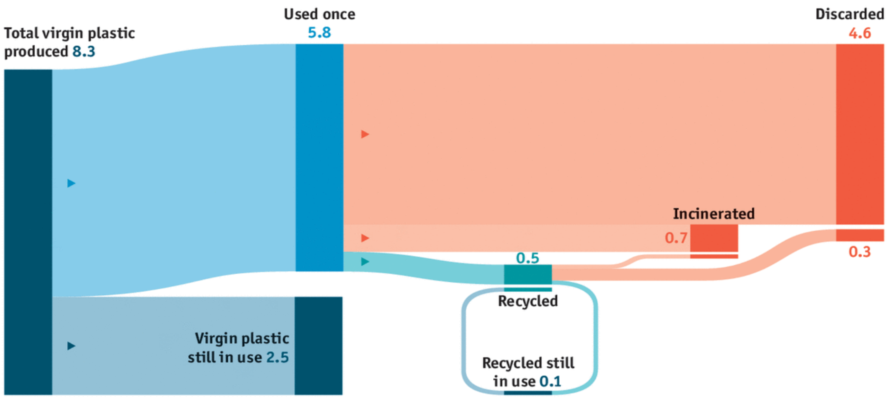


Figure 3 - Global plastic production and use in billion tonnes, from 1950 to 2016 (Geyer et al., 2017)

During this period the total amount of primary plastic produced including polymers, synthetic fibers, and additives accounted 8.3 billion tonnes, from which nearly 30% is still in use. The cumulative amount of solid plastic waste produced since the 1950s that has not been burned or recycled is at 4.9bn tonnes, meaning that more than half of all the plastic ever made was sent to landfills or discarded; 8% incinerated and 6% recycled, of which 1,2% is still in use, 1,2% was later incinerated and 3,6% was later discarded or sent to landfill. Only 9% of the world's plastic has been recycled from the 5.8 billion tonnes of primary plastic no longer in use (Geyer *et al*., 2017).

2.1.3 | Plastic Pollution

The same unique properties that make plastics suitable for such a broad range of products also account for the massive pollution nowadays. Its growth has far exceeded the capacity of waste management to sustain (Parker, 2018). In addition, the fact that none of today's mass-produced plastics is biodegradable leads to a chain of externalities that has long been the subject of environmental scrutiny (Geyer *et al*., 2017). These externalities are condensed in three main focus areas: *(1) natural systems degradation as a result of mismanaged waste, (2) greenhouse gas emissions derived from plastic production and incineration, and (3) health and environmental impacts from substances of concern.* (MacArthur, 2016). Plastic pollution emerges from both terrestrial and marine environments, supported via two means: intentionally, through illegal or inappropriate discharge; and accidentally, as a result of poorly contained waste. Carried by the elements, on shore plastic litter migrates to waterways, where it gets added, adjacent to the disposal from marine vessels and offshore petroleum platforms (Webb *et al*., 2013). According to estimates, the current pace of plastics leakage into the ocean is equivalent to dumping on it the contents of one garbage truck per minute, conjectured to increase to two per minute by 2030 and four per minute by 2050. The major share of outflow is represented by packaging, fuelled by the exacerbated consumption 'single-use' plastics destined to being littered after one brief utilization and hardly ever recycled. Aside from being the largest application of plastics polymers with about half of total plastic industry volumes internationally, packaging also encompasses 62% of all items collected in worldwide coastal clean-up operations (MacArthur, 2016; COM, 2018). It is observable that high-income countries, including most of Europe, North America, Australia, New Zealand, Japan and South Korea have effective waste management infrastructure and systems, storing its discarded waste into securely closed landfills. On the contrary, there is a high rate of inadequately disposed waste across low-to-middle-income countries in South Asia and Sub-Saharan Africa, which dispose deficiently 80 to 90% of plastic (Richie and Roser, 2018). However, the wealthier nations also take place on exacerbating this current waste status, as for decades they have been exporting most of their plastic waste (70% in 2016) to less developed countries in the East Asia and Pacific (Brooks *et al*., 2018). In 2010, five countries alone were generating half of the world's mismanaged plastic waste: China, Indonesia, the Philippines, Vietnam, and Sri Lanka, where fast economic growth is occurring but with underdeveloped or non-existent waste collection systems. According to an estimate by Jambeck *et al*., (2015), if there were merely 50% increase in adequate waste management infrastructures in the 20 top-ranked countries, the volume of mismanaged plastic waste would decrease 41% by 2025, dropping to 26% if applied to the top 5. As a consequence, contamination of the marine environment by synthetic fibbers of plastic waste generated on land entering the ocean is now a serious concern, as plastic debris has been found in all major ocean basins (Geyer *et al*., 2017). In its original form they can remain in the ocean for hundreds of years and even longer when fragmented (MacArthur, 2016) into minuscule particles that even small marine invertebrates may ingest (Jambeck *et al*., 2015). **Figure 4** highlights the weight that East Asia and the Pacific region have on the global mismanaged plastic waste, occupying a colossal share of 60%

in 2010. China exclusively is responsible for nearly one third (Geyer *et al*., 2018), which is the outcome of being the world's plastic waste primary importer, making up 45.1% of all cumulative imports its reporting began in 1992. Nevertheless, in 2017, China established a permanent ban on the import of non-industrial plastic waste that is estimated to allow the displacement of 111 million tonnes of plastic waste by 2030. Since elsewhere infrastructures are insufficient to manage the discharged waste, this policy raised the question of where it would go now. For the countries initially exporting the most plastic waste, this can also be used as an opportunity to develop and expand internal markets (Brooks *et al*., 2018). Accordingly, in the 2025 scenario shown in **Figure 4**, the rate of mismanaged plastic waste will stabilize across East Asia and Pacific, to the detriment of increasing it in the surrounding regions of South Asia or across Sub-Saharan Africa.

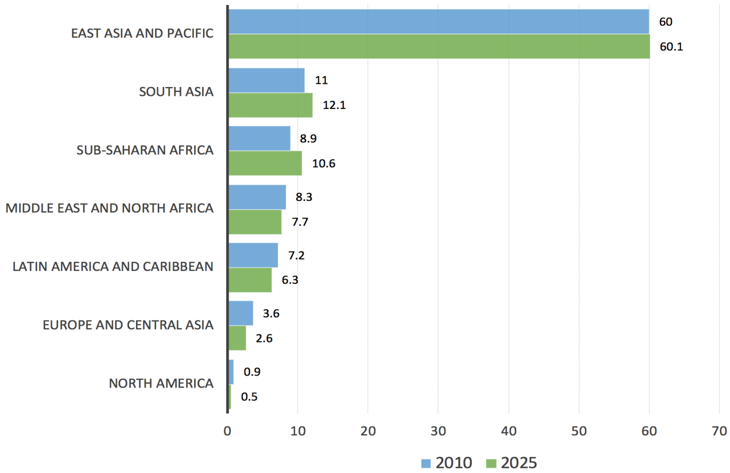


Figure 4 - Global mismanaged waste by region, in 2010 and 2025 (Geyer et al., 2017).

Another significant concern regarding plastics is the increasing greenhouse gas footprint associated with their production and end life path. Beyond 90% of plastics originate from non-renewable fossil feedstocks, with increasingly carbon impact as consumption surges. Given this projected growth, in 2050 the entire industry will account for 20% of total oil production and 5% of the annual carbon budget, while in 2014 plastics production and after use incineration were already taking 6% of global oil consumption and 1% of the annual carbon budget. The production stage represents the major contribution on the carbon burden as it requires about half of the total fossil feedstocks allocated to the plastic industry. Upon the end-life of plastics the carbon trapped inside the material is then released into the atmosphere either by incineration or through leakage over many years when sequestrated in landfills (MacArthur, 2016). Lastly, the leaching of chemicals from plastic and their potential to be transferred to both humans and wildlife need to be addressed (Thompson *et al.*, 2009). Many mass-produced products are composed of complex blends of stabilisers, plasticisers and pigments (MacArthur, 2016). Additives of high production volumes and wide usage as bisphenol A (BPA) and certain phthalates are of particular concern, to a degree that, since they leach out of products due to not being chemically bound to the plastic matrix. For instance, these substances form a substantial proportion, by weight, of Polyvinyl Chloride (PVC) where they are used as plasticisers (Thompson *et al.*, 2009). As a consequence, some regulators and businesses have already been acting upon the presence of BPA in the market since it proved to be hazardous for the hormonal and reproductive system (ClientEarth, 2019).

2.2 | Plastics Classification

There are two main categories of plastics: Thermoplastics and Thermosets, whose primary difference is their behaviour when reacting to the application of heat. The first category is responsible for 85% of total plastic demand in the EU (Deloitte, 2018) and exhibits reversible characteristics as it can be melted when heated and solidifies when cooled and therefore, can be repeatedly moulded (Plastics Europe, 2017). The former accounts for the remaining 15% of the EU's overall demand (Deloitte, 2018), undertaking chemical transformations when heated, which invalidates the ability to be re-melted and reformed after their initial shape (Plastics Europe, 2017).

At the urging of recyclers during the 1980s the Society of the Plastics Industry (SPI) developed the Resin Identification Code (RIC), through which bottles and containers are marked with a numeral from one to seven corresponding to a type of plastic resin. Plastics coding enables consumers, waste recovery facilities and other stakeholders to more properly sort articles prior to recycling. By facilitating this quality control sorting process, the RIC system drives more effective recycling efforts while also ensuring that the recycled plastic is as homogenous as possible. ASTM D7611 currently provides codes for the six most commonly found resin types, with a seventh category created for all other types (Clauson, 2013). These categories are shown and explained in **Table 1**.

Table 1 - Plastics classification summary table

Type of plastic	**Properties (ACC, 2019; RDC, 2019)**	**Applications** Virgin Grades **(Suez, 2019)**	**Applications** Recycled grades Major use / minor use **(Suez, 2019)**	**Recyclable (RDC, 2019)**
1 PETE **Polyethylene Terephthalate**	• Clear, tough, and has good gas and moisture barrier properties. • High impact capability and shatter resistance • Solvent resistant • Capability for hot filling	Carbonated soft drink bottles, fruit juice bottles, pillow and sleeping bag filling, textile fibres	**BEVERAGE BOTTLES** Clothing, geo-textiles, bottles for detergents etc., laminated sheets, clear packaging film, carpet fibres	**Yes** Commonly recycled
2 HDPE **High-density Polyethylene**	• Excellent moisture barrier properties • Excellent chemical resistance • Hard to semi-flexible and strong • Well suited to packaging products with a short shelf life • Never safe to reuse an HDPE bottle as a food or drink container if it didn't originally contain food or drink	Crinkly shopping bags, freezer bags, milk bottles, bleach bottles, buckets, rigid agricultural pipe, milk crates	**FILM, BLOW MOULDED CONTAINERS** Agricultural pipes, pallets, bins for compost and kerbside collections, extruded sheet, crates, garden edging, household bags, oil containers, pallets	**Yes** Commonly recycled
3 V **Polyvinyl Chloride**	• Good chemical resistance, weatherability, flow characteristics and stable electrical properties. • High impact strength, brilliant clarity, excellent processing performance • Can leach a number of hazardous toxic fumes • Poor heat stability	Electrical conduit, plumbing pipes and fittings, blister packs, clear cordial and fruit juice bottles	**PIPE, FLOORING** Pipe and hose fittings, garden hose, electrical conduit, shoes, road cone bases, drainage pipes, electrical conduit and ducting, detergent bottles	**Sometimes** Recyclable at special points

Type of plastic	Properties (ACC, 2019; RDC, 2019)	Applications Virgin Grades **(Suez, 2019)**	Applications Recycled grades Major use / minor use **(Suez, 2019)**	Recyclable (RDC, 2019)
4 LDPE **Low-density Polyethylene**	• Toughness, flexibility and relative transparency, particularly suitable for packaging where heat sealing is required • Good moisture barrier properties • Rated as less toxic and safe for use, when compared with other plastics	Garbage bags, squeeze bottles, black irrigation tube, silage and mulch films, garbage bins	**FILMS: BUILDERS, CONCRETE LINING AND BAGS.** Agricultural pipe, nursery and other films	**Sometimes** Recyclable at special points
5 PP **Polypropylene**	• Excellent chemical resistance • Hard, but flexible • Strong and can withstand higher temperatures	Film, carpet fibre, appliances, automotive, toys, housewares, crates, palls, bottles, caps and closures, furniture, rigid packaging	**CRATES, BOXES, PLANT POTS** Compost bins, garden edging, irrigation fittings, building panels	**Yes** Not widely recycled
6 PS **Polystyrene**	• Excellent moisture barrier for short shelf life products • Excellent optical clarity in general purpose form • General purpose PS is clear, hard and brittle • Relatively low melting point	Refrigerator bins & crispers, stationery accessories, coat hangers, medical disposables. Meat and poultry trays, yoghurt and dairy containers, vending cups	**INDUSTRIAL PACKAGING, COAT HANGERS, CONCRETE REINFORCING CHAIRS** Moulded products, coat hangers, office accessories, spools, rulers, video cases and printer cartridges	**Yes** Commonly recycled
7 OTHER	This code indicates that a package is made with a resin other than the six listed above or is made of multi materials (laminates) acrylonitrile butadiene styrene (ABS), acrylic, nylon, polyurethane (PU), polycarbonates (PC) and phenolics	Automotive, aircraft and boating, furniture, electrical and medical parts	**AGRICULTURAL PIPING** Furniture fittings, wheels and castors. Fence posts, pallets, outdoor furniture and marine structures.	**No** Nearly impossible due to risk of contamination of recycling

In general, plastics with recycling symbol #2, #4 and #5 are generally considered safe and have low risk of leaching. Plastics in categories #1, #3, #6 and #7 should be cautiously used, especially with food or drink. Of these, #1 PET is less alarming, but needs to be stored in cool environments and should not be reused. #3 PVC (commonly labelled it as the “poison plastic”) and #6 PS leach potentially a number of hazardous toxic fumes specially when melted or subject to heat (Pochepetskyi, 2020). Plastic #7 is of primary concern due to being associated with BPA leaching into food or drink products packaged in PC containers (Eartheasy, 2020). There are no standards and protocols regarding reuse and recycling is nearly impossible since it requires high temperatures to break it down and most curbside recycling programs do not accept it (Eartheasy, 2020; QLP, 2020).

2.3 | Manufacturing Landscape

2.3.1 | Packaging Industry

Despite 40 years having passed since the launch of the first universal recycling symbol, today only 5% of after-use plastic packaging material value is retained for a subsequent use (Ellen MacArthur, 2016).

This highlights the significant potential to capture greater value by radically improving recycling and by compounding action and innovation across the global value chain (MacArthur, 2017). According to the Ellen MacArthur Foundation, these set of actions are based on three major insights (1) *Without fundamental redesign and innovation, about 30% of plastic packaging will never be reused or recycled*, (2) *For at least 20% of plastic packaging, reuse provides an economically attractive opportunity* and (3) *With concerted efforts on design and after-use systems, recycling would be economically attractive for the remaining 50% of plastic packaging*. The first insight, the one that will be further explored in detail, comprises four packaging segments (small-format, multi-material, uncommon plastic and nutrient contaminated packaging) that represent at least half of the plastic packaging items and roughly 30% of the total market by weight. Since these packaging types currently have no viable reuse or recycling pathway, a combination of redesign and innovation of materials, formats, delivery models and after-use systems are required. For small-format plastic packaging items, the potential of format redesign is represented in the classic example of beverage cans where the tear-off tab, a small-format element, laborious to collect and prone to leakage, was replaced by the stay-on tab. Redesigning a delivery-model could entail the use of reusable or returnable packaging items, for instance sachets in shops could be replaced by a dispenser (MacArthur, 2017). The Disappearing Package (TDP) is another illustration of the potential do supplant billions of small format items being used by redesigning the packaging concept that answered the question “Can waste be entirely eliminated?”. The TDP consists of a package itself that is a sheet of laundry water soluble pods stitched together creating a sheet, so the consumer can tear off each pod and use one at a time. With the last pod, the package itself is gone (TDP, 2020). Since redesign efforts take time and might not be applicable to all small-format items, another potential solution may involve designing it with compostable materials (MacArthur, 2017). For multi-material packaging, the innovations would need to explore both material and reprocessing technology. The different material layers can be replaced by recyclable mono-material while maintaining the same functionalities, which generates more suitable for recycling packages. Ellen MacArthur (2017) highlights two notable innovation in reprocessing technologies, that although they currently only exist at pilot scale, can provide viable after-use pathways with a closed-material loop for currently unrecyclable multi-material packaging. These are thermochemical recycling, such as pyrolysis, and disassembly of multi-material laminates. Regarding the use of uncommon materials PVC, PS, and EPS in packaging applications is already phasing out due to the increased pressure to adopt alternative solutions already in place. Finally, expanding the use of compostable materials for selected nutrient-contaminated applications would contribute to natural capital preservation by increasing the value capture of organic material through composting or anaerobic digestion.

The second insight aims to focus towards new delivery models based on reusable packaging. Such models could be viable for a wide range of consumer goods segments, including laundry liquid, home cleaning, bath and shower products as shown by Splosh (2020) and MyReplenish (2020), and to other products that mainly consist of water, such as sprays for lawn and garden use, pet-care products and even the beverage market, as demonstrated by Sodastream (2020) and MiO (2020). It is estimated that this model could lead to savings of 80%-90% for packaging material, 25%-50% for packaging cost, 85%-95% for transport cost. All together would represent an 80%-85% reduction in greenhouse gas emissions versus nowadays single use bottles. Lastly, the third insight mainly underlines the necessity to scale up high-quality recycling processes and develop and deploy innovative sorting mechanisms for post-consumer products, naturally accompanied by boosting demand for recycled plastics through voluntary commitments or policy instruments and explore other policy measures to support recycling (MacArthur, 2017). All in all, implementing changes in plastic packaging design has a direct and vital impact on the economics of collection, sorting and recycling. For consumer goods companies this design should consider three designing requirements (1) *Designing out contaminants*, (2) *Designing for more effective sorting* and (3) *Designing for easy dismantling* (MacArthur, 2013). Plastics with contaminants like colorants, plasticisers and stabilisers are difficult to recycle or contaminate existing recycling streams and some additives affect plastic's density which lead to unnecessary losses in float-sink sorting procedures (MacArthur, 2013). The value in the after-use system can also be achieved through a design that favours the shift from coloured or opaque materials to clear or light-coloured translucent materials (MacArthur, 2017). Sorting process can also be eased through avoiding the use of the carbon black pigment, as it is not detected by near-infra-red equipment, and large labels, as it can be mis-detected as the actual packaging material (MacArthur, 2013). An easy disassembly design can be achieved both by shaping format (closures and closure liners, valves, pumps, triggers, sleeves, labels, inks and glues) and polymer choice regarding not using multiple polymers or mixing different types of materials that cannot be separated in the same packaging type (MacArthur, 2017). Since this project aims to develop a zero-waste toothpaste packaging, the next section highlights the recent initiatives in this industry.

2.3.2 | Toothpaste Packaging

Toothpaste tubes have a substantially cylindrical tubular body portion, one end of which is sealed by the conventional method of folding and crimping, and the other involving a relatively rigid shoulder portion of generally conical configuration, that terminates in a nozzle portion from which the contents of the tube may be dispensed. The cap serves as the closure for the nozzle as well as the support for the toothpaste tube when in vertical position. These tubes are usually made of plastic, aluminum, or a plastic-aluminum composite made from sheets of plastic laminate and a layer of aluminum pressed together in a film, which makes them ineligible to be accepted at typical recycling facilities (Mazzoni, 2018). Since 2018 this paradigm has been changing since Colgate and TerraCyle partnered to develop *The Colgate® Oral Care Recycling Programme* as a free recycling solution for oral care products and packaging in the UK. Once these items are received by TerraCycle they are sorted out by composition, shredded and melted into hard plastic pellets that can be remoulded into new recycled products such as benches and construction applications, alleviating the need to manufacture new virgin plastics (Colgate-Palmolive Company, 2018). With a worldwide demand of up to 20 billion toothpaste tubes every year and being the world's top toothpaste player by market share, Colgate has a significant contribution to what arrives at the landfill (Holger, 2019). In that regard earlier this year, the company developed the industry-first new *Smile for Good* toothpaste exclusively made from HDPE, which is an already widely recycled plastic used in milk jugs and other plastic bottles. Along the five years the project took to reach its final result, HDPE alone was tested but it turned out to be too rigid. In order create a squeezable tube, different grades and thicknesses of HDPE laminate were combined into a tube that meets recycling standards, while protecting the product and compatible to the demands of high-speed production (Guzman and Ries, 2020). The product was inclusively recognized as the first recyclable toothpaste tube assessed by the entities that set recyclability standards for North America and Europe, APR (The Association of Plastic Recyclers) and RecyClass, respectively (PRN, 2020). Building on Colgate's ongoing efforts, the company has established that by 2025 intends to reach the goal of 100% recyclable, reusable or compostable packaging (Holger, 2019; Wood, 2020). One aspect of packaging that has not changed is that toothpaste tubes still come in cardboard boxes for the simple reason that it makes them easier to pack and stack (PN, 2015).

Accordingly, the packaging design follows the guidelines set by the Food and Drug Administration (FDA): "In terms of toothpaste packaging, the FDA is concerned with the toxicity of fluoride, an active ingredient in almost all toothpastes due to its proven cavity-fighting power. Thus, the Agency has placed a package size limitation on all dentifrice (toothpaste and tooth powder) products. According to the final monograph, such products may not contain more than 276 milligrams of total fluorine per package. This requirement is what keeps toothpaste tubes at their relatively small size. Additionally, the FDA also thought it important to avoid exposure of water and other moisture to certain toothpastes. Thus, all fluoride powdered toothpastes must be packaged in a tight container. This is defined in the section as a container that protects the contents from contamination by extraneous liquids, solids, or vapours, from loss of the article, and from efflorescence, deliquescence, or evaporation under ordinary conditions of handling, shipment, storage, and distribution. Such a container must also be capable of tight closure." (Sandier, 1997).

Mass-market Packaging Comparison

The mass-market toothpaste packaging comprehends 3 main material sets (1) Aluminium, (2) Plastic as PET or HDPE and (3) Plastic laminate (Laminate tubes are made of aluminium foil surrounded by layers of acrylic resin and PP on both sides). The respective pros and cons are shown in **Table 2.**

Table 2 - Pros and cons of the three main types of mass-market toothpaste tubes

	Aluminium	**Plastic**	**Plastic laminate**
Pros	Recyclable	Recyclable	Cheap
Cons	Cracks and splits cause the product to leak	None compared to aluminium and plastic laminate	Difficult to recycle

From a life-cycle cost perspective the aluminium and the laminate tubes options are equivalent. However, regarding the environmental performance, the life cycle energy takes into account greenhouse gas emission, acidification potential, carcinogen production, eutrophication, solid waste, air and water pollution (Orlini, 2015). A life cycle analysis (LCA) were conducted on both laminate and aluminium tubes, with two versions of the aluminium tube modelled (100% virgin aluminium and 50% recycled) revealed the results exhibited in **Figure 5.** The laminate tubes have the best environmental performance (37% less life cycle energy compared to aluminium tubes) while the 100% virgin aluminium tubes present the poorest environmental performances due to raw material extraction and production (Orlini, 2015).

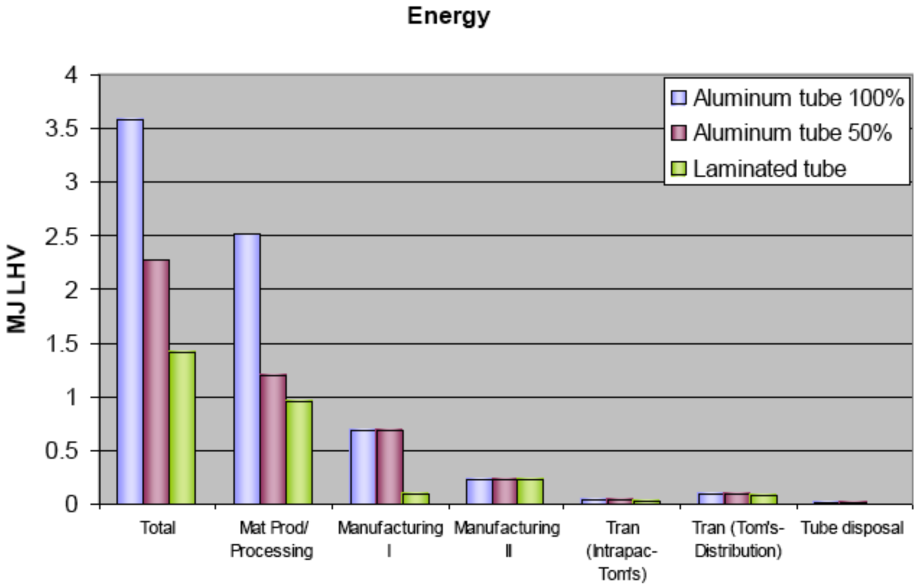


Figure 5 - Lifecycle Energy Resource comparison for 3 different types of toothpaste tubes (Orlini, 2015)

Sustainable Alternatives

An alternative toothpaste packaging using the Colgate brand as the object of study was born from an academic project by Allan Gomes to create a new design concept called the *Coolpaste*. The aim was to develop a sustainable design with redesigned physical and graphics features so that the packaging has less impact on the environment but allowing it to keep its durability while being transported or stacked on shelves. By eliminating the redundant paper box without affecting the integrity of the product, *Coolpaste* established a new standard in terms of sustainable packaging and eco-design as it allowed the product to be lighter, reduced waste, eliminated the chemical inks and simplified branding (Thukral, 2020; Lin, 2019). As shown in **Figure 6** the proposed prototype would hang instead of being stacked and with a not just merely recyclable but also biodegradable packaging (Thukral, 2020).

Figure 6 - Sustainable Packaging Design by Allan Gomes for the Federal University of Minas Gerais (Thukral, 2020)

Other toothpaste concepts that avoid plastic have been developed by several companies that can come as a solid block, in tablets or as a powder. The Miswak Plant, used by ancient Arabs to whiten and polish the teeth can be effectively used as a natural toothbrush for teeth cleaning with the advantage to be inexpensive and commonly available (Lafi and Ababneh, 1995). However, such alternatives can compromise the usability criteria when compared with the conventional toothpaste gel. The comparison between the classic toothpaste tube and other four alternatives available in the market are displayed in **Table 3**. The three parameters *(1) robustness, (2) logistics efficiency and (3) Ergonomic convenience* were classified on a 1-5 scale where 1 is the lowest and 5 is the highest score. The first comprises how willing the product is to suffer performance degradations when rapped, overloaded, dropped, and splashed (Taguchi and Clausing, 1990); the second describes how the product features and packaging affects the productivity, efficiency and cost of logistical operations, from truck loading and warehouse picking productivity, to customer productivity and packaging waste reduction; lastly, the third aspect is relative to ergonomic parameters that qualify the ease of handling and cleanliness of the options available (Kord and Pazirandeh, 2008).

Table 3 - Comparison between mass-market toothpaste and sustainable alternatives

No.	1	2	3	4	5
Description	Mass-market toothpaste tube	Glass Jar	Solid Toothpaste	Dental tabs	Miswak Plant
Format	Gel	Powder or gel	Solid unit in a wooden stick	Tablets	Stick
Primary Packaging	Plastic and aluminium layer pressed together + plastic lid	Glass jars + metal/plastic lid	Cardboard box	Paperboard packet (can be sold in bulk)	Plastic packet
Secondary Packaging	Cardboard box	Cardboard box	-	-	-
Robustness	● ● ● ● ●	● ●	● ●	● ● ● ●	● ●
Logistic Efficiency	● ● ● ●	●	● ● ●	● ● ● ● ●	● ● ● ● ●
Ergonomic convenience	● ● ● ● ●	● ●	● ●	● ● ●	●
Reusable package	✗	✓	✗	✗	✗
Recyclable package	✗	✓	✓	✓	✗
Pros	- Easy and convenient to use - Cheap	- Excellent barrier as Glass is chemically inert - Safer than plastic (that can melt and leak into food) - Environmental consciousness: completely recyclable and reusable	- Lasts longer than conventional toothpaste - Saves packaging material	- Formulated without water, they are smaller, lighter and easier to transport and ideal to travel with - Less packaging	- Renewable source - No need of toothpaste, toothbrush and large amounts of water - Great for traveling
Cons	- Difficult to recycle	- Toothbrush has to be dipped into the jar to apply the paste which works well for a single person, but if used by several people (for instance a family) entails a poor level of hygiene - Heavier and fragile packaging leads to lower efficiency and higher cost of logistical operations	- Lack of squeaky-clean feeling when compared with mass-market toothpastes - Storage is an issue - Not quite so solid toothpaste as it easily fragments	- More expensive than regular toothpaste - Not that easy to source, select retailers. - Initial taste	- Issues with keeping it in good quality. If kept it outside it dries out in 1-2 days and becomes unusable - Intense smell and flavour

2.4 | Problem Characterization

Plastic is undoubtedly the material that made modern life possible has made. Although versatile, cheap and useful, it has faced a noticeable shift in production throughout the years from durable and reusable plastics towards single-use and disposable products (Geyer *et al*., 2017). Plastic packaging encompasses plastics' largest application and encountered by virtually everyone daily (MacArthur, 2017). The short life span of these single-use plastics has led to a current take-make-dispose culture that is potentially one of the greatest challenges that the environment is facing (Geyer *et al*., 2017; Ritchie and Roser, 2018; UNEP, 2018). The toothpaste industry alone produces more than 20 billion tubes every year that are usually made of plastic laminate and aluminium, which is cheap and convenient to use. The small size, blended material and leftover toothpaste inside toothpaste tubes make recycling almost impossible (Mazzoni, 2018). Unrecyclable packaging doesn't just end up in landfills. It can get swept into waterways, which contributes to the growing problem of plastic pollution of the world's oceans and damages marine ecosystems. There is also emerging evidence that marine plastic can absorb and spread toxins through the marine food web, and possibly to humans (Geyer *et al*., 2017). The toothpaste is a product used every day, multiple times a day, whose tube packaging and linear process model hasn't changed in the last 50 years and therefore has to be discarded once it is empty. To cope with this mismanaged waste and unexploited recycling alternatives, this research focuses on toothpaste packaging re-design, in order to develop a circular product that beaks the old conception of the toothpaste. For this reason, it is necessary to understand the modifications required in terms of product design, process and supply chain, so that they can be fully integrated into the new generation of toothpaste packaging without compromising usability and durability criteria, while maintaining its efficiency, pleasurable texture and hygiene standards.

2.5 | Conclusions

Plastics extraordinary versatility, high resource efficiency, lightweight, low cost and resistance led to an exponential growth in plastic production over the last century. Mainly driven by the packaging industry, there has occurred a noticeable shift from durable and reusable plastic towards single use plastics, whose lifetime ends within the same year they are manufactured. Littering and the end-of-life methods for plastic waste comprehend recycling, landfilling and thermal destruction through incineration. Furthermore, the same unique properties that make plastics suitable for such a broad range of products also account for the massive pollution nowadays, which leads to a chain of externalities condensed in three groups *(1) natural systems degradation as a result of mismanaged waste, (2) greenhouse gas emissions derived from plastic production and incineration, and (3) health and environmental impacts from substances of concern.* Furthermore, a detailed analysis of the most common thermoplastics was presented and the manufacturing landscape for plastics main application, packaging, was described with a focal point on toothpaste packaging. There is a significant under-exploited potential to capture greater value in plastics that could be radically improved by recycling and compounding action and innovation across the global value chain. Accordingly, the full characterization of the problem was described, featuring the need to shift from the current linear process model of the toothpaste tube into a circular product concept through a fundamental packaging redesign.

3 | State of the Art

This chapter presents the theoretical background to address the problem identified in the previous chapter as well as the chosen methodology for the research. Section 3.1 summarizes the relevant insights on the Circular Economy as a pathway towards product sustainability and its evolution over time, reinforcing the relevance of business models and product design which will be used as foundations for the upcoming sections. Accordingly, section 3.2 analyses the Circular Business Models (CBM's) and introduces the areas of strategic decisions for businesses who want to move towards the CE. Moreover, in section 3.3 the process design methodology is presented. Subsection 3.3.1 is dedicated to deepening the understanding on the product design stage, by approaching the steps followed by an innovation from a concept to a fully specified state. Moreover, subsection 3.3.2 focuses on "Design for X" tools and subsection 3.3.3 specifies the Design for Environment, its benefits and impacts over the common product design process. Finally, an additional literature review is performed in section 3.4 dedicated to the methods and tools applied in the Design for Environment approach.

3.1 | Circular Economy

The Circular Economy (CE), also called 'closed loop' economy (De los Rios and Charnley, 2017), is perceived as representing the business operationalization of the concept of sustainable development, and has been gaining momentum across the globe since the late 1970s (Macarthur, 2013) as industries and economies are increasingly dealing with the catastrophic effects of pollution, global warming, and resource scarcity (Franco, 2019). Kenneth Boulding's (1966) article *The Economics of the Coming Spaceship Earth* describes a paradigm shift to a "spaceship economy", where everything is engineered to be constantly recycled, as a result of earth's perception of a closed and circular system with no unlimited resources and everything engineered to be continually recycled. Influenced by Boulding's (1966) work, the concept was primarily introduced Pearce and Turner (1990) in their *Economics of Natural Resources and the Environment*. The modern definition of the CE has been evolved to incorporate different features and contributions described in **Table 4**.

Table 4 - Relevant theoretical influences on the CE concept (Macarthur, 2013)

Author	School of thought	Definition
McDonough and Braungart (2007)	Cradle-to-Cradle	Focus on design for effectiveness in terms of products with positive impact, which differentiates it from the traditional design focus on reducing negative impacts. Products are ideally designed eases their disassembly and the recovery of their components, either to upgrade some elements or to use individual parts for the next generation.
Stahel (2010)	Performance economy	Pursues four main goals: product-life extension, long-life goods, reconditioning activities, and waste prevention. It also insists on the importance of selling services rather than products, an idea referred to as the 'functional service economy', now more widely subsumed into the notion of 'performance economy'.
Benyus (2002)	Biomimicry	Relies on 'innovation inspired by nature' and comprehends three key principles. (*1) Nature as model: E*mulate its forms, processes, systems, and strategies to solve human problems. *(2) Nature as measure:* Use an ecological standard to judge the sustainability of innovations. *(3) Nature as mentor:* View and value nature not based on what to extract from the natural world, but rather on what is possible learn from it.

Author	School of thought	Definition
Graedel and Allenby (1995)	Industrial Ecology	Also referred to as the 'science of sustainability', this framework adopts a systemic point of view, designing production processes in accordance with local ecological constraints whilst looking at their global impact from the outset, and attempting to shape them so they perform as close to living systems as possible.
Hawken *et al.* (1999)	Natural Capitalism	Describe a global economy in which business and environmental interests overlap, recognising the interdependencies that exist between the production and use of human-made capital and flows of natural capital, underpinned in four principles. *(1) Radically increase the productivity of natural resources. (2) Shift to biologically inspired production models and materials*. (*3) Move to a "service-and-flow" business model. (4) Reinvest in natural capital.*
Pauli (2010)	Blue Economy	According to the official manifesto, it is based on 'using the resources available in cascading systems, (…) the waste of one product becomes the input to create a new cash flow'. Built on 21 founding principles, solutions are determined by their local environment and physical/ecological characteristics, putting the emphasis on gravity as the primary source of energy.
Lyle (1996)	Regenerative Design	All systems can be orchestrated in a regenerative manner; or in other words, that processes themselves renew or regenerate the sources of energy and materials that they consume. As a consequence, daily activities are based on the value of living within the limits of available renewable resources without environmental degradation.

The CE definition that will be adopted throughout this dissertation is the one proposed by the Ellen Macarthur Foundation, of "an industrial economy that is restorative or regenerative by intention and design" (MacArthur, 2013). This approach is more comprehensive as it considers both the environmental and economic advantages of the CE (Lieder and Rashid, 2016), and highlights the role of design in the development of ease of reuse, disassembly and refurbishment products, with the understanding that the foundation of economic growth stands on recycling, through the reuse of far-reaching volumes of material recovered from end of-life products, rather than the continuous extraction of resources on a take-make-dispose system (Macarthur, 2013).

Four principles of the CE were outlined by the MacArthur (2013) as points of action to eradicate negligent resource depletion and strengthen existing material value in industry *(1) Optimise the use of resources and energy throughout lifecycles, (2) Maintain products and components in use for longer, (3) Materials cycle through the system as many times as possible through cascaded uses (4) Utilise pure materials for improving quality of post-life use.* It is within this context that the circular economy acts as a pathway to product sustainability. Therefore, it becomes vital for product manufacturers to consider *(1) business models* and *(2) product design* in the development of truly circular industrial systems. While the first focus on the way products are commercialized and consumed, product design is mostly concerned in potentializing materials value at any point in their lifecycles (Franco, 2019). The following two sections present the relationship between these two concepts and the CE.

3.2 | Circular Business Models (CBM's)

CBM's are positioned at the core of the CE and integrate an essential prerequisite for its dissemination as they "enable economically viable ways to continually reuse products and materials" (Bocken *et al.*, 2016). Moreover, CBM innovation enables organizations outpace common sustainable business models that focus only on efficiency, productivity, and greening the supply chain (Franco, 2019). Nowadays, the central element of a CBM is its value proposition (Lewandowski, 2016). **Figure 7** displays a ReSOLVE framework developed by Ellen Macarthur Foundation (2015), composed of six business actions (1) Regenerate, (2) Share, (3) Optimise, (4) Loop, (5) Virtualise and (6) Exchange, that converts the principles of circular economy into the above mentioned value-centred propositions.

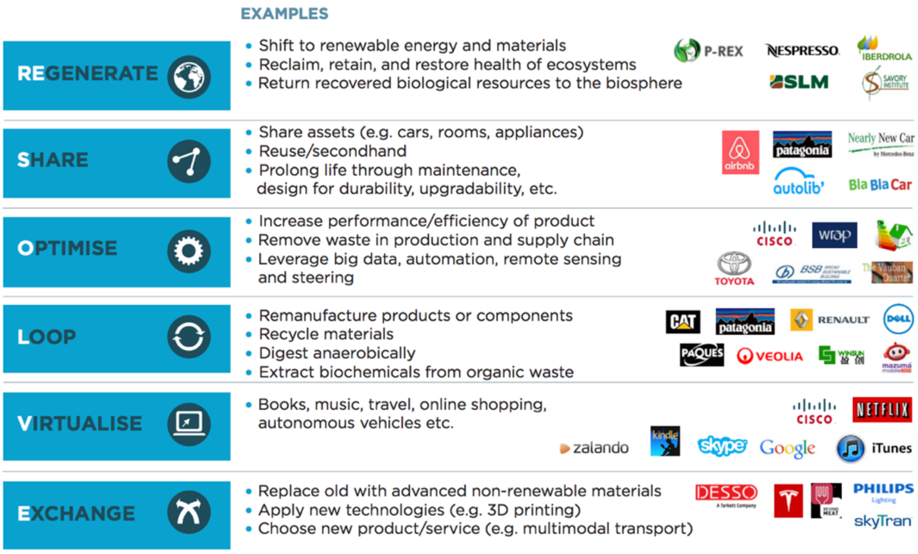


Figure 7 - ReSOLVE framework six action areas for businesses who want to move towards the CE, with examples for each principle (MacArthur, 2015)

Regenerate aims at returning resources to the biosphere by shifting to renewable sources of energy and materials; *Share* to keep product loop speed low and maximise utilisation of products; *Optimise* to increase performance and remove waste in production and the supply chain; *Loop* to keep components and materials in closed loops and prioritise inner loops; *Virtualise* to deliver utility virtually, when possible; and *Exchange* to Replace to apply new materials, services and technologies (e.g. 3D printing) (MacArthur, 2015). The design of a product will be highly impacted by these strategic decisions either on the choice of product life scenarios and of business model. By way of illustration, designing a product that is meant to be leased and refurbished multiple times during its lifetime will demand designers to have a profound understanding of how the product and its parts behave on the aging process, and of how to determine which parts should last, and which should be replaced, and when (Bakker *et al*., 2014). At last, it is crucial that, in the long run, this design research of the new CBM's and "circular products" deliver solutions with a lower environmental impact. For instance, a scenario of reverse logistics may require a considerable amount of extra service kilometres and new parts needing to be produced, reason why scenario-based life cycle assessment is always recommended to a assess whether the benefits of a circular business model outweigh the negatives (Bakker *et al*., 2014).

3.3 | Product Design

Product design aims to design an aesthetically pleasing, well performing and reliable product during its lifetime, which meet or exceed customers expectations, while enabling it to be easily and quickly manufactured. Design includes determining three key issues *(1) the concept, (2) package and (3) process implied by the design*. However, not all new products imply a radical innovation through completely new knowledge or resources. Rather, some simply entail incremental innovations leading to smaller, continuous changes (Slack *et al*., 2007). In addition, the economic systems coupled with increasingly competitive markets, makes the configuration of the products no longer exclusively guided by the needs of the users, but also affected by the competition that may adopt a strategy of product differentiation, copy of existing products or cooperation with competitors (Löbach, 2001).

The design activity is itself a process that requires a number of steps on the path followed by an innovation from a concept to a fully specified state, moving from the *(1) concept generation* stage to a *(2) screening* stage, *(3)* a *preliminary design* stage that produces a design to be *(4) evaluated and improved*, before reaching the *(5) prototype and final design*. In the first stage an idea is transformed into a concept with an overall specification for its design, comprised of the activities shown in **Figure 8**.

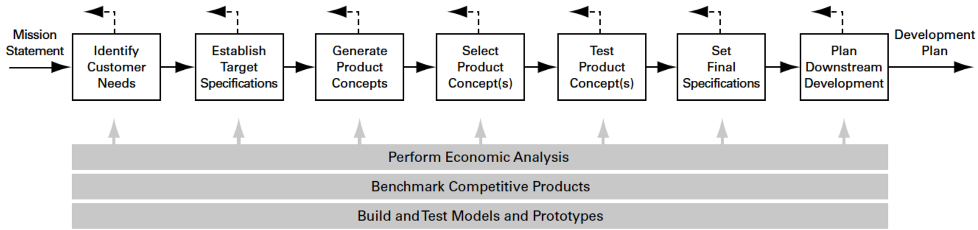


Figure 8 - Activities comprising the concept development phase (Ulrich and Eppinger, 2012)

Firstly, the target market needs are identified and hierarchically ordered to produce a fully constructed statement, showing importance weightings for many or all of the needs. Next, the target specifications provide specific description of what a product has to do, translating the customer need into technical terms. With the previous specifications several product concepts are generated by including a mix of external search, creative problem solving within the team, and structured exploration of the spectrum of solution fragments the team generates. As a result, this activity delivers a set of 10 to 20 concepts usually in the form of sketches and short descriptive texts. On the subsequent stage, the different product concepts are examined and consecutively excluded to identify the most promising one. Afterward, the chosen concept is verified to ensure that the customer needs have been met, assess the product's market potential and identify possible shortcomings that may arise during later development. Ultimately, the target specifications set earlier are revised after the selection and testing of the concept, giving rise to the final specifications. At this point, the team must have the adequate values of the metrics that reflect the intrinsic constraints of the product concept, its cost-performance trade-offs and the limitations identified through technical modelling. The project planning stage involves creating a detailed development schedule that formulates a strategy to captures the required resources to complete the project and the minimum associated development time (Ulrich and Eppinger, 2012). Screening the concept takes place afterwards to ensure that the product is a logical integration to the company's portfolio (Slack *et al.,* 2007). As support tasks, it is relevant to perform both an economic analysis and a benchmarking of competitive products. The first support task is used to validate continuity of the overall development program and to resolve specific cost trade-offs, whereas the understanding of the second is crucial to prosperous positioning of a new product and can provide an abundant source of ideas and insight for possible improvements for the design of both the product and production process (Ulrich and Eppinger, 2012). The Quality Function Deployment (QFD) and the Pugh Matrix (PM) are two simple and fast concept selection methods based on decision matrices. The QFD is used during the problem definition phase to transfer customer requirements (CR) into specification before manufacturing. This tool ensures that there is an accurate translation of CR into pertinent technical requirements during each stage of the product development process (Kuo *et al*., 2001). Developed by the Kobe Dockyard of

Mitsubishi Heavy Industries and widely used by Toyota (Chan and Wu, 2002), the QFD (also known as the 'house of quality' because of its shape) is a matrix that tries to capture and establish a relationship between what the customer needs and how it might be achieved. To do so, the matrix identifies and scores CR (whats), identifies the design characteristics of the product which will operationalize CR (hows) and represents a view of the interrelationship between the *whats* and *hows*. In addition, the matrix represents the ranked relative importance of each design characteristic as well, the degree of technical difficulty and the correlations between the various design characteristics (Slack et al., 2007). Similarly, the PM developed by Stuart Pugh relies upon a series of pairwise comparisons between design candidates against a number of criteria or requirements, leading ultimately to which best meets that set of criteria. One its key advantages over other decision-making tools is its ability to handle a large number of decision criteria. An adaptation for a weighted decision matrix can be made, operating in the same way as the basic PM but introduces the concept of weighting the criteria in order of importance (Burge, 2009). Having generated an acceptable, feasible and viable product concept, the next stage is to create a preliminary design, turning it into a manufacturable product (Slack *et al*., 2007). In this stage all the product's component parts and the way they articulate are identified, often using component structures and flow charts as support tools. To do so, the decision falls on the multitude of elements shown in **Figure 9**, which include the product's form, materials, and the production techniques (Ullman, 2010). The form of the product is defined by spatial constraints that provide the envelope on how components are configured relative to each other and how they are connected to each other so that they work together to achieve the desired function and better fit within the manufacturing specifications. The manufacturing method is kept in mind the whole time during the development process, so that the components can be designed to fit with that process, and vice versa. This can be chosen either from the price and precision levels which the component needs to be fabricated and is largely influenced by the quantity of the product to be manufactured, since it is difficult to justify high tooling costs for a product that will be built only once. Injection moulding is the case in this regard, in which plastic components are only cost-effective if the production reaches at least 15,000 units. Otherwise, the component cost for low-volume production is almost entirely determined by the mould cost. Regarding material selection, its availability is the most constraining point. Finally, these last two elements of product design are undoubtedly influenced by the prior-use knowledge for similar applications (Ullman, 2010). The resulting design is then subject to an evaluation stage, which involves re-examining the design (Slack *et al*., 2007) based on several DfX tools (Ullman, 2010), traditionally used to maintain or improve product quality. In an effort to create a more sustainable society, further tools that have the same benefits while simultaneously aim to reduce environmental impacts were developed (Ulrich and Eppinger, 2012), which will be presented further in section 3.4.

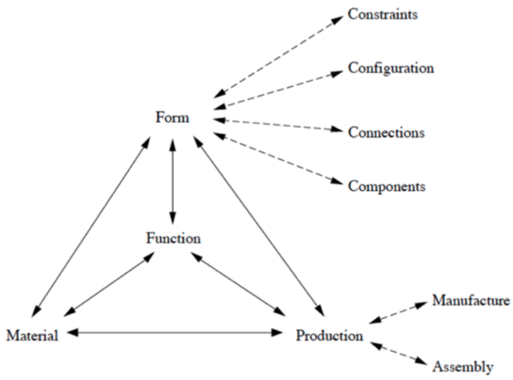


Figure 9 - Basic elements of product design (Ullman, 2010)

Similarly, Deloitte (2019) prosed the UNLEASH Innovation Process that is meant to advance ideas and solutions through the innovation process, ultimately leading to the implementation of solutions that can help address the Sustainable Development Goals (SDGs). This process comprises five phases that are closely linked with the design stages presented above *(1) Problem Framing, (2) Ideation and Idea Selection, (3) Prototyping and Sketching, (4) Testing and Refining, and (5) Implementing.* For each stage a number of requirements and tools are proposed, as exhibited in **Table 5**.

Table 5 - UNLEAH Innovation Process (Deloitte, 2019)

1	**Problem Framing**	Develop a well-defined problem statement based on user / customer wants and actionable insights.	• Well-defined problem framing
			  • User, need, and insight
			• Problem Framing Tree
			• User Profiles
			  • User Profile Matrix - Survey

2	**Ideation and Idea Selection**	Come up with a multitude of ideas that address the problem framing. Down select ideas and choose one to focus on.	• Brainstorming • Value vs. complexity mapping • Stakeholder ecosystem mapping • Pugh chart • Market research on selected idea

3	**Prototyping and Sketching**	Create a tangible prototype of the idea, so that a potential user / customer can experience the proposed solution.	• Design specifications
			  o Desirability, business, and technical
			• Sketch modelling
			• Rapid prototyping
			  o Looks-like and/or works-like prototype
			• Prioritization of what assumptions to test
			  • Priority vs. confidence mapping
			• 3D Modelling - CAD

4	**Testing and Refining**	Get user / customer feedback on the prototype. Make changes to the solution. Evaluate if there is the need to go back to an earlier phase.	• Results of user and customer testing o Interviews, inquiries, focus groups • Finalized prototype

The Problem Framing comprises the first stage in the innovation process proposed by Deloitte (2019) where the aim is to “develop a well-defined problem statement based on user / customer wants and actionable insights”. During the initial stage of problem structuring when its definition is still complex and vague, problems and their inter-relationships can be identified, visualized and prioritized using the problem tree (Veselý, 2008; Ammani *et al.*, 2010). It represents a scheme of cause – effect relationships between problem conditions (Ammani *et al.*, 2010) and like every tree has its “stem”, “roots”, and “branches”. Its stem stands for the core problem, its roots are the causes and its branches form the problem’s effects (Veselý, 2008). As also introduced in Unleash by Deloitte (2019), the user should be at the centre of every step of the innovation process so that the solutions are grounded in a deep understanding of you’re the user’s wants and needs. Therefore, in this stage a user profile is developed based on the data collected from a survey performed to potential customers of the product. Surveys are very useful to collect standardized information instantly from a wide audience, irrespective of their geographical location, in a cost-effective way (Ilieva and Healey, 2002). This tool enables the gathering and comparison of information across different groups of stakeholders on an array of issues surrounding their behaviour, thoughts, and feelings (Buchanan and Hvizdak, 2009).

In this regard, User-centered design (UCD) is a broad term to describe design processes in which end-users influence how a design takes shape (Abras *et al.*, 2004). Whilst previously usability may have been qualified as a bonus, it is now an expectation with “users becoming disenchanted with products which do not support an adequate quality of use" (Jordan *et al.*, 1996, pp. 1). ISO 9241-11 has defined usability as the "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO, 2018). Effectiveness is defined as the "accuracy and completeness with which users achieve specified goals"; efficiency is defined as the "resources expended in relation to the accuracy and completeness with which users achieve those goals"; and satisfaction is defined as "freedom from discomfort, and positive attitudes towards the use of the product" (ISO, 2018). Despite the fact that the ISO definition does not consider other aspects, in *Usability Engineering*, Nielsen (1993) suggests five qualities of a usable product: learnability, efficiency, memorability, errors (low rate, easy to recover), and satisfaction. Learnability (also perceived as ease of learning) and memorability are measured through the time and effort required, respectively, to reach a determined level of use performance, and to return to that same specified level of use performance after a specified period away from the system (Petrie and Bevan, 2009). An error is defined as a "function performed by a user that does not lead to the aimed result" (Sippola, 2017), therefore a usable product should be clear enough so that the least possible errors are committed by users. Despite some errors occur repeatedly, its number can be minimized by good instructions, among other aspects. Satisfaction relies on how pleasing it is to use, which is an emotional facet of the user experience that correlates with the user's motivation and thus the effectiveness of use (Sippola, 2017). Later these concepts were condensed by Quesenbery (2004) into the 5Es of Usability – Effective, Efficient, Engaging, Error tolerant and Easy to learn. **Figure 10** displays the best-known iterative UCD process described in the ISO 9241-210 standard.

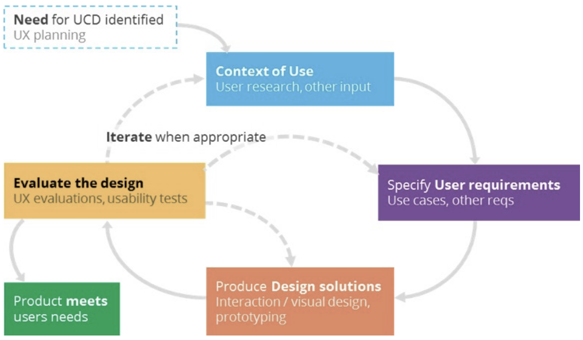


Figure 10 - UCD process according to the ISO 9241-210 standard (Sippola, 2017)

This process allows to determine what the needs and problems encountered by users are and when using a product. This ultimately allows to improve usability. The most common evaluation methods comprise usability testing with users where actual end users execute regular tasks with a finalized product or a prototype. Along with these tests, complementary data can be collected resorting to, for example, questionnaires, interviews and focus group discussions (Sippola, 2017). In an environmental benchmarking, products are rated in five categories - energy usage, environmentally relevant materials, end-of-life, material composition, and packaging (Rose, 2000).

Ultimately, the outcome of prototyping and final design stage is a completely developed specification for the package of products, together with a specification of the processes for their making and delivery to customers. All in all, process design and product design are interrelated. Small changes in the design of products and services can have profound implications for the way the operation eventually has to produce them. Similarly, the design of a process can constrains the freedom of product and service designers to operate as they would wish (Slack *et al*., 2007).

3.4 | Design for X

Formerly, engineering design was solely established upon the contemplation of product functionality. The design moved sequentially from the design department to the process-planning department and then to the manufacturing department, without any feedback given to the designer, which many times gave rise to an overly difficult product to manufacture with avoidable manufacturing costs. To solve this problem, the value engineering and producibility engineering approaches were put into use (Kuo *et al*., 2001). The first concept is primarily concerned with both function and cost of a product, while the second aims to guarantee that the available techniques, tooling, and test equipment can satisfy the product specifications at suitable costs with the product's selling price (Howell, 1982). However, three problems arise in the conventional manufacturing system while using this two concepts (1) *such optimization, if not carefully monitored, could be accomplished at the expense of product manufacturability*, (2) *implementation of value engineering is usually stated as a company policy but not strictly followed in a scientific manner; therefore, the most significant savings may not be achieved* and (3) *although value engineering and producibility engineering are highly valid methods in themselves, they enter into consideration too late in the traditional manufacturing system, i.e. after the product design has been completed* (Kuo *et al*., 2001). As time went by, the marketplace for manufactured products has become growingly competitive with forevermore selective customers. In the search for more productivity, efficiency and lesser environmental impacts product, design has integrated requirements from all fields affecting industrial corporations (Rose, 2000). Such changes entailed an expansion for product design, which means that optimizing the traditional functional requirements of the product, *i.e*. performance, is no longer enough to remain competitive in the market (Rose, 2000). The implementation of Design for Assembly (DfA) and Design for Manufacture (DfM) led to massive benefits counting simplification of products, reduction of assembly and manufacturing costs, improvement of quality, and reduction of time to market (Kuo *et al.*, 2001). DfM demands that the components best fit the design guidelines for a determined manufacturing process, that when followed result in consistent components and limited waste. DfA computes the overall efficiency of its assembly and the facility with which components can be retrieved, handled, and mated. For the majority of the products the assembly takes time and therefore it has an impact on cost, so the easier to assemble a product is, the more likely it will have a shorter cost (Ullman, 2010). More recently, the core concern has expanded to ensure that product excels in all other aspects that lead to customer satisfaction beyond cost, quality and reliability, as environmental impact concerns are requiring product designers consider to environment, recyclability, lifecycle, etc, issues during the design stages (Kuo *et al.*, 2001). Several methods aiming to integrate different aspects of the product's lifecycle when designing it, known as DfX methods, are already documented in literature. With the purpose of showing their complementary nature, Chiu and Kremer (2011) reviewed and organized the DfX methods in two main themes: design for efficiency and green design. Additionally, those methods were categorised into three ranges of perception (1) *product scope,* (2) *system scope*, and (3) *eco-system scope*, as overall evidenced in **Figure 11**.

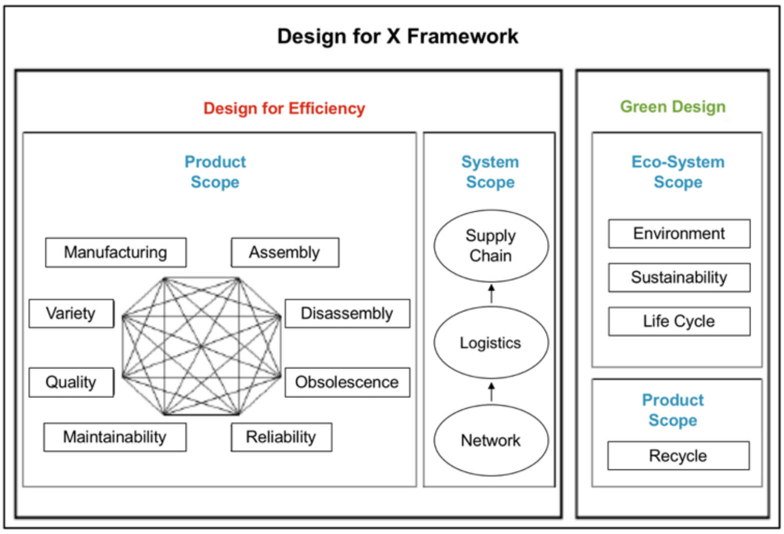


Figure 11 - Framework for Design for X Perspectives (Chiu and Kremer, 2011)

Efficiency is defined in this context as the ratio of useful design process output (e.g., designed artefact and the process itself) to the total input to the design process and the designed artefact (e.g., information, materials). Green design assumes as an underlying precondition the inclusion of natural system (Ogot and Kremer, 2004). Regarding efficiency, two ranges of perception were considered. The product scope covers DfM, DfA, design for variety (DfV), design for quality (DfQ), design for reliability (DfR), design for disassembly (DfD), design for maintainability (DfMa) and design for obsolescence (DfO), whereas the systems scope encompasses design for supply chain (DfSC), design for logistics (DfL) and design for network (DfN). Regarding green design category, the authors group design for recycle (DfRe), design for sustainability (DfS), design for environment (DfE), and design for life cycle (DfLC) (Chiu and Kremer, 2011). **Table 6** presents a literature overview on these concepts.

Table 6 - Literature overview on the DfX tools

DfX	Reference	Definition
DfM	Das *et al.*, (2000, p.457)	"An approach for designing a product so that (i) the design is quickly transitioned into production, (ii) the product is manufactured at a minimum cost, (iii) the product is manufactured with a minimum effort in terms of processing and handling requirements, and (iv) the manufactured product attains its designed level of quality."
	Kirkland (1988)	Designer's selection of a particular material is influenced by factors which includes (1) raw material selection, (2) process selection, (3) develop a modular design, (4) use standard components, (5) design parts to be multi-useable, (6) avoid separate fasteners, (7) minimizing assembly directions.
DfA	Ullman (2010, p.331)	"Measures a product in terms of the efficiency of its overall assembly and the ease with which components can be retrieved, handled, and mated. A product with high assembly efficiency has a few components that are easy to handle and virtually fall together during assembly."
	Boothroyd and Dewhurst (1986)	Based on the premise that the lowest assembly cost can be achieved by designing a product in such a way that it can be economically assembled by the most appropriate assembly system. In the assembly, two factors that influence the assembly cost of a product or subassembly: (1) the total number of parts, and (2) the ease of handling, insertion, and fastening of the part.
DfV	Chiu and Kremer, (2011)	Product and process designs that meet the market demand for product variety with the most appropriate balance of design modularity, component standardisation and product offerings.

DfX	Reference	Definition
DfQ	Crow (1983)	The objectives of are: (1) design of a product to meet customer requirements, (2) design of a robust product that can counter or minimize the effects of potential variation in manufacture of the product and the product's environment, and (3) continuously improve product reliability, performance, and technology to exceed customer expectations and offer supervisor value.
	Chiu and Kremer, (2011)	The QFD is an important technique to implement DfQ because QFD carefully considers the customer requirements and transfers them into specification before manufacturing, translating them into relevant technical requirements throughout each stage of the product development process.
DfR	AGREE (1957)	Reliability is defined as “the probability of a product performing without failure a specified function under given conditions for a given period of time”.
	Ireson and Coombs (1988)	Provided a list of guidelines for design for DfR which are (1) simplicity, (2) use of proven components and preferred designs, (3) stress and strength design, (4) redundancy, (5) local environment control, (6) identification and elimination of critical failure modes, (7) detection of impending failures, (8) preventive maintenance, (9) tolerance evaluation, and (10) human engineering.
DfD	Brennan, Gupta and Taleb (1994)	Defined disassembly as “the process of systematic removal of desirable constitute parts from an assembly while ensuring that there is no impairment of the parts due to the process”
	Harjula *et al*. (1996)	Pointed out that DfA method might be compatible with DfD after addition of environmental criteria such as ease of removal and selection of recyclable materials.
DfMa	Kapur and Lamberson (1977)	Defined maintainability as “the probability that a failed system can be repaired in a specific interval of downtime”. The basic objective of DFMa is to assure that the product can be maintained throughout its useful lifecycle at reasonable expense without any difficulty. Maintainability design guidelines describe qualitative product requirements (1) accessibility, (2) ability to detect and isolate failure, (3) weight limitations of replaceable units, (4) dimensional limits to allow replaceable units to be transported from their installed location to a repair shop or for shipment to their manufacturer's facility, and (5) design requirements to make replaceable units compatible with robots for removal and replacement in remote locations or hazardous environments.
DfO	Bulow (1986)	Designing a product with an artificially limited useful life, so that it becomes obsolete or no longer functional after a certain period of time, forcing consumers to purchase replacements
DfSC	Lee and Sasser (1995)	Aim of designing products and processes to more effectively manage supply-chain-related cost and performance. DfSC utilises product line structure, bill of materials and customisation processes of a product to optimise the logistics costs and customer service performance.
DfL	Mather (1992, p.7)	“… to delight the customer with product when needed”. He argued that some materials-related issues such as acquisition, storage, transportation and delivery resulting from product design cannot be solved by marketing and manufacturing techniques. Provided two DfL guidelines for logistically effective design to be applied during the detail design phase (1) replacing unique components necessitating long lead times with standard components through redesign. When such a redesign is not possible, (2) leaving the processing of unique components with long lead times to the final stages (e.g., form postponement).
	Dowlatshahi (1996)	Proposed that logistics engineering, manufacturing logistics, Design for Packaging (DfP) and Design for Transportability (DfT) should be reviewed concurrently while designing for logistics.
DfN	Maltzman *et al*. (2005)	It was first highlighted in the telecommunication industry and proposed as an extension for the DfM when the final product is a customised complex system. Described that the goal of DfN is to make a network more successful for both service providers and vendors, which meet or exceed the customer expectations. DfN focuses on improving processes, tools and components (i.e., network elements and software) hence the product considerations and network considerations are synchronically addressed

DfX	Reference	Definition
DfE	Fiksel and Wapman (1994)	Defined design DfE as "the systematic consideration, during new production and process development, of design issues associated with environmental safety and health over the full product life-cycle".
	Horvath *et al.*, (1995)	Stated three main goals of DfE: (1) minimize the use of non-renewable resources, (2) effectively manage renewable resources, and (3) minimize toxic release to the environment.
DfLC	Riggs and Jones (1990)	Based on the early product concept, including product/market research, design phases, manufacturing processes, qualification, reliability, customer service, maintainability, and supportability issues.
	Boothroyd and Alting (1992)	Distinguished six phases in the product lifecycle: (1) need recognition, (2) design development, (3) production, (4) distribution, (5) use, and (6) disposal.
	Huthwaite (1989)	During the product development, product manufacturing and product usage, there is a society cost incurred, including waste, pollution, and health damage.
DfRe	Chiu and Kremer, (2011)	Intends to utilise the value of product in the end-of-life phase using either non-destructive, or destructive recycling techniques. DfD-related methods can be used for non-destructive recycling purposes; to create maximum recyclability and a high content of recycled material in the product. Different materials should not be mixed, if not necessary; different parts should be labelled for easy separation of materials.

With ongoing challenges, experience has shown that the best approach to address the core problem is to improve the product instead of merely reacting to the symptoms. Therefore, it is preferred to improve first the source, or product, and only next examine the process. In this context, with DfX, tools the emphasis of the critical design decisions is shifted to the start of the development process (Rose, 2000). The following subsection will explore DfE in particular. When effective, DfE can have the same performance benefits as the common DfA or DfM tools, while simultaneously reducing environmental impacts (Ulrich and Eppinger, 2012).

3.4.1 | Design for Environment

Design strategies undertaking ecological challenges generally comprise a variety of concepts. According to Franco (2019) these include *product stewardship* (Hart, 1995), *green design* (Fullerton and Wu, 1998), DfE (Chen, 2001), *sustainability-driven product design* (Byggeth *et al*., 2007; McLennan, 2004), DfS (Arnette *et al*., 2014), *ecological product design* (EPD) (Hartmann and Germain, 2015), *eco-design* (Deutz *et al*., 2013), *cradle-to-cradle design* (Braungart *et al*., 2007), *and regenerative design* (Lyle, 1996). Despite authors have used distinct terminology for environmentally friendly design approaches, all of them are more or less equivalent today (Ulrich and Eppinger, 2012). These practices contribution towards sustainable manufacturing has grown during the past decades (Sanyé-Mengual *et al.*, 2014). DfE or eco-design aspire to develop environmentally compatible products and processes (Ramani *et al.*, 2010) to reduce lifecycle impacts while preserving performance standards and value for money (Holdway *et al*., 2002), considering such issues as business opportunities (Ramani *et al.*, 2010). DfE, an inherent constituent of the DfX paradigm, encompasses all life cycle phases from material extraction, manufacturing, transportation, usage and end-of-life (Rose, 2000). According to Hauschild *et al.* (2005) DfE has eight unequivocal axioms *(1) manufacture without producing hazardous waste, (2) use clean technologies, (3) reduce product chemical emissions, (4) reduce product energy consumption, (5) use non-hazardous recyclable materials, (6) use recycled material and reused components, (7)* *design for ease of disassembly, (8) product reuse or recycling at end of life,* that can be addressed by three design areas *(1) process design, (2) material design, (3) energy consumption design.* The target of process design is the minimization of processes' inherent energy consumption, wastes and pollution. Material design focuses on the selection and use of raw materials to minimize the total amount of materials required as well as reduce amount and hazardousness of wastes and emitted pollutants. Design for energy consumption is concerned with the reduction of the product's energy demand when manufactured or used through an efficient selection of materials and processes, as the energy activity is the greatest responsible for the production of greenhouse gases, acidifying gases like NOx and SO2, and volatile organic compounds. The same author considers that environmental considerations are just one among many other priorities while developing a product, as **Figure 12** exhibits. This implies that, "even from an environmental point of view, the weight given to the environmental performance of the product should not be higher than that which gives the strongest competitive edge to the product" (Hauschild *et al.*, 2005). If the performance of the product in the marketplace is not enough to override other less environmentally conscious products, there will be no relief on the environmental burden. Nevertheless, environmental improvement can be easily achieved without undermining other important parameters of product performance. On the contrary, the work of optimizing environmental performance generally stimulates creativity and brings innovative design solutions to the product development process, which allows to improve overall performance, together with environmental performance. Holdway *et al*. (2002) stated that the benefits of eco-design to business include greater resource efficiency (materials, energy, labour), added functionality and effectiveness, better product differentiation in overcrowded markets, reduced environmental impact during use and disposal and opportunity for innovation (new product forms). For the purpose of this work the issue of specific interest are the levels of eco-design innovation that are often identified in **Figure 13**. These levels can be seen to be derivatives of the development of eco-design: the approaches of refining and repairing are less effective when compared to redesigning and rethinking of products and entire systems. Accordingly, Sherwin and Bhamra (1999) suggested that the target for innovation shall be nearby stages 3 and 4, redesign and rethink as **Figure 13** highlights.

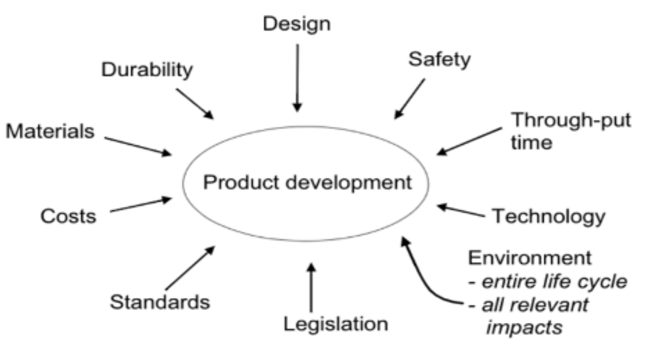


Figure 12 - The many priorities to the new product set by different stakeholders (Hauschild et al., 1999)

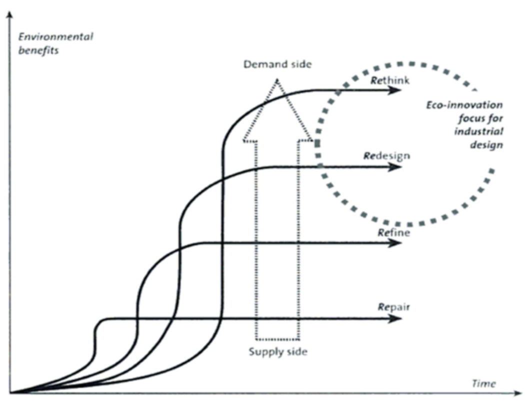
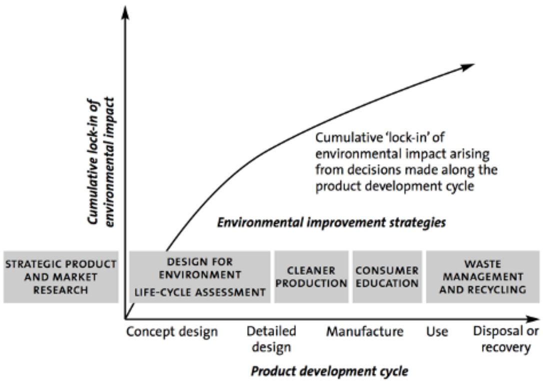


Figure 13 - Revised approach of eco-design innovation for industrial design (Thompson & Sherwin, 2001)

The importance of the early stages of the innovation process seems to be a consistent theme within the engineering design perspective. The product design stage of the life cycle has the most significant environmental impacts as it was estimated that 80% of the environmental burdens are locked in during this stage (Sanyé-Mengual *et al.*, 2014), which will establish the pollutants and wastes a product will discharge during its lifetime, the energy it will consume, and how easily its components will be reutilized in consequent uses and manufacturing cycles (Franco, 2019). This concept is presented in the left side of **Figure 14**, together with the types of strategy applied to address environmental performance (Lewis *et al*., 2001). Therefore, the earlier environmental issues are considered during development, the higher is the chance of reducing both their associated impacts and costs, as it is also acknowledged that 70% of the final product costs are determined in the design process (Birch *et al*., 2012). However, when a new design project starts the knowledge about the final product is very little, particularly is the product is new for the designers, mainly because the information at disposal is only qualitative. As the work on the product progresses, the knowledge about it increases, while simultaneously the freedom of action for each decision taken decreases, since most projects are driven by time and cost. Consecutively, later changes imply higher costs since previous work must be redone. This is relation is shown in **Figure 14** on the right and is called the *Design Paradox*. The paradox occurs on account of "when the general design information is needed, it is not accessible, and when it is accessible, the information is usually not needed" (Lindahl, 2005).



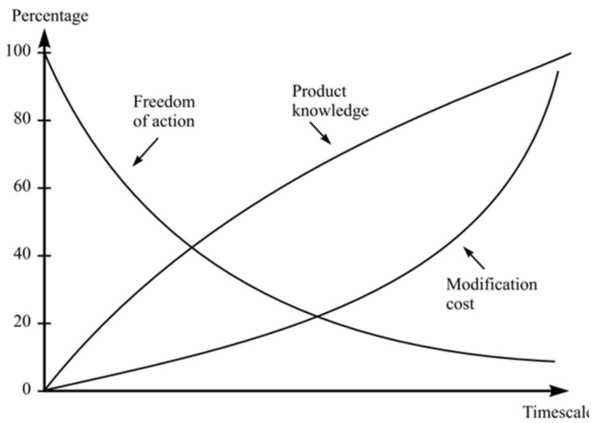


Figure 14 - On the left: Conceptual representation of environmental 'lock-in' over a product's development cycle (Lewis et al., 2001). On the right: The relation between "Freedom of action", "Product knowledge" and "Modification cost" (Lindahl, 2005)

3.4.2 | Strategies, methods and tools for DfE and Eco-Design

A number of eco-design tools and methods have been developed during the past decades (Ramani *et al.*, 2010) to aid in the sustainable development when designing a product. Some tools are meant for an early use while others are intended to be employed during the detailed design phase (Hauschild *et al.*, 2005), and can be divided into qualitative and quantitative. The first group includes the easiest to use tools based on checklists, which comprehend a set of items used for assessing a product over its entire life cycle from the environmental perspective (Ramani *et al.,* 2010*)*. Following the production, use and disposal phases of a product, the MET matrix (Materials, Energy and Toxicity) is based on a qualitative analysis of inputs and outputs focusing on these three aspects, in order to identify and *evaluate the main environmental impacts of products. Another qualitative tool is the Eco-design Strategy Wheel (ESW),* *which according to Crul and Diehl (2009) proposes seven general strategies that cover a wide range of improvement directions (1) Selection of low-impact materials, (2) Reduction of materials usage, (3) Optimisation of production techniques, (4) Optimisation of distribution system, (5) Reduction of impact during use, (6) Optimisation of initial lifetime, and (7) Optimisation of end-of-life system.* The ESW is illustrated in **Figure 15**. For each axis of the diagram presented, it will be necessary to obtain a scale evaluation of 0 to 5 and thus design and evaluate performance at the beginning and end of the project. Next to the 7 strategies described above, the ESW also shows the '0' strategy of a completely new product design – an important strategy in light of innovation potential (Crul and Diehl, 2009). On all clusters, the wheel discriminates 33 eco-design principles that constitute potential solutions to improve the environmental profile of a product system, while taking into account all its life cycle stages (Van Hemel and Cramer, 2002).

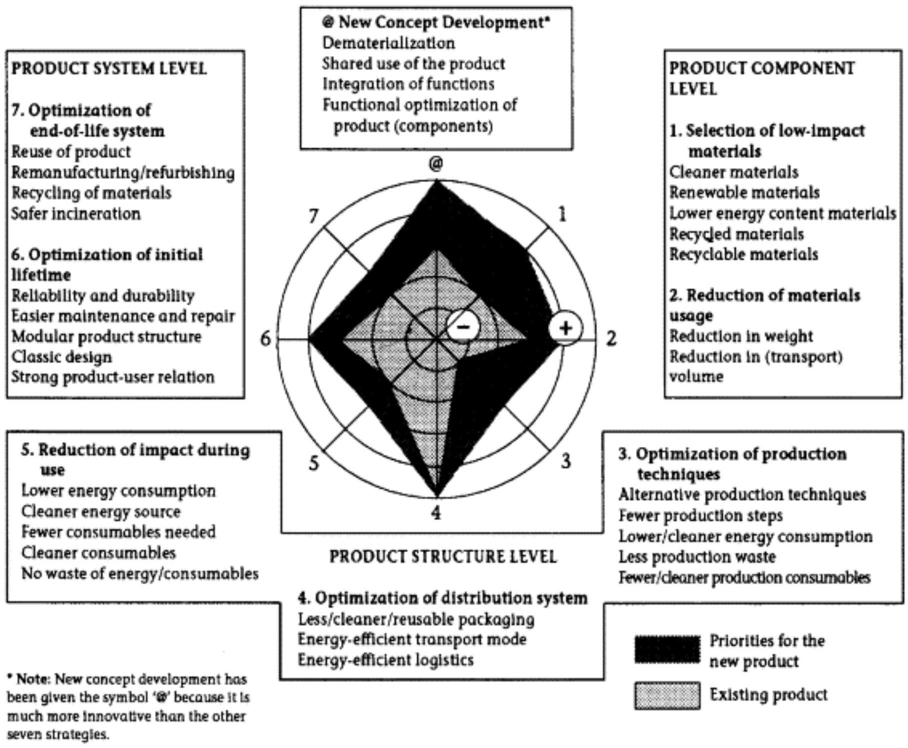


Figure 15 - The ESW (Van Hemel and Cramer, 2002).

These tools are particularly developed for the early stages of the product development process. In comparison with LCA based tools, these tools are far more subjective, and its adequate use requires vast experience and knowledge. Even in this scenario, the challenge remains when trade-offs between different life cycle stages or different environment impact categories exists. Furthermore, these tools can rarely provide concrete solutions (Ramani *et al., 2010*). The use of LCA tools as key to assist designers on the product's life costs assessment and consequently manage material choices for ecological optimisation is systematically promoted by authors (De los Rios and Charnley, 2017). According to them, these are already being used tools and with a reasonable degree of confidence, which are divided into qualitative and quantitative tools. LCA is a quantitative tool specifically defined by related ISO 14040 and 14044 standards (ISO, 2006) as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (Rio *et al.*, 2011), and from the environment assessment tools available for evaluating the environmental profile of a product or process, LCA has arisen as the most objective one (Ramani *et al*., 2010). **Figure 16** exemplifies the steps to determine the environmental impact of a product in an LCA framework.

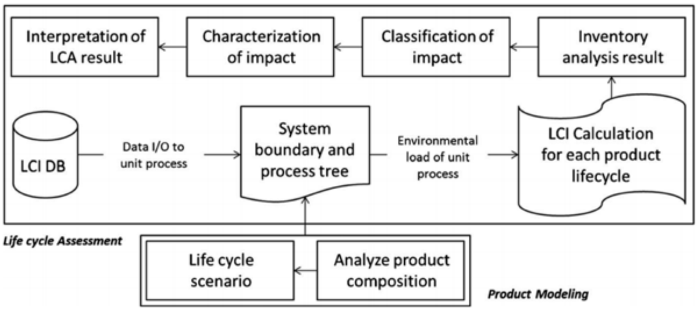


Figure 16 - Steps for identifying environmental impact (Ramani et al., 2010)

LCA has some limitations arising from the fact that its unsuitable for use in early stages of product development when detailed specifications are lacking to allow for measurement of material use, energy consumption, and impacts (Holdway *et al.*, 2002). This is particularly true for new product design since reference information from previous generation products or competitors is not available (Ramani *et al*., 2010). Therefore, LCA is only possible after data respecting energy consumption can be gathered, at the product use stage (Rose, 2000). Additionally, LCA can be costly and time consuming (Holdway *et al*., 2002). In a need 'quick and dirty' tools to be used early in product design (Rose 2000), recent efforts have been made to developing simplified or streamlined LCA to address this issue. However again, uncertainties about the early design elements, i.e., shape, component interactions, etc. have become a significant impediment as it is impossible to estimate to what extent the fidelity can be maintained. Applying LCA-based tools to early design has another major obstacle associated that lies in the fact that, inherently, LCA is not design oriented. Rather it is designed to analyse certain structures and components, not environmental costs associated with functions required by customers or the technologies used to achieve those functions (Ramani *et al*., 2010).

3.4.3 | Drivers and barriers for DfE

There are several driving forces and barriers that play a decisive role in the success or failure of the several eco-design solutions presented in the previous section. Van Hemel and Cramer (2002) concluded that the eco-design is strongly driven by internal and external stimuli. Internal stimulating factors originate inside the company itself, from environmental commitment and the aspiration to maintain or enhance commercial values and competitive advantages, like cost reduction, increased efficiency, image improvement and employee motivation. From outside the company, external stimuli include those factors that influence the attitude towards the environment within the company. **Table 7** summarises the factors that motivate or, conversely, discourage the implementation of each eco-design improvement option in the three categories: external drivers, internal drivers and barriers.

Table 7 - External drivers, internal drivers and barriers, used in assessing the motivation to either realise or reject the company's suggested eco-design improvement options (Van Hemel and Cramer, 2002).

External drivers (direct influence of external parties, their attitude and/or activities)
1. The option is subject to legislation and government regulations, actual or pending 2. The option is subject to environmental pressure from industrial organisations 3. The option is subject to the environmental demands of customers at the consumer, industrial or institutional market 4. The option is subject to negative media attention caused by environmental action groups 5. Suppliers offer newly developed eco-efficient materials or components related to the specific option 6. Competitors have already applied the specific eco-design option to their products 7. Another external stimulus is perceived for the option
Internal drivers (reasons why eco-design option is interesting, regardless of the influence of external parties)
1. The company expects a reduction of the environmental impact (commitment to reduce the environmental impact) 2. The company expects a reduction of costs (lower cost-price of the product) 3. The company expects an image improvement (leading to competitive advantage) 4. The company expects new market opportunities (competitive advantage: increasing actual market share/access to new markets) 5. The company expects an increase of the product's functional quality 6. The company expects a synergy with product requirements other than functional quality demands or low costs 7. The company expects a commercial benefit, other than those mentioned in 2, 3, 4, 5 or 6 (e.g. synergy with care systems, risk reduction, increased efficiency in production, storage, distribution, etc.) 8. The company regards the option as an interesting long-term innovation opportunity 9. The company perceives another internal stimulus
Barriers standing in the way of the suggested eco-design improvement options
1. Doubt about the environmental benefit of the option suggested 2. The company does not feel responsible for realising the option 3. The option only becomes relevant if supported by environmental legislation 4. The option only becomes relevant if supported by market demands 5. The option creates a commercial disadvantage for our company 6. The option creates a conflict in connection with actual functional product requirements 7. The option is not a challenging technological innovation opportunity for our company 8. Realisation depends on available technical possibilities; at the moment there is no proper alternative 9. The company regards new investments in redesigning the product in question as fruitless 10. The company lack sufficient time to realise the option in question 11. The company lacks sufficient knowledge to realise the option in question 12. The company perceives another type of barrier

In order to gain a better understanding of the most influential factors, the authors assessed the extent to which a company had managed to realise and prioritise an eco-design option associated with a certain external driver, internal driver and barrier. In the companies analysed, the research revealed that internal drivers seem to have a greater influence than external drivers on decision-making regarding eco-design. The most influential internal drivers identified were *(1) Innovational opportunities*, *(2) Increase of product quality* and *(3) New market opportunities*. In this context, environmental quality is frequently seen as an element of product quality which can result as a stimulus for product innovation (Van Hemel and Cramer, 2002). From a previous study performed by Smith *et al.* (1996), emerged that companies tend to realise those eco-design options that match their more traditional commercial values in product development, meaning that generally they did not anticipated to produce a 'greener' product, but rather a product that would perform better, create a new market, increase or maintain market share, or satisfy market demands or regulatory pressures. Generally, these environmental factors were merely taken into account in 'pursuit of commercial aims'. Concerning the external drivers, Van Hemel and Cramer (2002) revealed that customer demands are an even greater influential impetus than governmental regulation.

With respect to the barriers, three of the eleven highlighted in **Table 7** were defined as 'no-go barriers' (*1) Not perceived as responsibility*, *(2) No clear environmental benefit* and (*3) No alternative solution available*, that proved to be so influential that their presence are an impediment for the implementation of the eco-design options. This means that the remaining other eight barriers were only initial barriers that still allow the successful implementation of these options if driven by several influential stimuli. Finally, there are 10 most frequently suggested eco-design solutions, among the 33 possible, that demonstrated to be the most successful ones, implying a concretisation within 3 years. The most influential external and internal drivers and barriers, as well as the most successful eco-design principles are outlined in **Figure 17**.

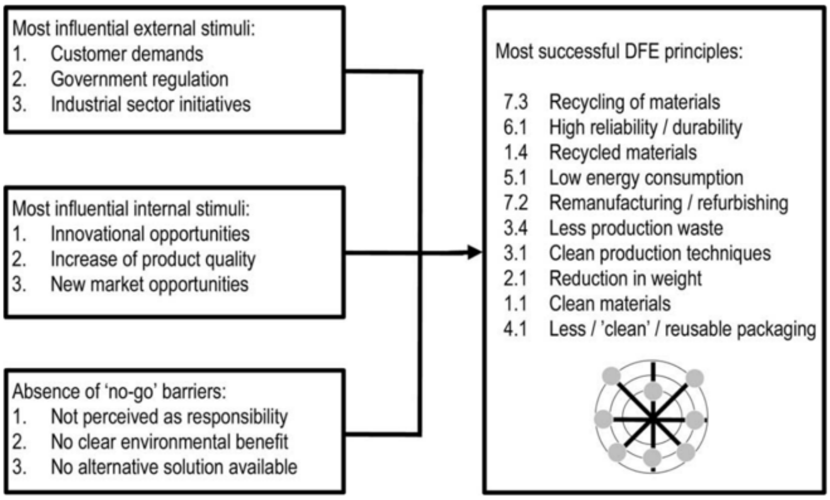


Figure 17 - The most influential stimuli and barriers, and the 10 most successful eco-design principles (Van Hemel and Cramer, 2002).

As a whole, eco-design improvement option only has a chance when supported by powerful internal and external drivers other than the foreseen environmental benefit alone, and not blocked by any no-go barriers. Promoting eco-design strategies in companies will be dependent not only upon on finding alternative solutions for technical problems, but most of all on economic and social factors like the acceptance of environmentally improved products in the market, and the way in which they perceive the market perspectives of these products (Van Hemel and Cramer, 2002).

3.5 | Conclusions

As industries and economies are increasingly dealing with the catastrophic effects of pollution, global warming, and resource scarcity the CE is the course of action to eradicate negligent resource depletion and strengthen existing material value in industry. Therefore, it becomes vital to consider both business models and product design in the development of truly circular industrial systems. A literature review was conducted to understand the product design process with a specification on DfE, its strategies and drivers and barriers. This chapter has revealed a main gap that should be addressed. Currently there are no solutions on the market that address a zero-waste packaging concept combined with a reuse system for toothpaste that, therefore, avoids it to be thrown once it is empty. In this regard, several product design methods were analysed (Slack et al. (2007), Ulrich and Eppinger (2012), Deloitte (2019)) that aid in develop an integrated product design strategy to address the gap identified.

4 | Methodology

4.1 | Research description

From the research conducted throughout Chapters 2 and 3 and from the identified gap, there are two ways in which the product can be improved. It can be by developing (1) a new CBM with a hybrid model where the toothpaste tube is a container that can be refilled with toothpaste bought separately, or (2) through the use of recyclable or biodegradable materials. This last one can deliver either an edible toothpaste packaging with a toothpaste tube packaging made of recyclable plastic, used as dispenser, or, in case of being non-edible, develop the toothpaste packaging with a biodegradable plastic or recyclable plastic (HDPE), soft enough to be collapsible but not too soft to lose balance when in vertical position. Based on the previous statements the following research questions were defined:

(1) How design methods can contribute to the design of a toothpaste, aiming at greater sustainability with a zero-waste packaging?

(2) Can a new circular business model deliver a higher convenience, performance and cost effectiveness in order to become more appealing than the current model adopted by the mass-market toothpastes?

4.2 | Methodology

To pursue the product design activity, an iteration process to accomplish the current project was defined based on the Literature Review. The methodology to be followed throughout the master dissertation will be based on the design process proposed by Slack *et al.* (2007) which was further extended to a multi-methodology approach to integrate a more UCD approach. Therefore, in each step of the methodology proposed by Slack *et al.* (2007) different methodologies will be applied, following directives of different authors. Accordingly, this approach is outlined in **Figure 18**.

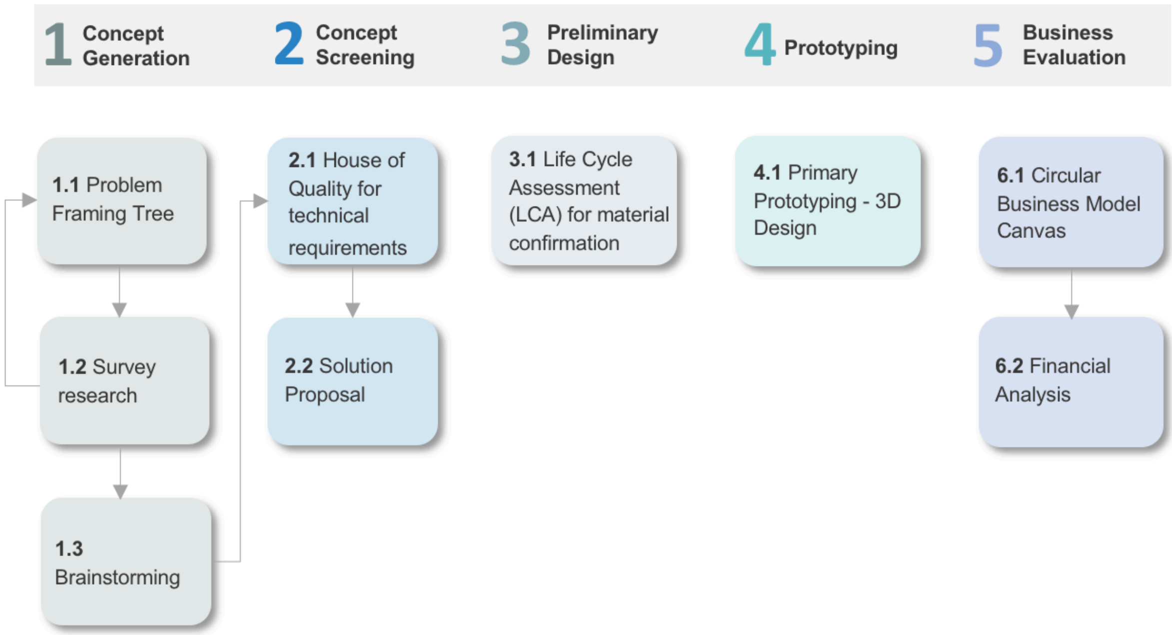


Figure 18 - Master dissertation methodology approach

Each step of the methodology will be further explained in the following sections.

Step 1: Concept Generation

The concept generation stage is characterized by the recognition and definition of what is the specific problem that requires a solution. As introduced in the literature review and based on the research developed by Deloitte (2019), Veselý (2008) and Ammani (2010), the Problem Framimg Tree provides a structured way to analyse the problem, by deconstructing and identifying the fundamental causes and their paramount effects. This tool is used due to its simplicity and its emphasis on visualization and discussion quickly allow a good overview of the extent of the problems. Creating a problem tree should ideally be undertaken as a participatory group event, with a focus group of about six to twenty-five carefully selected people. According to the mentioned authors a good problem framing consists of a number of steps. Five steps should be followed.

1. **Define the purpose**
2. **Identify major existing problems:** Openly brainstorm and identify major problems, which stakeholders consider to be a priority. This first step can either be completely open with no pre-conceived notions as to what the priority problems might be, or more directed, through specifying a 'known' high order problem or objective based on preliminary analysis of existing information and initial stakeholder consultations. If a problem is too broad or general, and it proves to be difficult to proceed with the analysis it should be eliminated.
3. **Select one main problem for the analysis:** From the problems identified through the brainstorming exercise, select an individual starter problem.
4. **Establish a hierarchy of cause and effects:** Problems, which are directly causing the starter problem are put below. Problems, which are direct effects of the starter problem are put above.

Continuing going deeper and narrower by asking "why?" "who?" or "how?" to get to some of the specific, underlying causes and motivations that are encompassed in the insight. Just like the branches of a tree, the branches mapped out in this activity may end up with some tangles. That is, different symptoms may result from the same underlying causes.

5. **Connect the problems with cause-effect arrows**
6. **Review the entire problem tree:** Verify its validity and completeness and make necessary adjustments. Consider important problems that have not been mentioned yet. If so, specify the problems and include them at an appropriate place in the diagram.
7. **Problem Identification.** Identify the core problem. The outcome of the problem tree should be concise and comprehensible.

Accordingly, a general structure of a problem tree is shown in **Figure 19**.

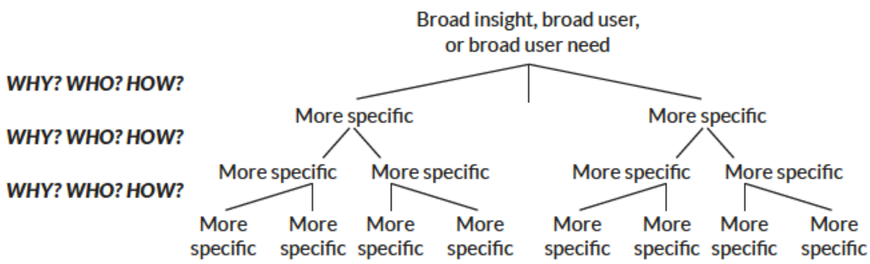


Figure 19 - General Structure of a Problem Tree (Deloitte, 2019).

From the elaboration of the problem tree, a concise statement should be presented as the focus problem of the project.

The QFD has been widely used as a multi-functional design tool to translate customer requirements into a product's technical attributes. Correctly rating the importance of every customer requirement is essential to the QFD process because it will largely affect the final target value of the technical attributes of a product. Traditionally, capturing customer requirements involves three steps in QFD (Lai *et al.*, 2008).

1. **Identifying customer requirements.**
2. **Structuring customer requirements.**
3. **Determining the importance weight for the individual customer requirements.**

The first two steps are usually accomplished via market survey. Well-designed solutions are grounded in a deep understanding of the user's wants and needs. The former is what the user desires and the latter is what the user requires. Wants and needs are not always the same, as the user may need one thing but want another due to a number of reasons. The user could have different priorities, may not see or understand what they need, or perhaps the user's want is a critical first step in obtaining the need, even though they may initially appear unrelated (Deloitte, 2019).

Based on the work by Cardoso (2012) the survey should follow the five steps shown in **Figure 20**.

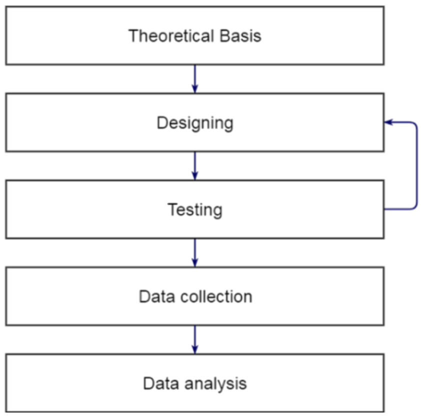


Figure 20 - Survey based research process (Adapted from Cardoso, 2012).

The survey design phase is characterised by the definition of its main characteristics, the information to be researched, the sample and the collection technique. The survey will be developed in electronic format, using the *Google Forms* platform. An introductory text was used to explain the study and its context, and the survey structure. The complete survey used in this step is presented next in **Appendix A**. The survey is divided into three sections: **I** - Consumer Insights; **II** - Product Information; **III** - Consumer data. The first part is aimed at understanding consumer information regarding the environmental problem that toothpaste represents, how willing they are to change their current toothpaste method and what reasons would prevent them from doing so. The second part aims to define product requirements, first understanding consumer thoughts on zero waste toothpaste solutions currently on the market by rating their preference for these solutions, and secondly by allowing them to rate a list of packaging criteria on a scale of 1 to 5. The last part focuses on collecting demographic data from the group of participants.

As illustrated in the methodology structure presented in **Figure 18**, both steps 1.1 and 1.2 work closely and iteratively as the results of the interviews and survey research will complement the information required to build the Problem Tree.

Deloitte (2019) proposed the following general guidelines for having a productive ideation and brainstorming session during the concept generation stage:

- **Defer judgment**. Encourage wild and crazy ideas, it could come from anywhere.
- **Be visual and tactile**. When explaining your idea, draw pictures or build simple mind maps or 3D representations.
- **Prioritize quantity**. Try to get as many ideas out there as possible. Sorting and focusing on ideas come at a later stage.
- **Keep the focus on problem framing**. While trying to come up with as many ideas as possible, also make sure that those ideas are relevant for the addressing the problem framing.
- **Keep the focus on your user / customer**. Seek inspiration by empathizing with the users through simulating their experiences when possible.

Step 2: Concept Screening

The Concept Screening stage aims at evaluating the proposed product solutions that result from the research performed during the Concept Generation stage. Step 2.1 will define a baseline for a proper solution based on the problem, user, need and insights identified in the previous phase. This solution should satisfy each of the points defined before and should be specified, as much as possible in terms of features and materials.

A commonly used technique for concept selection is QFD as it is used to translate customer needs into technical requirements, starting from the Voice of the Customer (VoC). QFD process remains the leading tool for setting engineering priorities and determining target levels of product performance through benchmarking. The primary feature of the QFD process is the House of Quality (HoQ), which provides inter-functional product planning mapping to link engineering attributes to customer desires, which are ranked in importance. The HoQ utilizes a weighted-sum multi-objective decision criterion, entailing technical test measures (benchmarking) analysis, technical importance rankings and estimates of technical difficulty to enable a decision maker to set performance targets for a designed artifact. Pugh's Method provides a method to compare alternative design concepts against customer requirements, with evaluations made relative to a base or favored concept, a process independent from the HoQ analysis (Hoyle and Chen, 2007).

The different parts of the quality matrix, HoQ, are shown in **Figure 21**. The HoQ and its process is described below by following the approaches suggested by Brown (1991), and Griffin and Hauser (1993). *Steps (1)* to *(3)* should be accomplished using the previous information gathered in the first stage.

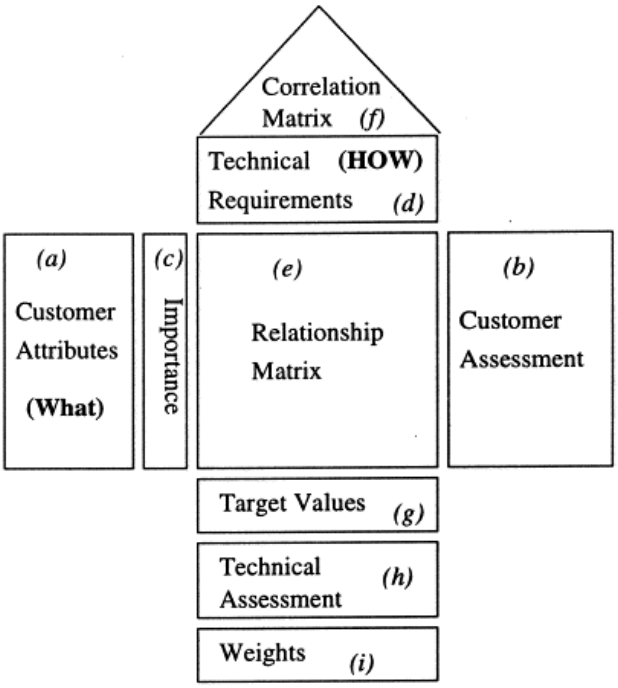


Figure 21 - House of quality matrix (Temponi et al., 1999).

1. **Identify the WHATs:** The wanted benefits in a product in the customer's own words are customer needs and usually called customer attributes (CA) or "what", area (a) in **Figure 21**. The CAs are usually determined by qualitative research with one-on-one interviews and/or focus groups (Griffin and Hauser, 1993). The priorities are usually indicated in the area designated as (c) in **Figure 21**. Customer perceptions are obtained and presented on the right-hand side of the matrix in **Figure 21**, area (b).
2. **Determination of HOWs:** Technical requirements (TR) are specified as the "how" of the HoQ and also called measurable requirements. TRs are positioned on the area marked as (d) on the matrix diagram of **Figure 21**.
3. **Preparation of the relationship matrix.** Determine which TRs impact which CAs and up to what degree. The relationships can be positive or negative, strong or weak; symbols to represent relationships are not standardized. The relationship matrix is the area identified as (e) in **Figure 21**.
4. **Elaboration of the correlation matrix.** The physical relationships among the technical requirements are specified the "roof matrix" and identified as (f) in **Figure 21**. This HoQ's step helps to keep track of collateral TRs requiring improvements and/or of TRs where trade-offs are necessary. Positive and negative correlation between pairs of TRs as well as the strength of the relationships are indicated in this matrix.
5. **Other measurements.** Often it is estimated cost, feasibility and technical difficulty for change in each of the TRs. Technical assessment or difficulty is identified by (h) in **Figure 21**. The target values, area (g), hold objective measures which should reflect the link among CAs, TRs, and customer assessments.
6. **Action plan.** The weights of the TRs, identified as area (i), are placed at the base of the quality matrix. These weights are one of the main outputs of the HoQ, and are determined by

$$Weight\ (TR)_i = V(TR)_{i1} * Imp(CA_1) + V(TR)_{i2} * Imp(CA_2) + \cdots + (TR)_{in} * Imp(CA_n) \qquad (1)$$

Step 3: Preliminary Design - Sustainability evaluation

LCA, also known as life-cycle assessment, is a primary tool used to support decision-making for sustainable development. Crucially, an LCA is a comprehensive method for assessing all direct and indirect environmental impacts across the full life cycle of a product system, from materials acquisition, to manufacturing, to use, and to final disposition (disposal or reuse). The application of LCA helps to promote the sustainable design and redesign of products and processes, leading to reduced overall environmental impacts and the reduced use and release of non-renewable or toxic materials. LCA studies identify key materials and processes within the products' life cycles that are likely to pose the greatest impacts, including resource demand and human health impacts. These assessments delineate the full benefits and costs of a product or process, which allows decision-makers to select the most effective solution (Brusseau, 2019). The LCA process is a systematic standardized method (ISO, 2006a, b) defined in four phases:

1. **Goal definition and scoping** − Define the primary objective of the study, indicate expected results, set the system boundaries and list the assumptions needed in the calculation. A clear definition of the system boundaries comprises which methods are going to be considered (impact categories), the life cycle, the physical, geographical and temporal boundaries, data limitations and quality of the data, which is useful for improved understanding and interpretation of the LCA results, as well as to enable them to be used for comparative purposes. This step has implications for all the other parts of the LCA study and will influence the methods and detail to which LCI, impact assessment interpretation, and reporting are carried.
2. **Life cycle inventory (LCI) analysis** – Create an inventory of flows from and to nature for a product system. Inventory flows include inputs of water, energy and raw materials; outputs of emissions to air, land, and water; sub-products; and other releases. It comprises de following stages:

- **Detail scope information (functional unit):** It is necessary to detail information regarding the scope by defining the functional unit. This reference is necessary to ensure comparability of LCA results, which is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis. It should be measurable and consider as well the function of the object under study, taking into account the user's perspective, and the effectiveness and durability of the product.
- **Collecting data:** Data collection of input/output data and a balance calculation to all unit processes, considering global mass and energy flows and most relevant phases in the system. This description should be schematized in a blocks diagram and the data can real or obtained from several other sources such as engineering calculations (models), literature data or databases. The quality of the data used in an LCI reflects the quality of an LCA.
- **Create a computer model:** Develop a model in *SimaPro* - the aim of the software is to combine and compile the system input and output information, producing results that are easier to analyse and aggregate.

- **Analyse and report the results:** For a correct interpret he results should provide information regarding geographical coverage, time period covered and methodology, i.e. what is the nature of the combination of technologies concerned (e.g. use of the average, better or worst option, etc).
- **Interpret the results and draw conclusions:** Interpret the results through the analysis of graphs, tables, indexes, and present conclusions about products, processes or activities. From here improvement measures can also be presented.

3. **Life cycle impact assessment (LCIA)** − Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis. LCIA consists of the following steps (ISO, 2006b):

- **Classification** assigns the LCI results to one or more impact categories.
- **Characterisation** converts the LCI results into common units and aggregates the results within the same impact category, quantifying the impacts resulting from the connections created in the classification through the formula:

$$S_j = \sum_i C_{i,j} \cdot E_i \qquad (2)$$

Where,

E_i is the mass or energy flow identified in LCI phase, for each component, $C_{i,j}$ is a characterization factor for components i in impact category j, and S_j is the category indicator of the impact j.

Many possible LCIA methodologies exist, which can be classified mainly into two methods (Desideri and Asdrubali, 2018):

- **Midpoint.** This method restricts quantitative modelling to relatively early stages in the cause–effect chain, and group LCI results in the so-called midpoint categories, which follow a problem-oriented approach, and translates impacts into environmental themes such as climate change, acidification, human toxicity, etc.
- **Endpoint.** Damage-oriented methods. These methods try to model the cause–effect chain up to the endpoint or damage category, such as human health, ecosystem quality, and resource depletion. This approach often comes with high uncertainties.

- **Normalisation** lists the values of the impacts resulting from the characterization phase with values assumed as reference. The purpose is to better understand the relative magnitude for each indicator result of the product system studied as it allows the analysis to be taken under a mutual scale. The following relation should be used:

$$N_j = \frac{S_j}{R_j} \qquad (3)$$

Where, R_j is the reference value, and S_j is the impact category, j.

- **Weighting** assigns weights to the different impact categories, conveying the relative importance of each one. It allows the aggregation of categories and impact into a final index whose main objective is to reduce the number of environmental indicators for analysis of results with the following relations:

$$W_j = \Omega_j \cdot N_j \quad \text{and} \quad I = \sum_j W_j \quad (4)$$

Where,

Ω_j is the ponderation factor,

W_j is the pondered index of the impact, and

I is the LCA index.

The LCA standards do not determine which impact assessment methods should be used in a study. Selection of the method should be made in the goal and scope definition phase (stage 1), considering the spatial and temporal aspects of the study. The CML 2001 impact assessment method is an example of the so-called midpoint methods that include only characterisation factors but not normalisation or weighting factors (CML, 2001). The ReCiPe method includes both midpoint and endpoint-indicators (ReCiPe, 2013). According to Goedkoop et al. (2008), the midpoint indicators without weighting can be seen as more robust and less subjective than the endpoint indicators, but they might be difficult to compare or interpret due to their abstract meaning. For this reason, and since different systems must be compared at this phase the ReCiPe method is the one that will be adopted.

SimaPro version 8.0 software was used for the analysis of the environmental burdens using ReCiPe Endpoint (H) Europe ReCiPe H/H. Out of the several LCA methods, the ReCiPe method finds its strength as one of the most recent and advanced LCA methodologies with its broadest set of mid-point impact categories and an impact calculation mechanism having a global scope. It combines the strengths of both mid-point-based approach of CML-IA, and endpoint/damage-oriented approach of Eco-indicator 99, which are globally recognized LCA methods (Carvalho et al. 2014). The ReCiPe method outlines five steps in life cycle impact calculation, such as (1) characterization, (2) damage assessment, (3) normalization, (4) weighting and (5) single score. Out of this, characterization is the only obligatory step according to the ISO standards while the rest of the steps are optional (ISO 2006a, b). Normalization and weighting options have been used in this context to simplify the impact indicator result and consequent comparison. Hence, in ensuing weight-based analysis, a specific weighting factor has been applied to each of the normalized end-point values, naming human health—40%; ecosystems— 40%; and resources—20%, to represent the results in a scale of severity. Finally, all the weighted end-point scores are aggregated to form the single-score result. Ecoinvent version 3.1 database has been used for all LCI input data in the study (Ecoinvent, 2018).

4. **Interpretation** − Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results. This phase should be reinforced with facts and calculations to support the results, such as uncertainty analysis, sensitivity analysis and contribution analysis.

From step 3.1, the set of materials to be incorporated in the final product should be defined to proceed to the primary prototyping step 4.1.

Step 4: Prototyping

Steps 4.1 at developing a primary form of the product, first as a 3D model and then as a physical prototype so that it can be perceived and appraised by potential users in the subsequent stage.

Following the research of Ulrich & Eppinger (2012), by using 3D CAD tools, industrial designers can generate, display, and rapidly modify three-dimensional designs on high-resolution computer displays. In this manner, there is the potential to generate a greater number of detailed concepts more quickly, which may lead to more innovative design solutions. The data generated can be directly transferred to engineering design systems, allowing the entire development process to be more easily integrated. The advantages of 3D CAD modelling include the ability to easily visualize the three-dimensional form of the design, the ability to create photo-realistic images for assessment of product appearance, the ability to automatically compute physical properties such as mass and volume, and the efficiency arising from the creation of one and only one canonical description of the design, from which other, more focused descriptions, such as cross-sectional views and fabrication drawings, can be created. 3D CAD models have therefore begun to serve as analytical prototypes which, in some settings, can eliminate one or more physical prototypes. When 3D CAD models are used to carefully plan the final, integrated assembly of the product and to detect geometric interference among parts, this may indeed eliminate the need for a full-scale prototype.

Accordingly, Ulrich & Eppinger (2012) present a four-step method for planning each prototype during a product development project:

1. **Define the Purpose of the Prototype -** Provide a quick model explaining the actual plans for the final product. It could be something as simple as hand-drawn sketches, integrated together (lo-fi prototype) to demonstrate the product to a fully functional product (hi-fi prototype), which the stakeholders and users can feel and use.
2. **Establish the Level of Approximation of the Prototype** - Degree to which the final product is to be approximated. The team should consider whether a physical prototype is necessary or whether an analytical prototype would best meet its needs. In some cases, an earlier model serves as a testbed and may be modified for the purposes of the prototype.
3. **Outline an Experimental Plan -** The experimental plan includes the identification of the variables of the experiment (if any), the test protocol, an indication of what measurements will be performed, and a plan for analysing the resulting data. When many variables must be explored, efficient experiment design greatly facilitates this process.
4. **Create a Schedule for Procurement, Construction, and Testing -** building and testing of a prototype can be considered a subproject within the overall development project. First, it should be defined when the parts will be ready to assemble, second, the date when the prototype will first be tested, and third the date when it expects to have completed testing and produced the final results.

Free-form fabrication (rapid prototyping) technologies enable realistic 3D prototypes to be created earlier and less expensively than was possible before. When used appropriately, these prototypes can reduce product development time and/or improve the resulting product quality. In addition to enabling the rapid construction of working prototypes, these technologies can be used to embody product concepts quickly and inexpensively, increasing the ease with which concepts can be communicated to other team members, development partners, or potential customers (Ulrich & Eppinger, 2012).

Step 5: Business Evaluation

Establishing any product on the market to be commercialized implies that ongoing value for customers has to be created. A business model will fit need as it describes the rationale of how to create, deliver, and capture value. Therefore, step 5.1 will guide through the steps necessary to elaborate a business model focussed on the launching of a sustainable product according to the Business Model Canvas, as proposed by Osterwalder and Pigneur (2010). The authors propose four clusters that comprehend the nine steps listed below:

1. **Infrastructure or "How?" answers**
   - **Key Activities -** The most important activities to execute the company's value proposition.
   - **Key resources -** The resources that are necessary to create value for the client. They are considered company's assets and are necessary to maintain and support the business. These resources may be human, financial, physical or intellectual.
   - **Partner Network -** The business alliances that complement the other aspects of the business model.
2. **Offering or "What?" answers**
   - **Value Proposition -** The products and services offered by the business. Quoting Osterwalder and Pigneur (2010) the value propositions are “the bundle of products and services that create value for a specific customer segment”. It describes how the company differentiates itself from its competitors and is the reason why customers buy from a certain company and not another.
3. **Customers or "For whom?" answers**
   - **Customer segments -** The target audience for a company's products and services.
   - **Channels** - The means by which a company delivers products and services to customers. This includes a company's marketing and distribution strategy.
   - **Customer Relationship:** A company establishes links between itself and its different customer segments. The process of customer relationship management is called customer relationship management (CRM).
4. **Finance or "How Much?" answers**
   - **Cost structure -** The monetary consequences of the means used in the business model.
   - **Revenue streams -** Income of a company. The way in which it makes money generated from each customer segment.

The Business Model Canvas (Osterwalder and Pigneur, 2010) is shown in **Appendix B**.

In addition, it is also required to create a financial justification prior to launching a product. Creating a business case for such a launch could be a struggle as the data may be incomplete or limited. However, a good financial justification for a new launch can be presented if a systematic stepwise approach is followed. Such an approach may require making reasonable assumptions which can help in completing the process when all of the data is not available. Below are the steps suggested by Sharma (2014) that can be taken to complete the entire process:

1. **Collect Data -** Gather information on the size of the market, demographics, Compounded Average Growth Rate (CAGR) of the market, and market location and scope (global versus regional). Other probing questions should be answered such as, "Will the new entrant crowd the marketplace?" or "Is there enough capacity in the market to entertain a new entrant? In addition, pricing of competitive product(s), if it exists, should be gathered.
2. **Estimate incremental investment needed as well as the Cost of Goods Sold (COGS) -** If the new product requires some initial investment such as additional R&D activity or developmental work, an advertising campaign, hiring a salesperson or a sales team, preparing marketing brochures, etc., then an estimated fixed cost for these tasks need to be prepared.
3. **Complete a breakeven analysis and estimate the fraction of market size required to get breakeven revenue -** A breakeven (BE) analysis is required to understand how many units must be sold in this new segment to recover the incremental fixed cost investment. The BE units are determined using equation 5.

$$Number\ od\ Breakeven\ Units = \frac{Total\ fixed\ Cost\ (€)}{Contribution\ Margin\ (€/Unit)} \tag{5}$$

4. **Create a Discounted Cash Flow (DCF) model to calculate Internal Rate of Return (IRR) and Net Present Value (NPV) for the launch -** Once the breakeven revenue is known, a DCF model can be created using market CAGR (or slightly less than the CAGR) as the sales growth rate assumption. If the NPV (and cash flow) is positive over a 5- or 10-year period and the IRR is greater than the discount rate, then it is fair to say that there is reasonable financial justification to move forward with the project. The IRR equals the discount rate that makes the NPV of future cash flows equal to zero.

$$NPV = \sum_{t=1}^{N} \frac{C_t}{(1+r)^t} - C_0 \tag{6}$$

   Where,
   C_t is the net cash flow at time t,
   C_0 is the initial investment,
   r is the discount rate, and
   t is the time of the cash flow.

5. **Complete a sensitivity analysis for the DCF model -** The final step in the process involves a sensitivity analysis of the DCF model by changing the market growth rate. Three scenarios (including optimistic, pessimistic and realistic) should be completed by doubling the growth rate (optimistic) or halving the growth rate (pessimistic). In addition, COGS is also assumed to be higher for the pessimistic scenario.

5 | Toothpaste Packaging Design

This chapter applies the five steps described in the methodology with the aim of creating new design proposal for a toothpaste container.

5.1 | Concept Generation

5.1.1 | Problem Framing Tree

A well-defined problem framing helps to find solutions by mapping out the anatomy of cause and effect around an issue. The more specific the problem framing is, the easier it will be for you to define, narrow down, and test potential solutions in future phases of the Innovation Process, and ensure that the solution created actually addresses a real problem. The problem tree developed targets the root causes leading to low adoption of sustainable toothpastes by consumers and is presented in **Figure 22** below.

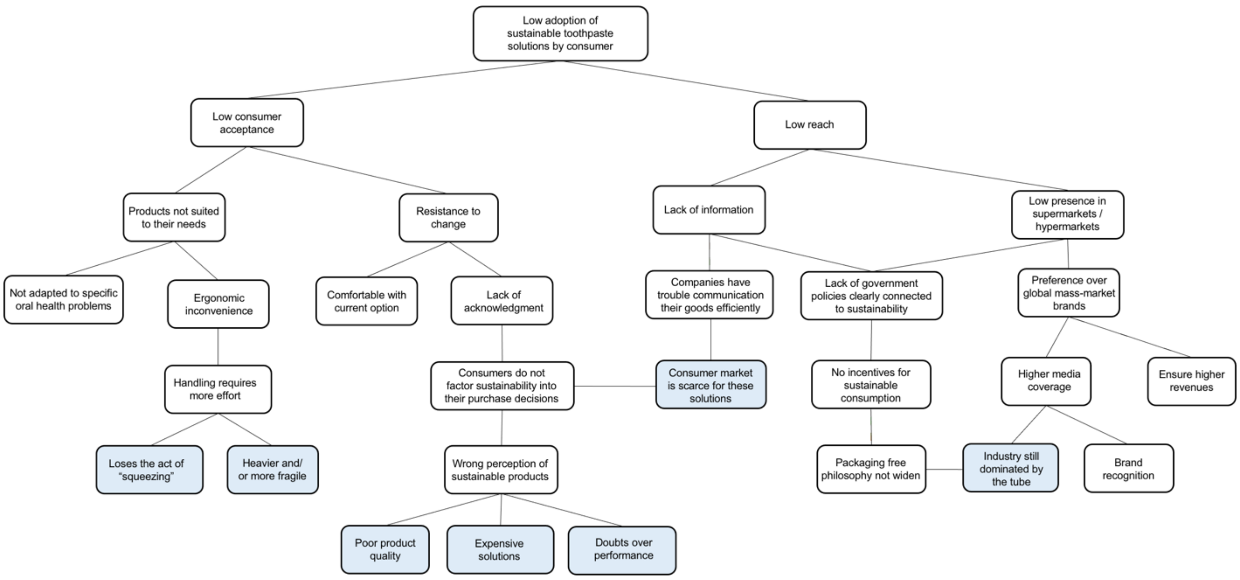


Figure 22 – Problem Framing Tree created

To achieve the Level 1 issue on the tree, each bottom level must be addressed first. Causes highlighted in the lower level represent the deepest level of detail, hence shall be easier to tackle. The solution is a product that addresses the problems highlighted in the lowest level and, consequently, with this solution, the causes of the level preceding it are also addressed.

This problem stems from two sources: consumers purposely reject the solutions, that therefore have a low uptake, or the solutions are not even reaching consumers, who end up unaware of their existence. The first may derive from the fact that these products are not adapted to their needs or from a resistance to change, and therefore many consumers are either comfortable with the solution they use and do not feel the need to change, or else for lack of acknowledgement they have a wrong perception of these products. This misconception by consumers is often associated with the idea that they are expensive products, and of questionable quality and performance. When these solutions are not suited to the consumers' needs, it can derive from the fact that there are no sustainable solutions adapted to specific oral health conditions but also because they require more handling effort on behalf of the user, who no longer applies the paste by squeezing the traditional gel format. The low reach stems from a lack of information conveyed and also from a low presence in the commercial stores frequented by the majority of consumers. It becomes clear that companies are having difficulties to communicate their goods in an efficient way because the market still lacks these solutions. In addition, a visit to the supermarket, proves that the industry is still dominated by the tube and despite the efforts for innovation in packaging, consumers do not dare to change their habits, while the competition game is held between GlaxoSmithKline (GSK) and Colgate-Palmolive, companies which have the five leading brands in sales. The next section presents the survey results aiming at identifying and structuring requirements from the customer point of view.

5.1.2 | Survey Research

It is particularly important to study the packaging of oral care products from the users' point of view. The results presented consider the data collected from 91 completed surveys, which were then exported to Excel and analysed. Descriptive analysis and graphical presentation tools are applied next. The sampling used is a non-probability convenience sampling, because of its speed, cost-effectiveness, and ease of availability of the sample (Etikan, 2016). Therefore, the demographic data that characterizes the sample for this study is mostly composed by the university community and is shown in **Table 8**. The large share of results is in the 21 to 30 age group, which accounts for roughly 84% of responses. This bias was not considered alarming, given the importance of the engagement of younger generations in environmental concerns.

Table 8 - Demographic data for this survey

Demographic variables		**Total Sample (n = 91)**	
		N	**%**
Age gap	<18	1	1.1
	18-20	2	2.2
	21-25	57	62.6
	26-30	19	20.9
	>30	12	13.2
Gender	Female	50	54.9
	Male	40	44
	Prefer not to say	1	1.1
Country	Portugal	79	86.8
	France	1	1.1
	Italy	4	4.4
	Brasil	1	1.1
	Switzerland	1	1.1
	Spain	3	3.3
	Sweden	2	2.2

The second section of the survey was meant to characterize the consumers knowledge, in order to understand how aware and concerned they are. As shown in the left side of **Figure 23,** the answers to the first question reveal that 92% of respondents are not aware of the environmental concerns circling toothpaste packaging, namely its technical challenge to be recycled due to the combination of plastic, aluminium and resins in its composition, which means that the major share of these materials is discarded by conventional means. Regarding this serious drawback of toothpastes, the vast majority (96.7%) say they consider this a concern, which reveals a group that is sensitive to these issues and that may be willing to change their habits, as **Figure 23** (right side) exhibits.

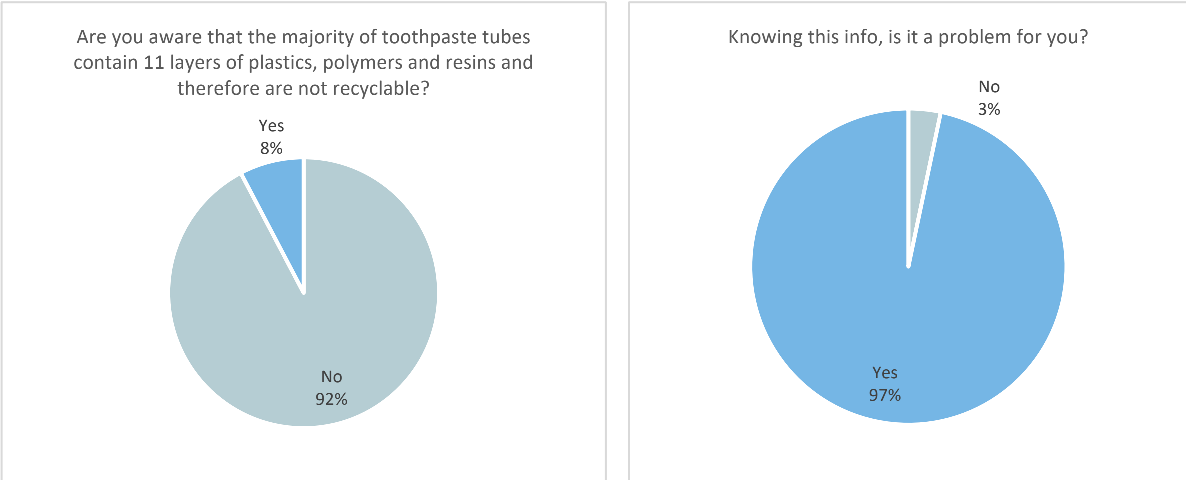


Figure 23 - Distribution of respondents regarding (On the left) their awareness on toothpaste packaging recyclability and (On the right) their concern on toothpaste packaging recyclability.

However, much remain to be done as the third question revealed that 89% of them are unaware of substitute alternatives in the toothpaste market. This means that these sustainable options are not reaching the masses, even though there is a willingness on behalf of the consumer to adopt them. In order to understand if price would be a barrier to purchase, the consumer group was asked if they would be eager to afford a more expensive sustainable option, as presented in **Figure 24**. About half (52%) said they would be willing to pay extra, while a similar proportion (44%) did not express a positive or negative response, certainly because their choice can be conditioned by several factors to be taken into account at the time of the decision. Only 4% declined to pay more.

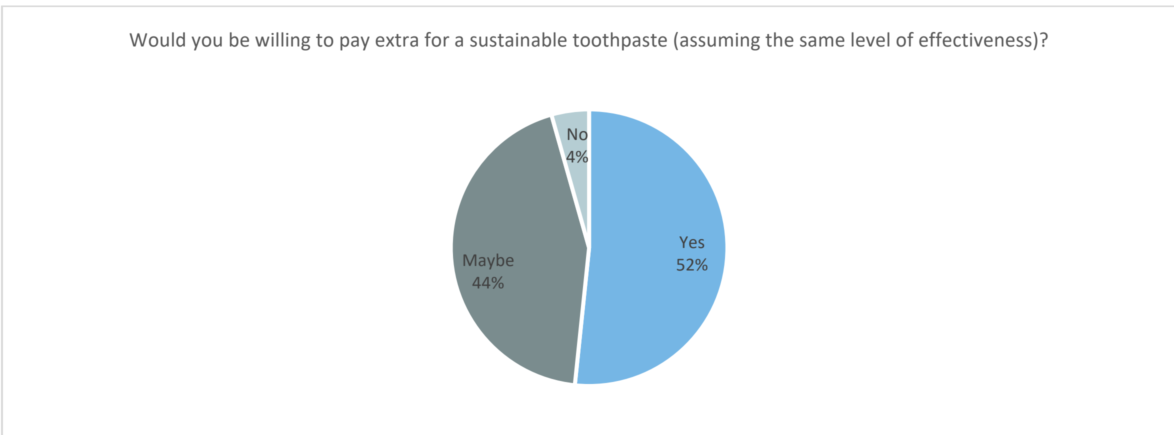


Figure 24 - Willingness of respondents on paying extra for a sustainable toothpaste

The last question on this section intended to understand which factors would prevent customers from adopting sustainable toothpaste solutions when compared to the current toothpaste option they are currently using (with the exception of 3 respondents who said they already used eco-toothpastes). The results are shown in **Figure 25**.

The majority of respondents refer that not having this type of solutions available in the channels where they regularly shop prevents them from adopting it. This result highlights the importance of availability at the first moment of truth, which may lead to the purchase of the product. Consumers cannot buy what is not available to them, and they want to experience ease in obtaining and using a product. If they hear about a product but it is not available in such channels, it becomes more difficult to reach the public and consequently a sustainable alternative that is introduced on the market will remain with a low take-up rate. Making the product more accessible to them may implicate putting it in different locations, distributing it differently or perhaps offering it online. Taking into account the nature of the product and the target demographic is, therefore, mandatory as some items sell better online with certain demographics, while others are more likely to sell where customers can view them or see how they work in person at a store.

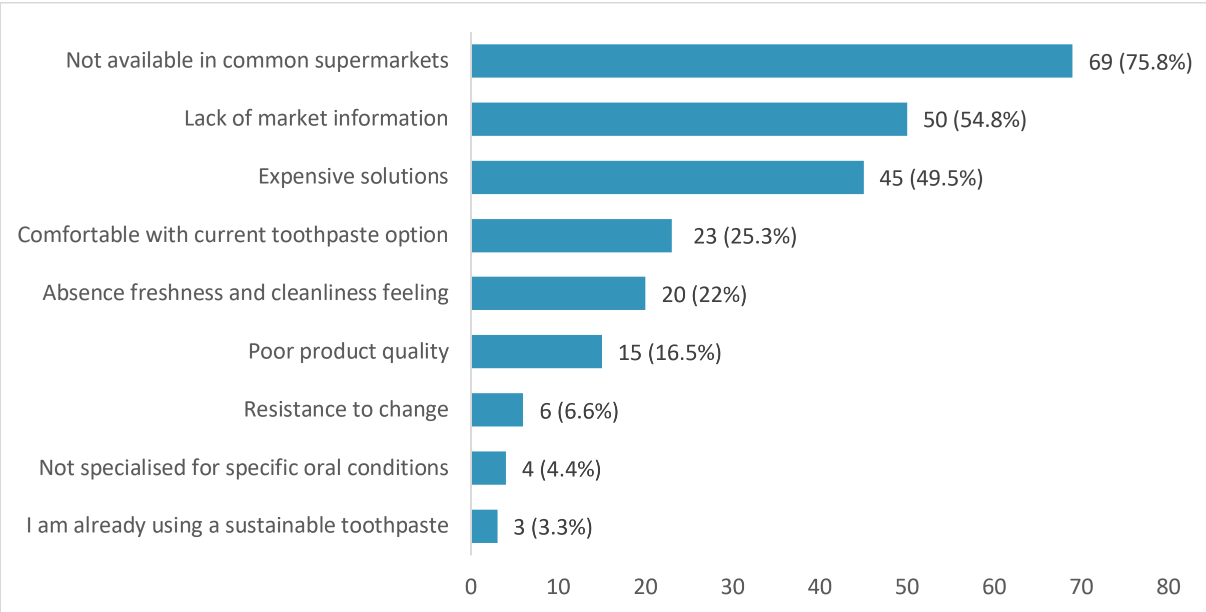


Figure 25 - Reasons that may prevent respondents from adopting sustainable toothpaste solutions when compared to the current toothpaste option they are using

About half refer that that the price to be paid for such solutions is a factor that can condition the purchase, since sustainable products are generally more expensive. These other eco-friendly toothpastes tend to be more expensive than traditional products, right now because demand is lower, and they cost more to produce. Approximately 55% indicate the lack of information and awareness on these solutions as being one of the obstacles. Again, consumers cannot purchase products they are not aware of. It is important to take into account that that the solution is not always more marketing, because the problem may lie with where the product is being marketed and what marketing vehicles are being used, *i.e.* to assess the key demographics of the target market and research where these marketing efforts are most likely to reach them. Another aspect that correlates with the one just mentioned, is the perceived value of the product. About a 17% of the respondents pointed 'Poor product quality', reflecting (1) actual lack of quality of some of these products or (2) consumers inability to recognize the benefits to create perceived value. Regarding the second aspect, if a customer cannot see the value, they will simply pass the product by. That perceived value comes in actually showing people using the product through advertisements, demonstrations, or other means. Regarding the toothpaste experience, 22% point the lack of freshness a cleanliness feeling after using it and 4% add that they need specialised solutions for specific oral conditions, such as sensitive gums or teeth, which are not found in the eco-toothpastes portfolio available. A total of 23 respondents reported to be comfortable with their current toothpaste option and therefore would not be willing to change. Similarly, 6.6% reported to be resistant to change. Innovation resistance is a normal, instinctive response of consumers, as naturally it may create a high degree of change in their day-to-day existence and disrupt their established routines. Finally, only 4 reported to be already adopting this type of sustainable alternatives.

Finally, the last section aims to extract information regarding consumers' views on sustainable toothpaste alternatives in order to understand their preferences and thus shape the product developed according to them. After the 5 example solutions have been presented, the first question revealed that at least one person had already tried each of the different types of toothpaste with the exception of edible pods. This makes sense as edible pods were developed by the American start-up *Poppits* who are not available just yet but launching Spring 2021. The results to this question exhibited in **Figure 26** show that the powder and solid toothpaste formats are the ones that generate the most 'not willing to try' answers, 18 and 15 respectively. Nevertheless, a large portion of them is open to experiment these products, which reveals the opportunity to explore both this market and solutions that can incorporate some of these concepts.

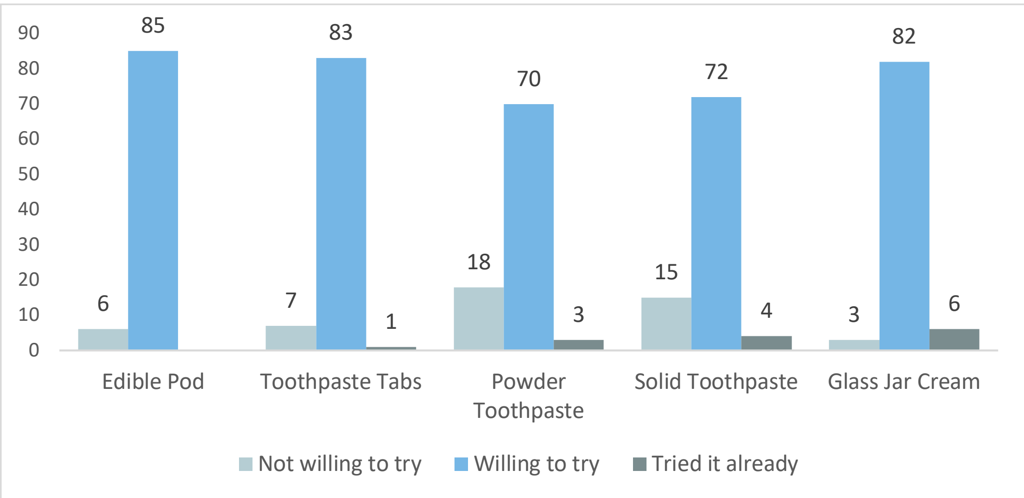


Figure 26 - Willingness to try zero waste toothpaste solutions

It was asked feedback from the respondents who answered "'not willing to try' in order to understand possible drawbacks and the feeling the customer gets during the purchase process, that might justify the low take-up rates of some of these products. The answers gathered were condensed in **Table 9.**

Table 9 - Feedback from the respondents who were not willing to try the different options

Toothpaste type	Feedback
Edible Pod	• May not provide effective cleaning • The membrane can leave a bad taste in the mouth while melting
Toothpaste Tabs	• Does not seem like they would clean enough • Aren't as reliable as regular toothpaste • Unpleasant taste
Toothpaste Powder	• May be difficult to use • Lead to waste • Lack of freshness • Feeling of dry mouth • Unpleasant texture
Solid Toothpaste	• Doesn't seem practical • Unhygienic • Lack of freshness • Could break down into pieces and could generate waste
Glass Jar Cream	• Unhygienic • Unpleasant • Fragile and heavy

On the last question respondents were asked to build a ranking in order of preference among the solutions presented, in terms of how comfortable they would be in replacing their current toothpaste option for one of these. A scoring scale 1-5 has been assigned according to the preferred position, from a weight of 5 points for the most favourite option to a weight of 1 point for the least favourite option. The results are shown in **Table 10** and illustrated in **Figure 27**.

Table 10 - Results from the scoring attributed to each toothpaste option

		Edible Pod		**Toothpaste Tabs**		**Toothpaste Powder**		**Solid Toothpaste**		**Glass Jar Cream**	
	Points	N	Score	N	Score	N	Score	N	Score	N	Score
1st option (Most favourite)	5	41	205	7	35	0	0	10	50	33	165
2nd option	4	26	104	17	68	11	44	5	20	32	128
3rd option	3	12	36	46	138	9	27	6	18	18	54
4th option	2	6	12	18	36	28	56	34	68	5	10
5th option (Least favourite)	1	6	6	3	3	43	43	36	36	3	3
	Total	91	363	91	280	91	170	91	192	91	360

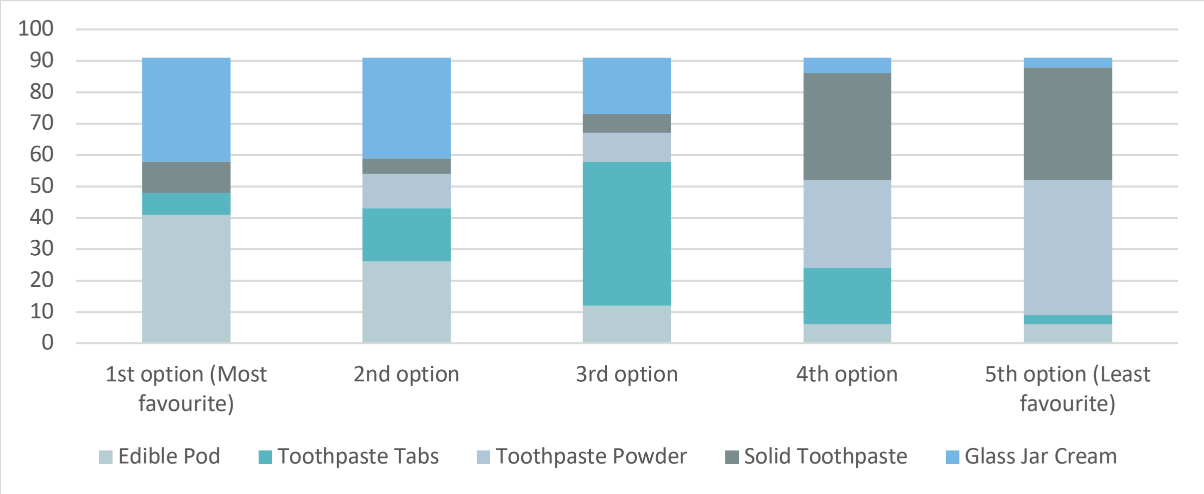


Figure 27 - Frequency of respondents' preference among the 5 toothpaste options

The results reveal a preference for gel-shaped toothpaste formats, with the highest score attributed to edible pods, followed by the glass jar. Although the way dent tabs are used is exactly the same as the edible pods, the fact of being solid can awaken in users the sensations aforementioned for solid pastes, which guarantees them a place in the middle of the ranking. The least favourite formats are the solid and powder toothpastes with the 4^{th} and last positions, respectively.

All in all, the results reveal a general lack of knowledge and awareness regarding the serious recycling drawback of toothpaste packaging, but the public is sensitive about it and open to adopt solutions that limit this problem. This is, therefore, a market with a high potential, but among the biggest obstacles to its growth are the lack of information, perceived value, the price to pay and the unavailability of these toothpaste items in the common customer's channels of purchase. When it comes to developing a new product, it is perceptible that the public ideally chooses a traditional gel paste, preferably one that brings them the greatest comfort of use and the least deviation from the oral hygiene routine they have always had. This last point is closely related to resistance to change and the comfort that the traditional toothpaste option provides, which are factors also mentioned by the participants and which should also be taken into consideration during the next development phases.

5.1.3 | Brainstorming

Design Requirements (DRs)

At this point, there has been an effort to translate the problems analysed in the previous stage into design specifications. The simultaneous satisfaction of all the DRs depict a paramount challenge in the design process as there may be conflicts emerging from the interactions between several features. In the following table, these requirements have been recorded, and divided into four basic categories, based on functionality, ergonomics, sustainability and aesthetics, so that it becomes easier to understand user needs in the concept selection stage.

Table 11 - List of Design Requirements

Functionality	Ergonomics
• Keep the product well preserved and fresh • Retain shape • Possibility of Controlled Dosage • Minimum waste • Leak proof • Portability • Logistics efficiency (stacking, warehousing, shelf display and transportation)	• Minimize effort required to dispense product • Ability to use with one hand • Ease of opening and closing • Intuitive use • Pleasing texture • Visibility of the amount of product remaining in the container
Sustainability	**Aesthetics**
• Avoid over-packaging • Use of sustainable materials • Recyclability • Reusability • Reduced waste • Possibility of cleaning residues of container • Facilitate disassembly for material detachment	• Attractive container • Colour Attributes • Differentiation from competitive products • Follow packaging trends • Make fashion statement • Eco-natural aesthetic

Concept Map

The development of the initial concepts was based on brainstorming technique to enhance the creative process and trigger the generation of new ideas. The diagram shown in **Figure 28** represents a mapping for these ideas with the design requirements mentioned above in its central axis.

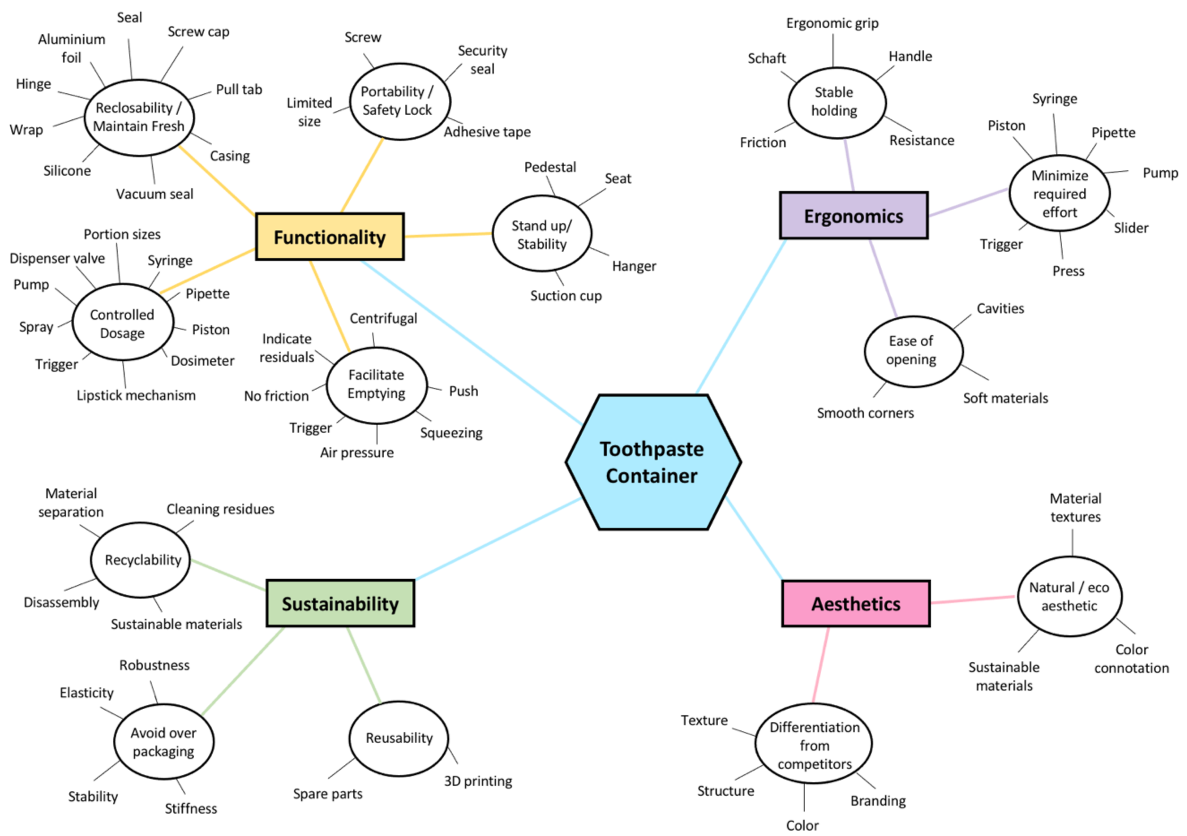


Figure 28 - Brainstorming concept map

In this early phase, one effective form of brainstorming is mind mapping. It consists of a visual representation of the ideas which can help on structuring and identifying relationships between concepts on the research topic at stake, by means of the decomposition of the main problem and the treatment of each sub problem separately.

5.2 | Concept Screening

This stage comprehends the evaluation of the concepts that result from the research performed during the Concept Generation stage, which will allow to narrow down the number of ideas into a single concept. This process consists of translating customer needs into technical requirements, starting from the VoC, through the HoQ, developed below.

5.2.1 | House of Quality

The first step toward understanding customer needs is to identify attributes and customer consequences. Attributes are defined as the physical or abstract characteristics of a product. They are objective, measurable, and reflect the producer's perspective. Consequences are a result of using attributes. Customers judge products based on their consequences, not their attributes. In other words, customers judge a product on its outcome, or effect of use on them. A product has many attributes, and each may have more than one consequence (Fisher and Schutta, 2003).

Customer Attributes (CAs)

Based on the inputs for the system design provided during stages 5.1.1 to 5.1.3 of the concept generation, the HoQ was used as the analysis tool for the several attributes extracted. The following CA's were derived:

1. **Hygienic:** Keep product well preserved and fresh, as well as prevents the toothpaste to touch the brush and then be drawn back into the container.
2. **No waste:** Almost all the toothpaste comes out.
3. **Easy to dispense:** It does not require too much effort to use.
4. **Retains shape:** the container retains its original shape.
5. **Reasonable cost**: It should cost about the same as present containers.
6. **Attractive container:** It must look good either on the shelf in the store and also on the counter in the bathroom.
7. **Leak proof:** Resistant to leaks.
8. **Squeezable:** People want to squeeze the container.
9. **Pleasing taste:** Enjoyable *toothpaste flavour*.
10. **Environmentally friendly:** Claim minimal, or no harm upon ecosystems or the environment.
11. **Resolve dental problems:** Clinically proven *toothpaste* for people with *sensitive* teeth and other *gum* problems.
12. **Portability:** The ability to be easily carried or moved.
13. **Possibility of Controlled Dosage:** The user decides the amount of toothpaste to be applied.

After listing the demands, the weights were assigned indicating the relative importance of each attribute. In order to do it, it was created a quest for potential users to rate. **Figure 29** shows the CAs with associated average weights from the responses collected.

Hygienic	5
Minimum waste	5
Easy to dispense	5
Retains shape	3
Reasonable cost	4
Attractive container	2
Leak proof	5
Squeezable	4
Pleasing taste	5
Environmentally friendly	4
Resolve dental problems	3
Portability	4
Possibility of Controlled Dosage	5

Figure 29 - Customer demands with associated weights

After listing the attributes, the customer importance ratings were assigned indicating the relative importance of each CA, based on the inputs from the survey. The ratings for the weights are between 1 and 5, with 5 being the most important rating. In this chart, apparently the consumer is the individual who brushes his teeth with the toothpaste. However, the term customer includes all people who should provide input for the system design: buyers, store managers, stockholders, employees, company management, and the company's Manufacturing and Marketing departments.

Technical Requirements (TRs)

The TRs are placed on the top of the house. These must be measurable and within the control of the manufacturer. The brainstorming with a product designer was used to develop the technical requirements, along with various Internet sources for references existing standards. Ten technical requirements were developed and organized using tree diagrams, to hierarchically structure ideas built from the top down using a logic and analytical thought process. The requirements for the toothpaste are the following:

1. **Malleable material:** toothpaste is easily squeezed through the container
2. **Hermetic:** completely sealed when tube is closed
3. **Squeezable top and bottom:** The container can be squeezed in the totality of its length
4. **Design for Logistics:** High productivity, efficiency and cost of logistical operations, from truck loading and warehouse picking productivity, to customer productivity and packaging waste reduction.
5. **Ergonomic convenience:** ease of handling and cleanliness
6. **Robustness:** the product is not prone to suffer performance degradations when rapped, overloaded, dropped, and splashed.
7. **Reusable:** Able to be used again

8. **Washable:** Able to be washed without damage
9. **Premium toothpaste:** The toothpaste itself is chosen by the consumer, so he can opt to use a mass-market option that he might prefer due to its texture, taste and therapeutic features.
10. **Different colors:** Available in different colors
11. **Limited size:** A size suitable for travel, especially small, compact, or able to be easily carried.

Relationship matrix

Once the CAs and the TRs were developed, a relationship matrix was constructed. The matrix defines the correlations between both as weak, moderate, or strong using a standard 9-3-1 scale. This matrix identifies the requirements that satisfy most customer demands and determines the appropriate investment of resources for each. Relationships were determined here on the basis of research conducted using resources available on the Internet. **Figure 30** displays the relationship matrix developed for the HoQ, along with the symbols that indicate a strong, medium or weak relationship.

	Customer importance rating (1 = low, 5 = high)	Percent of customer importance rating	Malleable material	Hermetic	Squeezable top and bottom	Design for Logistics	Ergonomic convenience	Robustness	Reusable	Washable	Premium toothpaste	Different Colors	Limited size
			▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
Hygienic	5	9%		◉	△			○	◉	◉			
Minimum waste	5	9%	○	◉	◉			◉	◉	◉			
Easy to dispense	5	9%	◉	○	○		◉	△					
Retains shape	3	6%	○			○		○	◉				
Reasonable cost	4	7%	△			◉		○	◉	◉	◉	△	○
Attractive container	2	4%	○				△					◉	
Leak proof	5	9%		◉			○	◉					
Squeezable	4	7%	◉	◉	◉	○	◉	○					
Pleasing taste	5	9%								◉	◉		
Environmentally friendly	4	7%	○			○			◉	◉			
Resolve dental problems	3	6%									◉		
Portability	4	7%				○	◉	○					◉
Possibility of Controlled Dosage	5	9%	◉		○								

Figure 30 - Relationship Matrix

The technical requirements that addressed the most customer consequences should be dealt into the design process to ensure a customer approved product. Ideally in the HoQ analysis, no more than 50% of the relationship matrix should be filled, and a random pattern should result (Fisher and Schutta, 2003).

Correlation Matrix

The roof of the house, called the correlation matrix, is used to identify any interrelationships between each of the technical requirements. Moreover, the symbols are used to describe the strength of the interrelationships, allowing the identification of which TRs support one another and which are in conflict. **Figure 31** shows the correlation matrix of the toothpaste container.

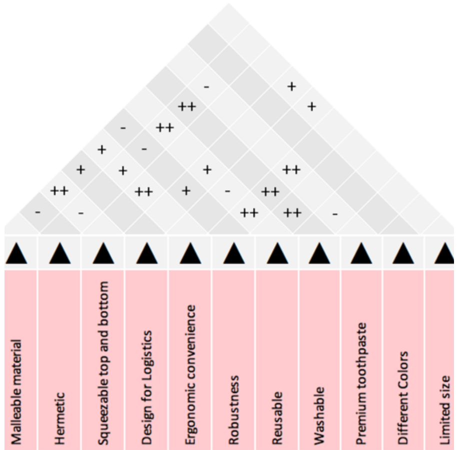


Figure 31 - Correlation Matrix

The relative importance of each technical requirement was calculated by multiplying the value assigned to its relationship with a specific consequence (9, 3, or 1) multiplied by the importance of that consequence; the values of all consequences were then added to yield the final weight. These weights were placed in a row at the bottom of the HoQ. A final weight is a comprehensive measure that indicates the degree to which the specific technical requirement relates to the customer consequences.

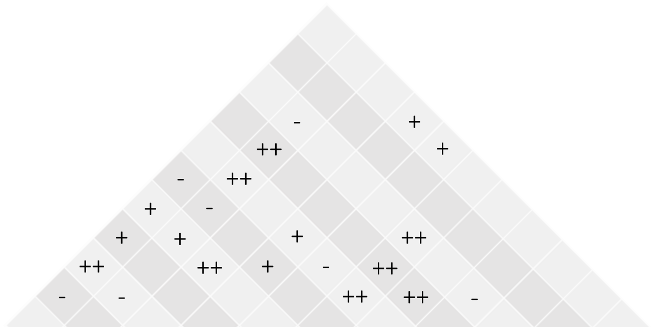
The full overall HoQ for the new toothpaste container product is shown in **Figure 32** below. From the HoQ, the most important quality characteristics worth to be considered for this product are (1) Malleable material with a weight of 17%, (2) Washable with a weight of 14%, followed by (3) Hermetic and (4) Reusable, both weighting 13%.

The HoQ realizes the need for a container composed of a malleable and flexible material, a characteristic that will allow it to have a better performance in the other technical requirements pointed. Such material is required to be robust and able to be reused through multiple washes, since hygiene is an attribute valued by the consumer especially given the product we are dealing with, that is required to be well preserved and fresh. By being malleable it will also allow the toothpaste squeeze and therefore the possibility to control the dosage applied for each use. The ability to choose the toothpaste that is used within the container is also valued by users. Many consumers already have their toothpaste brands of choice, whether for the taste, the feeling of freshness it provides or even for being suited to particular medical conditions.

The next section will detail the proposed solution taking into account the research carried out up to this point.

Correlation matrix	
++	Strong positive
+	Positive
–	Negative
– –	Strong negative
	Not correlated

Relationship matrix		
◉	Strong	9
○	Medium	3
△	Weak	1
	No assignment	0



	Customer importance rating (1 = low, 5 = high)	Percent of customer importance rating	Malleable material	Hermetic	Squeezable top and bottom	Design for Logistics	Ergonomic convenience	Robustness	Reusable	Washable	Premium toothpaste	Different Colors	Limited size
			▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
Hygienic	5	9%		◉	△			○	◉	◉			
Minimum waste	5	9%	○	◉	◉			◉	◉	◉			
Easy to dispense	5	9%	◉	○	○		◉	△					
Retains shape	3	6%	○			○		○	◉				
Reasonable cost	4	7%	△			◉		○	◉	◉	◉	△	○
Attractive container	2	4%	○				△					◉	
Leak proof	5	9%		◉			○	◉					
Squeezable	4	7%	◉	◉	◉	○	◉	○					
Pleasing taste	5	9%								◉	◉		
Environmentally friendly	4	7%	○			○			◉	◉			
Resolve dental problems	3	6%									◉		
Portability	4	7%				○	◉	○					◉
Possibility of Controlled Dosage	5	9%	◉		○								
Importance rating			4.52	3.44	2.15	1.50	2.48	2.65	3.50	3.83	2.00	0.41	0.89
Percent of importance			17%	13%	8%	5%	9%	10%	13%	14%	7%	1%	3%

Figure 32 - House of Quality for the new toothpaste design

5.2.2 | Solution Proposal

The research conducted in section 5.1.2 revealed that the majority of customers are willing to switch to a sustainable alternative, however they are reluctant on abandoning a familiar format to which they are already accustomed, especially regarding the type of paste, which should preferably be a gel.

Hence the selected concept which meets the majority of design requirements is based on the squeeze mechanism that combines both research queries. The solution is based on a CBM with a hybrid model where the toothpaste tube is a container made of recyclable materials that can be refilled and therefore reused with toothpaste bought separately. This design stands on the ease of reuse, disassembly and recycling, rather than the continuous extraction of resources on a take-make-dispose system. Therefore, this proposed system will bridge the CE principles of optimizing the use of resources and energy throughout lifecycles by mapping of the connections between design decisions and resource demand in the manufacturing, use and end of life phase through the use of the LCA method, and maintain products and components in use for longer by extending the product life from a few weeks to years. This product's innovative design and development process integrates the eight DfE axioms that brings together environmental and business benefits, since it allows for greater resource efficiency, added functionality and effectiveness and better product differentiation in an overcrowded market such as the toothpaste market. Next, the product will be broken down into its components, explaining the features and functionalities of each one in a perspective of "works like" and "looks like" prototype.

Reusable toothpaste tube

The most important quality characteristics that can be derived from the HoQ narrow down the number of material options. It should have plastic properties, since it has to be extremely malleable and robust, allowing a long-life cycle through a great number of reuses and washes, while lightweight for maximized logistics efficiency. Silicone has become very popular as an alternative to plastic over the years. Silicone rubber is an elastomer composed of silicone, itself a polymer, containing silicon together with carbon, hydrogen, and oxygen. It is non-reactive, stable, and resistant to extreme environments and temperatures from -55 °C to +300 °C while still maintaining its useful properties. Due to these properties and its ease of manufacturing and shaping, silicone rubber can be found in a wide variety of products, including automotive applications, cooking, baking, and food storage products, apparel such as undergarments, sportswear, and footwear, electronics, medical devices including use in implants, menstrual cups and catheters, and as a sealant used in building construction and maintenance. Silicone, like plastic, can be recycled multiple times, however it usually has to be sent to a specialized recycling company to be properly recycled. It can also be incinerated safety without toxic off-gassing. When burned, silicone reverts back into its harmless ingredients (amorphous silica, carbon dioxide, and water vapor), unlike plastic which releases toxins when burned (David Suzuki Foundation, 2021).

Taking this in consideration, the tube is made of soft and squeezable BPA free food grade silicone that only dispense its contents when the silicone body is pressed. Each container includes a flip cap and a dispenser valve to protect from leaks, spills or drops. This high-end material is safe, nontoxic, non-allergenic and non-reactive, eco-friendly, extremely durable and resistant, possessing a long lifespan up to 30 years (United Silicones, 2020). It can be transparent, which is convenient to control the remaining amount. In addition, this tube's wide mouth opening makes refills and cleaning easy. The cleaning of these durable containers can be executed by soaking them in warm soapy water or by using the dishwasher. These tubes can also be made in several sizes and different colors. The standard tube of toothpaste usually has a volume of 75 ml and weighs between 90 g and 100 g (ChackPack, 2020). Therefore, this prototype will follow a similar standard having a size of 80 ml, which is an easy to carry and travel with size that consumers are already used to have in their homes. The described travel silicone bottle is shown in **Figure 33.**

Figure 33 - Travel silicone bottle configuration (Amazon, 2021)

This silicone bottle concept has an additional feature: a zip lock top. Several companies produce silicone zip bags like the ones shown in **Figure 34**, ideal to replace single-use plastic bags and plastic food storage containers with lids. These containers are equipped with a double closing design suitable for all liquids without leaking.

Figure 34 - Silicone zip top containers (Zip Top, 2021)

This feature will allow an easy refill process for the toothpaste, which is inserted through the top opening. On the other hands, when closed, the zip will ensure that the toothpaste does not escape.

Toothpaste Cap

The Cap is made of polypropylene, which is known for good impact strength, durability, cost effectiveness, thermal resistance, and pliability. PP is 100% recyclable (Omnexus, 2020) and considered safe for reuse (Eartheasy, 2020), and one of its greatest benefits is that it can be employed in the manufacture of living hinges as it does not break when repeatedly bent, either through computer numerical control (CNC) or injection moulding, thermoforming, or crimping (CM, 2020). The lid has a set of spikes that ensure that when the refill is placed inside the container it is perforated to release the toothpaste, as **Figure 35** displays.

Figure 35 - PP lid indicating the positioning of the set of spikes

Toothpaste Refills

Like Tide pods, there are already companies developing sustainable solutions for processing personal care and cosmetics products by packaging them in water-soluble and biodegradable film. Similarly, individually portioned instant coffee, pasta, oatmeal or servings of protein powder encased in edible packaging that dissolves as soon as it hits water could become a staple in households as firms seek to reduce packaging waste, boost convenience, and help consumers engage in portion control.

The toothpaste gel pods presented earlier have a breakthrough design capable of replacing traditional toothpaste tubes. These small pods called Poppits developed by a Florida-based start-up are eco-friendly and leave zero waste. On the outside each pod is sealed in a biodegradable soluble film that melts inside the mouth and releases the dentists recommended amount of toothpaste. This edible food-grade film is made of Polyvinyl Alcohol (PVOH), which is safe, GRAS-certified by the FDA, environmentally friendly and is used in other nutrition supplements and food products. It dissolves completely in water and naturally breaks down into water and carbon dioxide. It does not persist in the environment, contaminate the recycling stream nor contribute to micro-plastic pollution (Poppits, 2021). Since the pods are made from an edible food-grade film, and therefore especially water sensitive, their current package is made from aluminium, which has the particularity of being rust-proof and infinitely recyclable, however its processing is water and energy-hungry and produces a variety of pollutants. In addition, the production results in major amounts of solid waste and sludge to be disposed of as only one-fifth of the raw material ends up in the final product. The companies that currently employ this technology can use two types of outer films (1) a *food grade film,* which due to its sensitive characteristics has to be packaged in more rigid and moist free packaging, as well as *(2) a technical film,* which possesses the same solubility properties but is thicker and therefore less sensitive, beyond the fact that it is cheaper. In the same scope, the US company MonoSol, which makes patented food grade water soluble film from PVOH, is already packaging hand wash, shampoo, conditioner or shaving cream in it (MonoSol, 2021).

Figure 36 displays the inspiration pods that gave rise to the concept to be used in this study. The proposed refill solution requires the same pod technology, but instead of having a pea size with the recommended amount of toothpaste for one brush, it holds the same amount of toothpaste of a regular tube of 80 ml. The company can use two types of outer films (1) a *food grade film* which must be packaged under the above conditions due to its sensitive characteristics, as well as *(2) a technical film* which possesses the same solubility properties but is thicker and therefore less sensitive.

Figure 36 – Water soluble film. On the left: Poppits toothpaste pod (Poppits, 2021). On the right: Hand wash pods (Monosol, 2021).

Refills primary packaging

As mentioned above, the refills are water and impact sensitive, which invalidates the use of paperboard to carry them. The best solution that combines the desired unique properties of keeping the liquids in but the microbes out, and a strong but lightweight container are Tetra Pak food cartons. These cartons are mostly made (about 75%) from wood. Aseptic cartons (those that don't need refrigeration) then use a layer of aluminium (5% of aluminium) to preserve the product and layers of plastic (20% of polyethylene) to seal the container. Non-aseptic cartons (for fresh products with shorter shelf lives) don't need aluminium. These materials are layered together using heat and pressure to form a six layered armour which protects the contents from light, oxygen, air, dirt and moisture. Furthermore, Tetra Pak cartons are lightweight, easy to transport and fully recyclable (Tetra Pak, 2021). A comparative LCA led by the german institute IFEU, compared the environmental footprint of cartons, glass jars, tin cans and retortable pouches by measuring its performance in eight categories. Cartons came ahead in all but one category (use of nature, because of their use of trees). The study showed that cartons' total primary energy consumption was the lowest of all four systems. The difference was even starker for CO2 emissions, with pouches emitting 57% more CO2 over their lifecycle than cartons, tin cans 120 per cent more and glass jars 150% more. Both studies put the differences down to raw material, weight and shape. Cartons' main raw material is wood, a renewable source, and paper mills use wood dust and waste as their main source of energy to convert it to paperboard. Steel, glass or aluminium containers on the other hand need large amounts of fossil fuel to convert their respective raw materials. Then there's the light weight and the rectangular shape, two attributes that make cartons highly efficient in transport compared to round and relatively heavy cans and jars (The Ecologist, 2010).

Thus, it is concluded that this type of carton is the material that makes more sense as packaging for the refills, that is proposed to come in packs of two, saving both on packaging material and transport, reducing the number of travels to the points-of-sale to purchase more units.

5.3 | Preliminary Design: Sustainability evaluation

The LCA results per step are going to be described below.

5.3.1 | Goal and Scope

A detailed explanation and description of each goal and scope phase is described next, in line with the principles of the ISO standards 14040–14044.

Goal Definition

The primary goal of this study is to determine the environmental burdens of adopting the new toothpaste package developed relative to the mass-market alternative packaging, using the LCA methodology.

The different toothpaste packaging systems at issue are (1) the food grade silicone (FGS) bottle with PP cap, (2) the standard laminate tube and (3) the HDPE mass-market variant for toothpaste container, which for the analysis will be called (1) *New System,* (2) *Traditional System 1* and (3) *Traditional System 2*, respectively. The three will package 75ml of toothpaste. In the theoretical substitution analysis, the impacts of current amounts of laminate and HDPE packaging are compared to a scenario in which these containers are substituted by the silicone as an alternative material that extends its lifecycle. All of the plastic resins investigated in this study are modelled to be sourced from fossil fuels (i.e., natural gas and petroleum). Though there have been recent developments in the production of biomass-based plastic resin, the market shares of these materials are not yet sufficient to warrant analysing their substitution with other materials (ACC, 2018).

All in all, this analysis was conducted to provide a transparent and detailed LCA whose results serve several purposes (1) To provide valuable information about the relative life cycle environmental impacts of toothpaste packaging when compared with the proposed packaging substitute, (2) Communicate the environmental burden that the current model represents, and (3) to provide contribution to sustainable development with key regional data for the European market.

Scope Definition

This section discusses the overall scope of the study necessary to accomplish the stated goal. The LCA components covered include the functional unit, product systems studied, study boundaries, sensitivity analysis, allocation, impact assessment methodology and assumptions.

From ReCiPe Endpoint (H), the impact categories addressed in the analysis include

- Agricultural land occupation
- Climate change Ecosystems
- Climate change Human Health
- Fossil depletion
- Freshwater ecotoxicity
- Freshwater eutrophication
- Human toxicity
- Ionising radiation
- Marine ecotoxicity
- Metal depletion
- Natural land transformation
- Ozone depletion
- Particulate matter formation
- Photochemical oxidant formation
- Terrestrial acidification
- Terrestrial ecotoxicity
- Urban land occupation

Functional unit

The functional unit (FU) is intended as a reference unit for which the inventory data are normalized (ISO, 2006a, b). The function examined in this LCA study is the packaging of toothpaste for retail. According to the manufacturers, the food grade silicone container will have an estimated lifespan of 10 years during which a warranty is offered, while the 75ml tube has an average lifespan of few months. The primary packages examined are technically equivalent regarding the mechanical protection of the packaged toothpaste during transport, the storage at the point-of-sale and the use phase. Considering this, and since the intention is to compare the environmental impact generated by toothpaste packaging with different lifecycles, the functional unit is the number of brushes over a 10-year period. Assuming brushing two times a day, this represents 7300 washes during the time boundary considered.

The American Dental Association (ADA) recommends a pea-size amount of toothpaste, which is about 0.25 grams of toothpaste. Creeth et. al (2013) investigated, using conventional toothpastes in Germany, the USA and the UK, how much toothpaste individuals dispense, and their interpretation of a 'pea-sized' amount of toothpaste. When asked to dispense the amount they would normally use, the majority of dosed substantially more than 0.25 g. **Figure 37** quantifies the amount of toothpaste for the different volumes illustrated. According to this study the quantity of toothpaste dispensed (g) under ‘pea-sized’ dispensing regimen averaged around 0.50 g, which is roughly the amount shown in (b) from **Figure 37**.

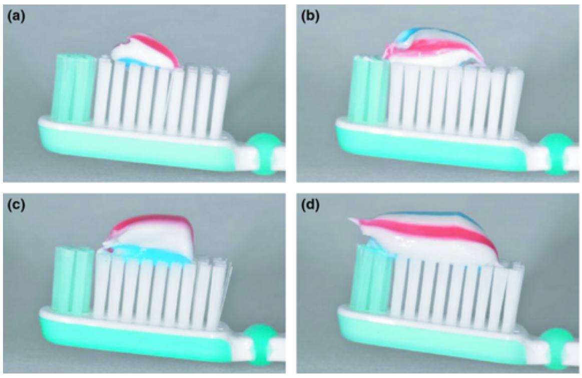


Figure 37 - Toothpaste dispensed in different quantities: (a) 0.25 g, (b) 0.50 g, (c) 1.00 g and (d) 1.50 g.

In order to determine the lifecycle of toothpaste to be used by one-person, other assumptions are relevant to take into consideration:

(1) Use 0.50 g of toothpaste per brush
(2) Toothpaste size of 75 ml
(3) Toothpaste density of 1.3 g/ml

With the density provided, 0.5 g is just under 0.4 ml of these toothpastes. This means that a tube will last approximately 188 brushes, which brushing twice a day corresponds to 3 months of use. Given this need, **Figure 38** illustrates the use of packaging over the 10-year period. Both Traditional Systems 1 and 2 require the same number of packages, which corresponds to 40 units (on the left of Figure 38). The New System, on the other hand, requires only one silicone squeeze tube, accompanied by 40 refills present in 20 packs (on the right of Figure 38).

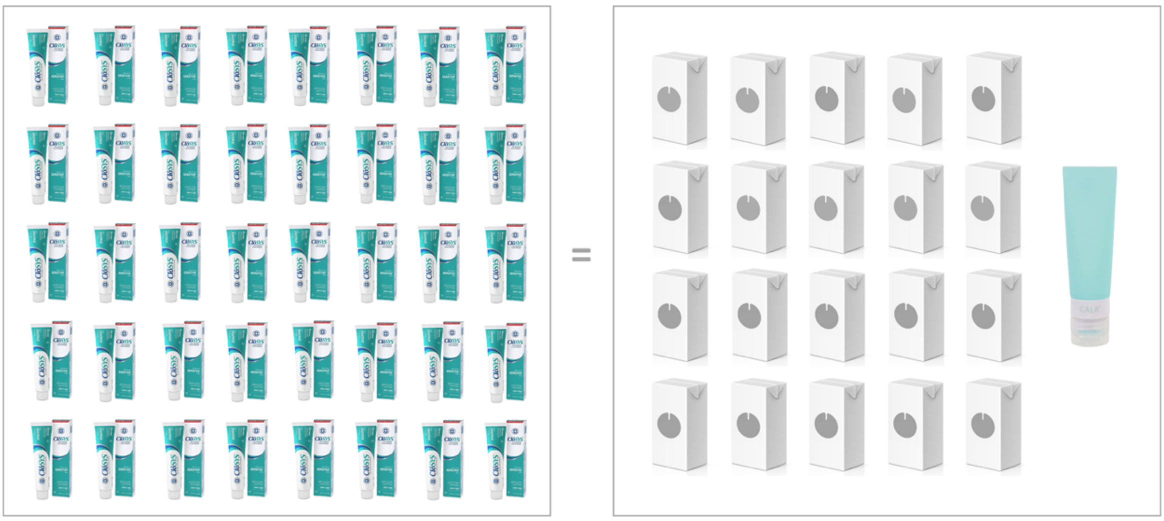


Figure 38 - Packaging requirements for the functional unit during the stipulated 10-year time frame

System boundaries

This study is a 'cradle-to-grave' LCA, in which the processes considered for each packaging system are the extraction of the packaging raw material, the resin production, the container formation (taking into account the different processing phases) and, finally, the end-of-life of packaging materials (tubes and secondary packaging). This study also includes the closed loop recycling through the recycling of carton and plastic materials during the manufacturing phases. The analysis carried out will comprehend the container alone, and therefore does not take into account the toothpaste inside of it, the loss during the filling phase or use of the toothpaste. In order to get the comprehensive results, the transportation was included within this system's boundaries, especially because of the long distances over which the raw materials for the composite packages needed to be transported. Finally, the materials end-of-life is also assessed, considering the European scenario as the reference, in terms of the percentage of raw materials recycled, incinerated and disposed to landfill. A scheme of the system boundaries and of the processes considered in the analysis is reported in **Figure 39** and **40** for the Traditional System 1 and 2, respectively, and **Figure 41** for the New System.

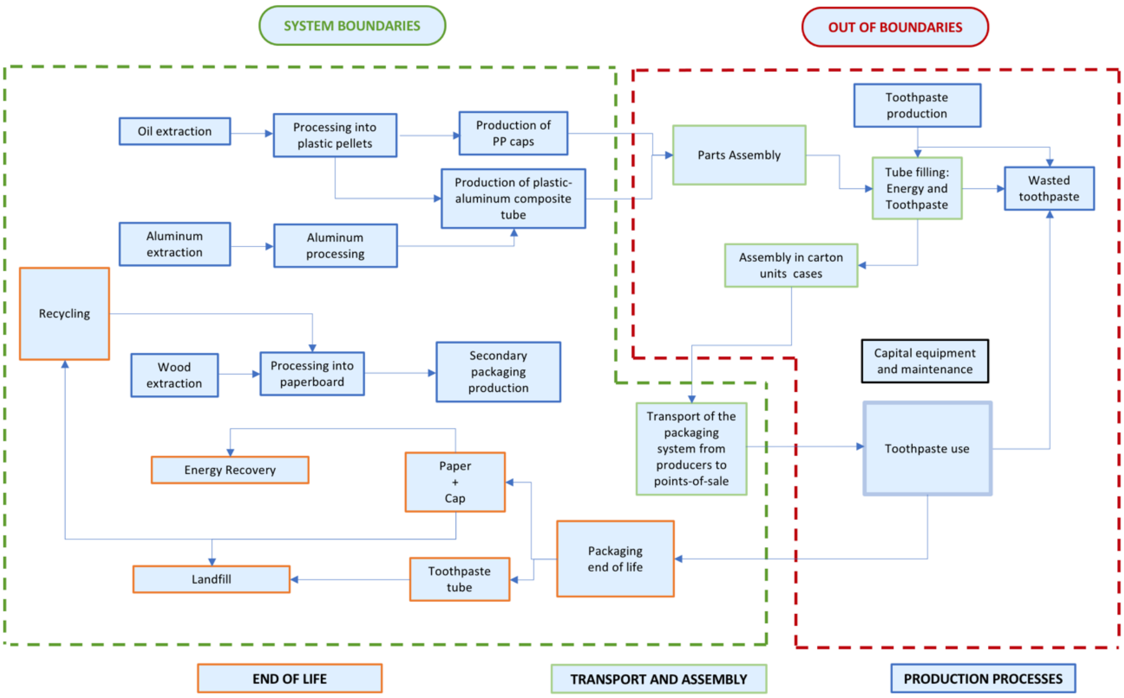


Figure 39 - Cradle-to-Grave Evaluation Boundaries for the Traditional System 1

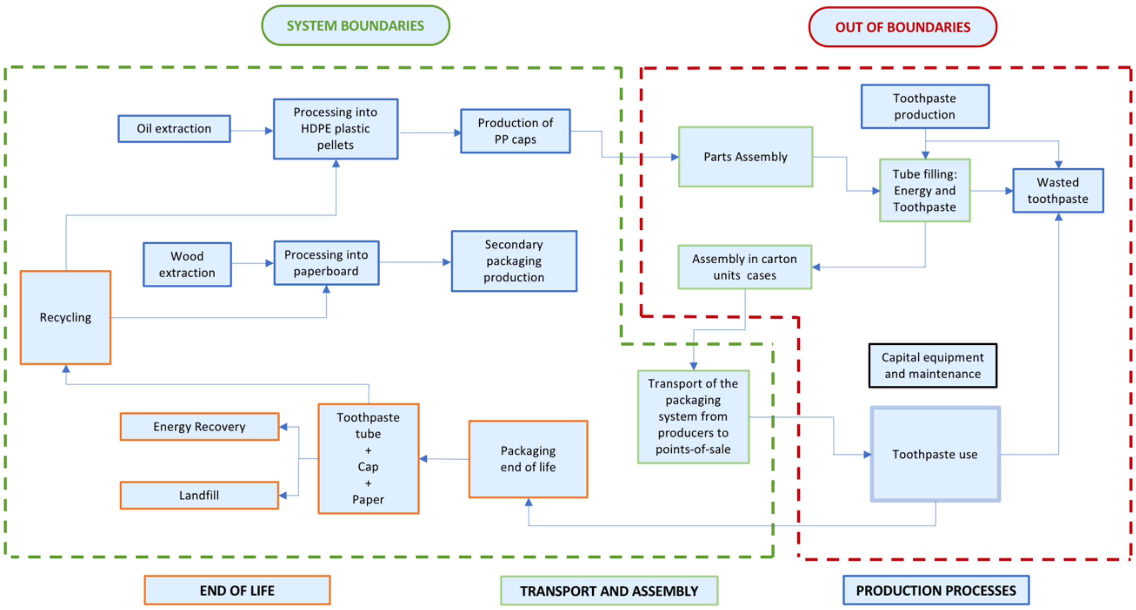


Figure 40 - Cradle-to-Grave Evaluation Boundaries for the Traditional System 2

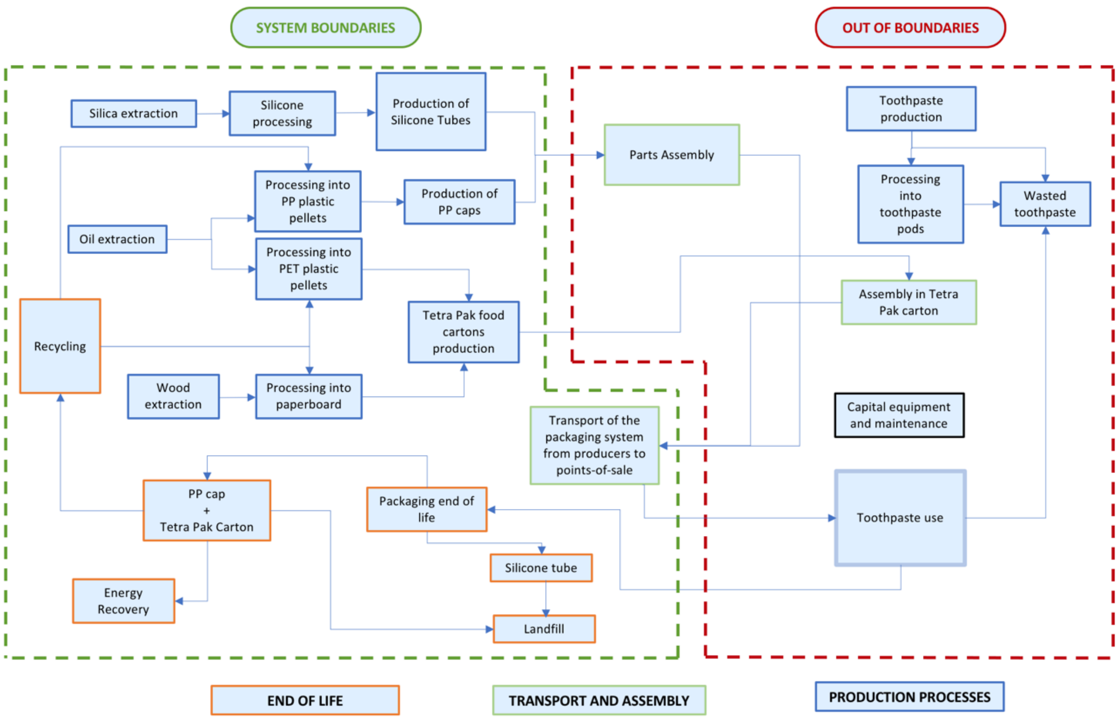


Figure 41 - Cradle-to-Grave Evaluation Boundaries for the New System

5.3.2 | Inventory analysis

The life cycle inventory analysis quantifies the resources usage, energy usage and environmental releases associated with the system under examination, by means of a mass and energy balance of each FU (ISO, 2006a, b).

Packaging materials

The average weights of the packaging materials are displayed in **Table 12.** Both packaging systems require a container and a cap, however only the HDPE requires a secondary packaging whereas the silicone tube system will require a primary packaging for the refills. All the average weights of the packaging materials for which no reference is given were obtained by weighing the empty containers directly. For those where this was not possible, reference is made to their respective source of information.

Table 12 - Weight of packaging materials for 1 FU

	Part	Material	Unit mass (g)	FU mass (g)	Process
Silicone Tube	Container	Food Grade Silicone	30	30	Extrusion
	Cap	PP	8	8	Injection moulding
	Refill primary package	Mutilayer carton (Tetra Pak™)	18 (Tetra Pak, 2008)	360	Beverage carton converting process
Laminate tube	Container	Plastic barrier laminate (PBL)	12	480	Injection moulding
	Cap + nozzle	PP	8	320	Injection moulding
	Secondary packaging	Paperboard	12	480	Carton board box converting process
HDPE tube	Container + Cap	HDPE	20 (Paben, 2019)	800	Injection moulding
	Secondary packaging	Paperboard	12	480	Carton board box production process

End-of-life of packaging

Data related to the packaging end-of-life scenario, such as the percentage of packaging recycled, incinerated or disposed in landfill are based on industry average data and for European conditions. For paper data as presented by the Confederation of European Paper Industries (CEPI, 2019) is used, for production of liquid packaging board average data as presented by the Alliance for Beverage Cartons and the Environment (ACE, 2020) is used and for plastics data as presented by Plastics Europe is used (Plastics Europe, 2019)**.** The end-of-life scenario of silicone is assumed to reach landfill in its entire flow, while for the PBL container a 50% rate for incineration and landfill was adopted. The assumptions for this study are showed in **Table 13**.

Table 13 - European end-of-life scenario for packaging materials

Packaging materials	Recycle (%)	Energy Recovery (%)	Landfill (%)
Paper (CEPI, 2019)	72	6	22
Plastic (Plastics Europe, 2019)	32.5	42.6	24.9
Multilayer carton (ACE, 2020)	47	29	24
Silicone	-	-	100
PBL	-	50	50

Transportation

In line with the life cycles previously described, the transport activities consist typically in the shipping of

1. The raw materials, from the material supplier to the packaging manufacturer.

2. The packaging materials, from the packaging manufacturer to the toothpaste producer.
3. The packaged products, from the toothpaste producers to the retailers.
4. The end-of-life materials to the respective points of treatment, either recycling, incineration or landfill.

The transport distances of raw materials in this study were calculated based on the average distances between each supplier and the manufacturing plants estimated by the Ecoinvent database for the European (RER), Switzerland (CH), rest of the world (RoW) or global (GLO) regions.

Regarding the transportation of the products from the producers to the retailers it was assumed a distance of 581 km (Eurostat, 2019), which is the average road freight distance within the European context.

Transport distances for different waste types may also vary according to the number of treatment sites. For example, hazardous waste may have the longest transport distance, owing to the limited number of sites, whereas inert waste may have the shortest. Current practice in generic databases take into account between 10 and 30 km for inert and non-hazardous wastes, as well as for incineration with energy recovery and around 100 km for hazardous wastes. Since this is not considered hazardous waste, a distance of 20 km was assumed. For recycled products sent to a recycling facility it is likely that the distance will be higher because, to date, the number of recycling facilities is still low, leading to higher distances than for landfill facilities. As an average value, 250 km for trucks can be assumed. (EeB Guide, 2012).

For the purpose of a sensitivity analysis, it was tested the hypothesis of having the New System silicone container being produced in China, where distances for both sea and rail freight were considered. For sea freight via de Suez Canal the average distance is 20 921.5 km (The Washington Post, 2018) and for the China-Europe rail freight the distance considered was 11 000 km (Manaadiar, 2018).

5.3.3 | Impact Assessment

The end-point results are aggregated to achieve the single-score LCA impact results which are presented in **Figure 42**. The Traditional System 1 and Traditional System 2 carry the total single-score (SS) impact of 671 mPt and 496 mPt, respectively, while the New System carries the total single-score impact of 134 mPt. The SS impacts indubitably demonstrate the New System as the most environment-friendly toothpaste container solution, representing less than a third of the impact generated by Traditional System 2 and five times less impact than the Traditional System 1. It is worth mentioning here that 1-point (1 Pt) LCA impact indicates the impact caused by an average global citizen over the time period of 1 year.

The New System improves all the three impact categories, but of special note is the relief it represents in the *Resources* category, which is the one whose weight is greater in the other systems. While *Resource*s impacts almost 50% of the SS of both Traditional Systems (43% for Traditional System 1 and 47% for Traditional System 2), it impacts only 20% in the New System. The major constituent of the Traditional systems are HDPE and LDPE, which come from hydrocarbons derived from crude oil, natural gas and coal – fossil fuels, which explains why for both systems this category gets the damage contribution based on fossil fuel depletion impact.

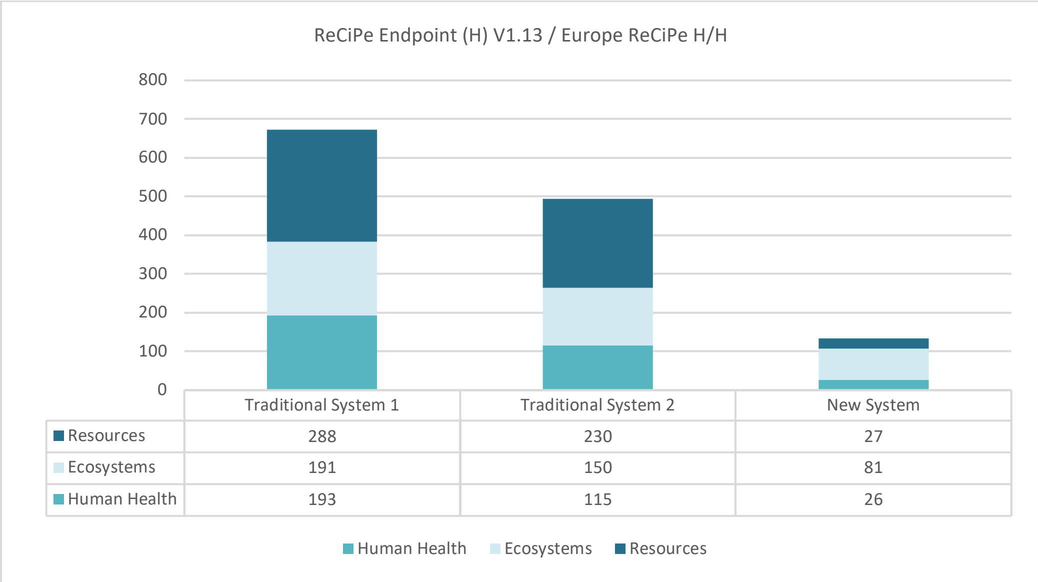


Figure 42 - Endpoint-based SS analysis using the ReCiPe Endpoint (H) V1.13 / Europe ReCiPe H/H

The *Ecosystems* category in the New System is the one which weighs the most, roughly 60% of its SS, precisely because of the constitution of its FU. For the New System, the most significant damage is contributed by the *Ecosystems* impact category. This impact is justified by the contribution of the impact category *Agricultural land occupation*, due to the need of wood for the Tetra Pak packaging. This package represents 90% of the volume of material needed for a FU, of which 75% is paper. In addition to *Agricultural land occupation*, the *Fossil depletion* and *Climate change Human Health* impact categories add up to a total of 83% of the impacts this system, as the Pareto Analysis in **Figure 43** exhibits. The Pareto Principle states that roughly 80% of consequences come from 20% of the causes, proving to be valid in all the systems studied.

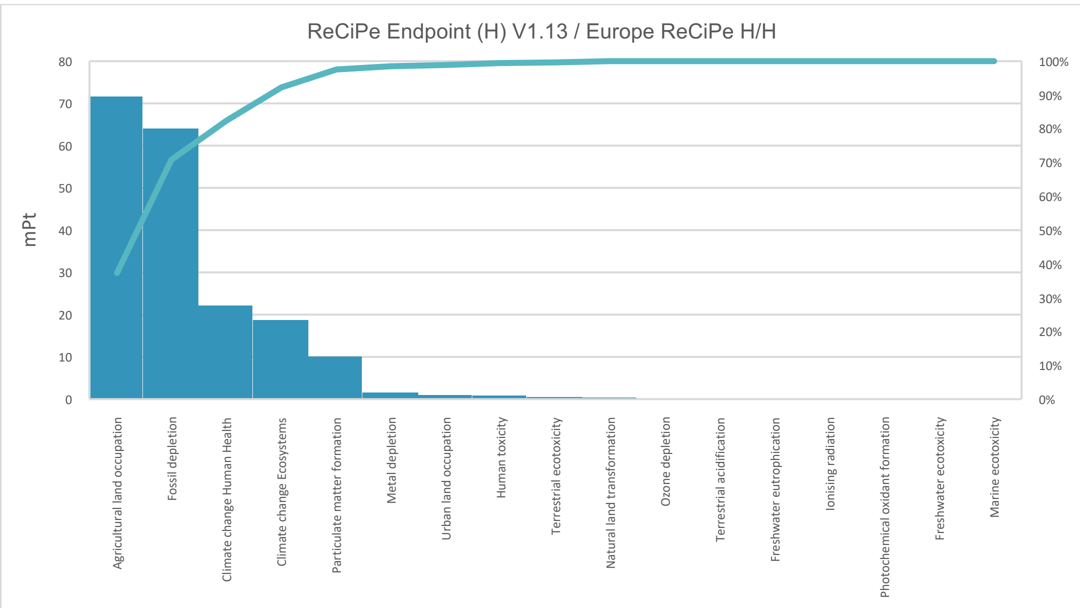


Figure 43 - Pareto Analysis for New System

The last two impact categories mentioned, see their weight coming mostly from the cap and silicone container components. While the base silicon comes from quartz, a plentiful resource, the hydrocarbons used to make silicone usually come from petroleum or natural gas.

Figure 44 illustrates the Tetra Pak refill packaging alone representing 89% of the SS and therefore almost the entire impact, since (as mentioned) it is the highest volume material in the FU and is not subject to successive reuse (although recyclable). Note that the contributions shown in **Figure 44** and **45** are only for the production phase of the components and does not include the waste scenario.

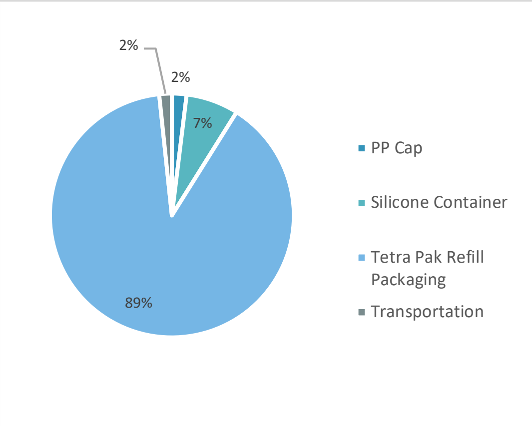


Figure 44 - Contribution by component

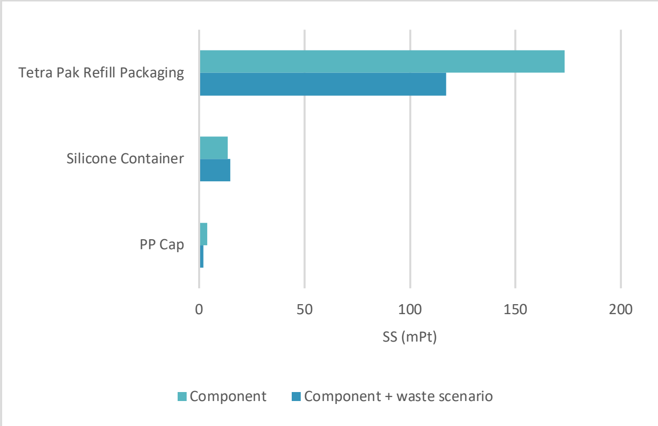


Figure 45 - Components impact Pre vs Post waste scenario

By including the waste scenario into the equation, the packaging component that showed the most impact is also the one that experiences the greatest SS reduction when this last stage is included in the product lifecycle, experiencing 32% reduction, as **Figure 45** exhibits. On the other hand, although with a reduced impact, when the waste scenario is considered into the silicone container its impact increases 9%. The treatment of this component adds to its total impact, since silicone is typically a difficult material to recycle and has to be treated in sanitary landfill systems. The incineration scenario was not considered, but it should be added that silicone doesn't give off toxic gases when incinerated. If incinerated in waste treatment plants, silicone only gives off silicon, carbon dioxide and water vapour, in comparison with the toxic gases generated by burning plastics. Finally, the cap is likely to see its impact reduced by up to 36%. The treatment of this plastic is particularly worthwhile as it not only leads to very significant energy and consumption of fresh raw materials savings from recycling and incinerating, but also reduces the accumulation of plastic waste in the environment, mitigating water and air pollution.

The results obtained in the Impact Assessent stage prove that the New System has the potential to replace the current traditional toothpaste systems, by demonstrating a very significant reduction in the environmental impact generated. This impact, quantified by the SS, showed that the New System has an impact 80% lower than the impact caused by the Traditional System 1 (the most commonly used today) and 72% lower than the Traditional System 2. This results also show that refill packaging weighs the most in its SS, since it is the only element of the system that is not subject to reuse. Due to the sensitive toothpaste packaging conditions, the refill container has to possess a very specific composition for which the existing margin for impact reduction was smaller compared to that of the main container (silicone body and the PP cap).

In summary, the impact assessment allowed to confirm the environmental viability of the New System, whose performance dethroned its Traditional peers. The next step is to test the robustness of this environmental performance through sensitivity analysis.

5.3.4 | Sensitivity analysis

A sensitivity analysis determines how different values of an independent variable affect a particular dependent variable under a given set of assumptions. In other words, it studies how various sources of uncertainty can contribute to the model's overall uncertainty. In this case it made sense to analyse two scenarios: firstly, to understand the impact on SS by producing larger refills, and therefore requiring less packaging, and secondly the impact of moving the silicone container production from Europe to China.

a) Vary the toothpaste volume from the current size to 150ml

The increase in container capacity leads to an increase in refill volume, which allows for fewer containers in the total life cycle, and therefore the SS impact tends to be lower. However, it stabilises as higher volume also requires more material, both silicone and Tetra Pak containers. This behaviour is described in **Figure 46** below.

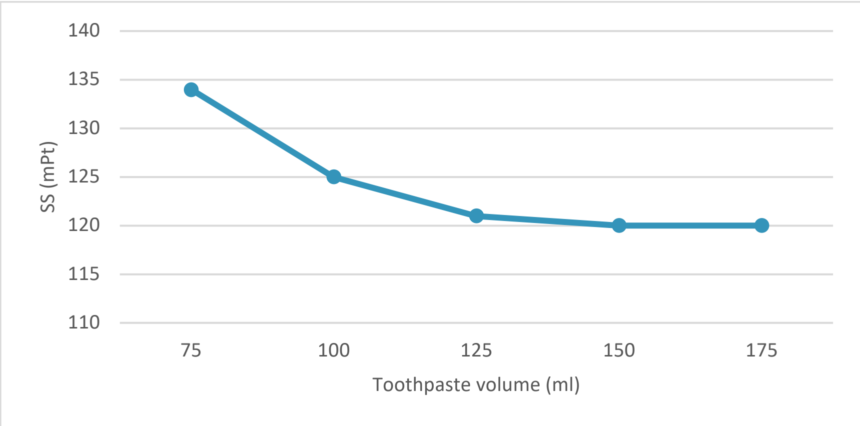


Figure 46 - Single Score variation with the change in the volume of toothpaste for the ReCiPe Endpoint (H) V1.13 / Europe ReCiPe H/H method

The aim of this analysis was to understand if using larger volume folders would have such a reduction in SS that it would compensate for consumers having to use larger packaging. From the results displayed above it can be observed that this reduction is very small, reaching at most a decrease of 15 mPt. Hence, it is concluded that the volume of the container will not be a feature target of change, given the residual benefit, as well as the opinion of consumers towards larger sizes. Such sizes may restrict the acquisition of this product, since it no longer has a travel size, making it less suitable to be transported.

b) Silicone tube production in China

Today, China is the world's largest manufacturing powerhouse and hence the need to understand if the increment of moving the production to this country would be considerable and decisive for the production site selection. Two possible transports for the New System were considered (NS China: Road + Train and NS China: Road + Sea) comparatively to the transport baseline by road in the European context with the aforementioned transport assumptions (NS Europe: Road).

As expected, there is an increase in SS since there is an added impact caused by the greater distance travelled. As it may be observed in **Figure 47,** the impact of moving production of this component to China is slightly higher when opting by train freight, versus the sea transportation. For comparison, Single Score of both Traditional systems 1 and 2 (TS1 and TS2) is described in the chart, still showing a much higher impact.

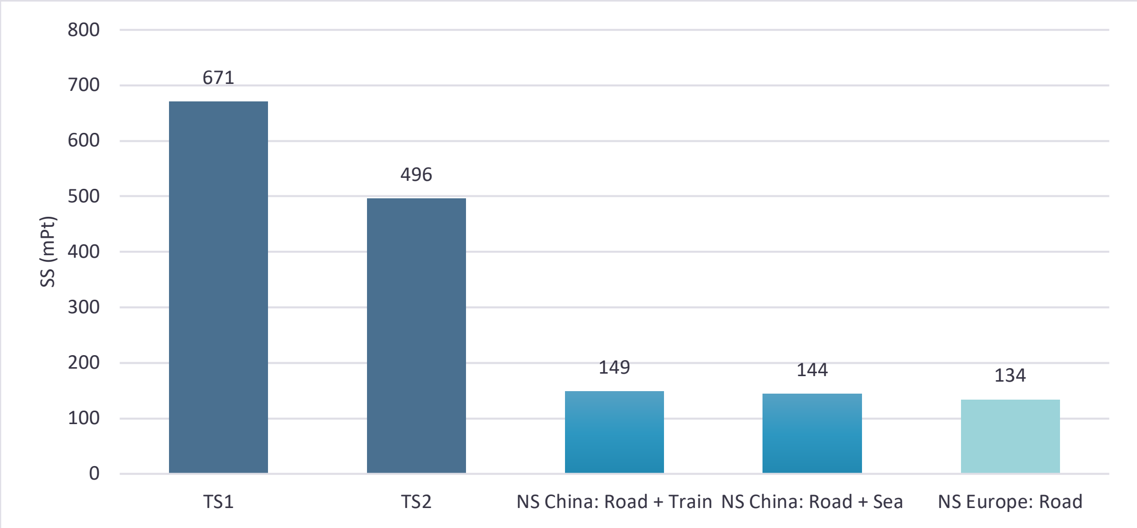


Figure 47 - Change on SS by moving the production of the silicone container to China for the ReCiPe Endpoint (H) V1.13 / Europe ReCiPe H/H method

For both transport means the impact is compared to the baseline for road transportation in Europe, leading to a SS increase of 7% and 11% for sea freight and train freight, respectively. Despite this increase, given that the total impact is small, these percentages translate into an increase of 10 mPt for sea and 15 mPt for train transportation, which shows that if there is a need to allocate production to China, even using the transportation with greater impact, it will not be a dealbreaker. There is therefore the flexibility and possibility to do so for financial reasons, as well as technology or raw materials availability.

The next section will present the primary prototype of the proposed solution.

5.4 | Prototyping

As already detailed in the solution proposal of the Concept Screening stage, the selected concept which meets the majority of design requirements is based on the squeeze mechanism. The aim is that this solution represents for the consumers the minimum disruption and effort of getting used to it, as it works in the same way as the standard tubes. This represents a great advantage over other solutions as it can be more easily adopted by a wider audience, especially if they can choose the flavour and brand of their favourite toothpaste for the refills.

The described system is shown in **Figure 48**.

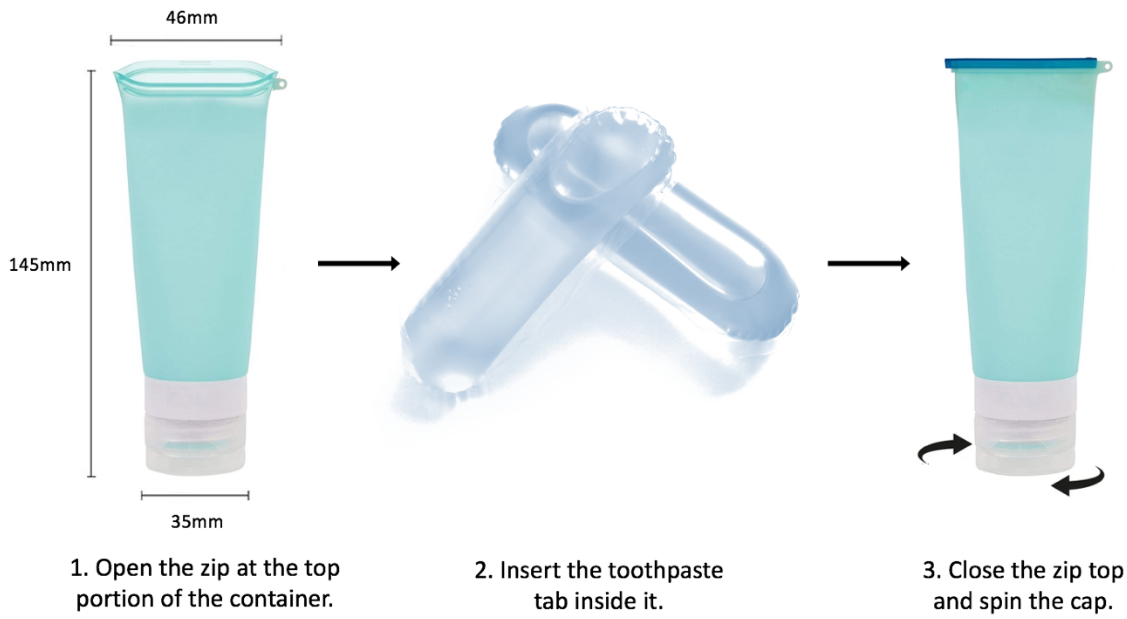


Figure 48 - Toothpaste design proposal

The user should open the upper portion of the container and insert the toothpaste refill inside. Then will have to close the top zip and finally rotate the lid so that the spikes inside pierce the thin water-soluble and biodegradable film, which will cause the toothpaste to be released into the container. When the toothpaste is finished, the container can simply be placed in the dishwasher and is ready for the next refill. In terms of functionality and ergonomics this design provides an intuitive use, that minimises the effort required to dispense product as it enables to use with one hand, allows the amount of toothpaste dispensed as desired by each user and is extremely easy of opening and closing. In addition, the material it is made of allows to maintain the toothpaste well preserved and fresh. The fact that it can be simply disassembly for material detachment is also a very important attribute as it facilitates the product to be reused, recycled at the end of its lifetime, or even replace parts if necessary. Although it is just a redesign of the traditional toothpaste tubes and a reformulation of its materials, this product is indeed differentiated from competitive products since, at this moment, there is no solution in the market with such characteristics.

5.5 | Business Evaluation

After proving environmental viability, two steps are taken to assess the business sustainability. Firstly, a financial analysis that will evaluate the viability, stability, and profitability of the project, and secondly the development of a business model to outline the plan for making a profit.

5.4.1 | Financial analysis

Data collection

Between 2021-2026 the global oral care market is expected to witness a healthy growth at a CAGR of 5.2%, expecting to attain a value of USD 45 billion in 2026. The growing awareness about oral hygiene and a higher penetration into emerging economies is likely to drive the industry. In Europe this market was worth nearly USD 8.78 billion in 2020 and is expected to attain USD 10.66 billion in 2026, growing at a CAGR of 3.3 % in the forecast period of 2021-2026. The Europe oral care industry is dominated by regional markets like Germany, which accounts for almost a fifth of the industry on the continent. The industry in Germany is being driven by the technological advancements made in the sector and growing awareness about dental hygiene. With people focussing more on personal grooming, teeth whitening products are getting a boost in the country. Increasing dental problems among children and adults, due to poor eating habits, and the rise in popularity for herbal oral care products are the factors primarily driving the toothpaste market. Moreover, rising premiumization and consumers seeking more targeted solutions are accelerating the growth of the market (EMR, 2021).

Incremental investment needed Cost of Goods Sold (COGS) estimation

The costs of launching the project are estimated and described in **Table 14**. The project requires initial investment such as additional R&D activity, an advertising campaign, hiring a sales team, equipment expenses in container moulds and a patent, with these last two amortized over 5 years.

Table 14 - Project cost estimates

Project cost estimates		
R&D development cost (1 scientist + 1 Technician)	€	25 000
SG&A (Advertising, product launch)	€	40 000
Capital Equipment expense (Amortized over 5 years)	€	30 000
Sales team (2 collaborators)	€	80 000
Intellectual property (Amortized over 5 years)	€	20 000
Total Year 1 Project Cost	**€**	**195 000**

Next step is to determine the Cost of Goods Sold (COGS) for this new product introduction. It was assumed that the Net Selling Price (NSP) per container is 4.99€ and the Variable Manufacturing Cost (VMC) is 1.5€ /unit, which accounts for 30% of the selling price. It was also considered a freight and packaging cost of 0.05€/unit, so the total Variable Cost (VC) is 1.55€/unit. Therefore, the value of the Contribution Margin (CM), which is the difference in the NSP and VC, is 3.44€/unit. These costs and contribution margin are summarized in **Table 15**.

Table 15 - Variable manufacturing cost and contribution margin per unit estimative

Variable Manufacturing Cost / Unit Estimates		
COGS (30% of SP)	€	1.50
Freight and Packaging	€	0.05
Total	**€**	**1.55**
Selling Price per Unit	€	4.99
Contribution Margin per Unit	€	3.44

Breakeven analysis and estimate the fraction of market size required to get breakeven revenue

A breakeven (BE) analysis is required to understand how many units must be sold in this new segment to recover the incremental fixed cost investment. The BE units are determined using equation 5 and is calculated in **Table 16.**

Table 16 - Breakeven Analysis

Breakeven Analysis		
BE Units		56 686
BE Value	€	282 863
Total Market Size (B €)	€	8.78
Market Share needed to breakeven		**0.003 %**

As seen in **Table 16**, the required breakeven revenue represents about 0.003% of the total market size. In addition, the CAGR in this case is assumed to be the 3.3% estimated for the European market. Therefore, it is reasonable to assume that there is enough room in the marketplace to recover its initial incremental investment.

DCF model to calculate IRR and NPV for the launch

It can be assumed that at least BE units will be sold in the first year. Using equation 6, it was found a positive NPV of 550 392€, assuming the market CAGR of 3.3% as the sales growth rate and 12% discount rate over a 5-year period. The same cash flows led to an IRR of 99.5%, which is clearly greater than the hurdle rate. Hurdle rate, the opportunity cost of capital and discounting rate are the same, so most companies use a 12% hurdle rate, which is based on the fact that the S&P 500 typically yields returns somewhere between 8% and 11% (annualized) (Standard and Poor's, 2021).

It is then concluded that there is a great potential for growth in the market, which is also complemented by a positive NPV and an IRR that exceeds by far the minimum attractive rate of return of 12%. The higher this IRR, the more desirable the investment is to undertake, and therefore these results demonstrate that there is reasonable financial justification to move forward with the project.

5.4.2 | Circular Business Model

A sustainable business seeks not only economic value but also social and environmental values for a much broader group of stakeholders. A sustainable business model can be defined as one that generates competitive advantage thanks to greater customer value while contributing to sustainable development of the organization and society. The circular business model canvas is extended and adjusted to the circular economy version of the business model canvas developed by Osterwalder and Pigneur (2010).

In addition to including the Cost structure and revenue stream derived in the previous section, this model extends the original business model canvas by adding an additional layer: an environmental layer. Also as a result of LCA, reductions in environmental impact are up to 80% when compared to the most common solutions on the market today. The aspects of the toothpaste business model are illustrated in **Figure 49**.

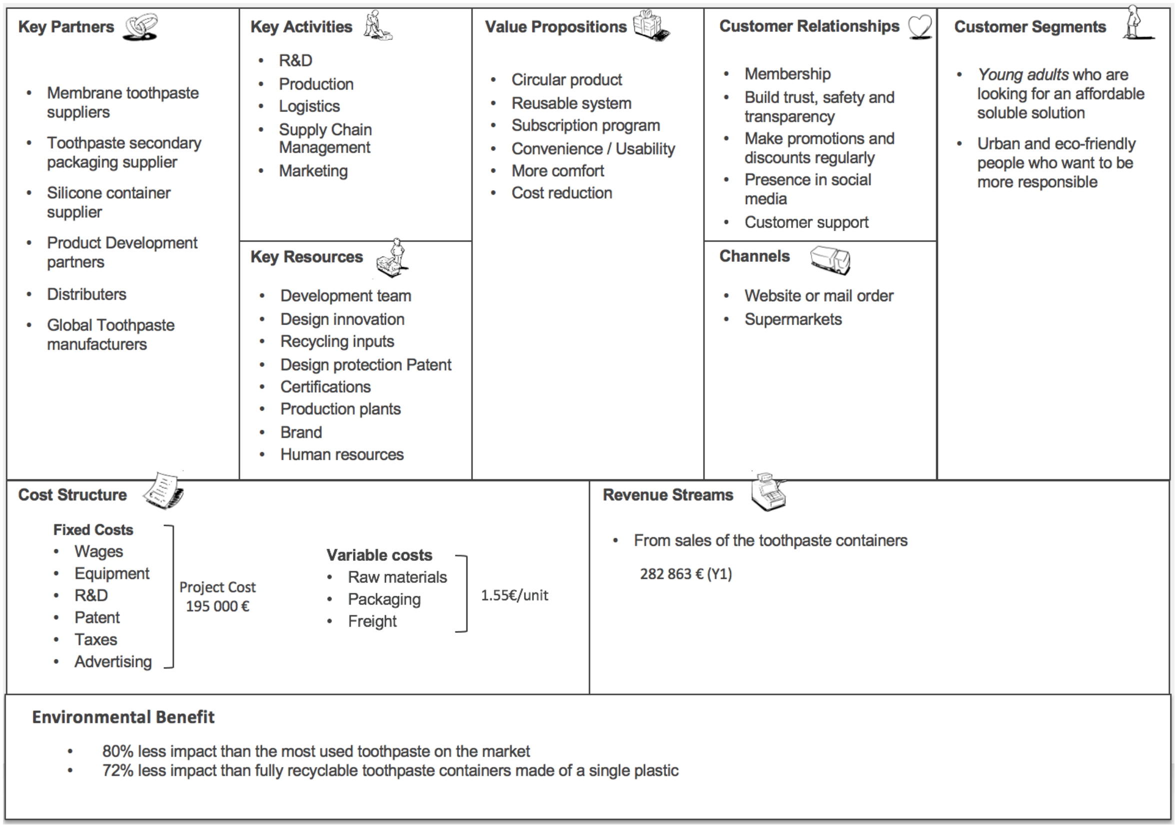


Figure 49 - Framework of the circular business model canvas. Adapted from Osterwalder and Pigneur (2010)

This model begins with the quest to sell a circular economy solution for the toothpaste packaging, based on a reuse system that is sustained through a subscription program. This will allow the customer to comfortably receive the toothpaste refills at home as soon as he needs it, making it easy to keep brushing uninterruptedly. This system is not only convenient, but it also reduces costs for the customer, because although it requires a higher initial investment to acquire the container, each refill unit will be cheaper, which allows him to save with continued use of the product. With the value proposition mentioned above, customers are entitled to a relationship of total transparency, security and support. Membership programs will be the means through which regular promotions and discounts will be offered to the customer through a coupon system. Here customer insights and feedback can be collected and used to improve their experience.

At present, the young consumers are shaping an environmental movement and becoming more and more aware of how their choices and consumer habits affect the planet, an awareness they are using to push brands to go zero-waste and get politicians to act upon it. Therefore, the main targeted segments are *(1) Young adults* who are looking for an affordable soluble solution with great sustainable features and (*2) Urban and eco-friendly adults and middle aged* who want to use an ecologically benign product associated with its commodity. The product will mainly be sold via virtual channels, and communicated with customers virtually, however it will be available in common supermarkets as well as its easy accessibility in these surfaces has proven to be an important factor when buying a toothpaste solution.

The availability of raw materials, technologies and specialists is ensured by the suppliers and distributers. Out of the group of suppliers represented, the most critical are the food-grade-membrane suppliers, as it is a specific technology and does not yet have a large-scale market presence. Both companies presented earlier, Poppits or MonoSol, are world-renowned suppliers of these membranes for cosmetic products with unparalleled expertise. Both the toothpaste pods and the packaging itself are the partner's responsibility that would ship the product worldwide. This partnership can be extended to include co-operation with global toothpaste manufacturers such as Colgate, which preserves the membrane technology yet containing a market leading toothpaste, with its experience and quality to develop a competitive strategy to face other competitors, especially in the emergent countries.
The main activities are in the first phase very focused on R&D, where the main resources will be the development teams for both product design and online presence, as well as patent protection and certificates. In a second phase the main activities will focus on supply chain management, from production in the local factory and distribution to supermarkets or to customers' homes. Here the main resources are raw materials from recycled streams that are transformed in production plans. In addition, the existing customers of the toothpaste partner become key resources, as they would also buy the container, which becomes a complementary product, as both goods cannot be used without each other. Finally, Marketing has a critical role in changing consumer patterns by informing, educating, and channelling needs of its current and potential customers towards the sustainable development. This availability of information and spread of awareness will facilitate the triggering of consumption opportunities.

6 | Final Conclusions, Limitations and Future Work

Plastic's inexpensiveness, versatility, lightweight and durability are qualities that have led plastic production to increase over the past century, largely outpacing most other man-made materials. This unique material has faced a remarkable global shift from durable and reusable to single-use applications. A short lifetime that led to a take-make-dispose culture coupled with to mismanaged waste and unexploited recycling opportunities, the environment is now facing a serious challenge that has to be acknowledged and addressed. In this context, the main waste management approaches have been analysed as well as the externalities related to plastic, coupled with a thorough analysis of the different thermoplastics and respective applications. In line with the project objective, the manufacturing landscape for the packaging industry is introduced along with the current solutions in the toothpaste packaging sector. Despite the fact that toothpaste market is one of the most dynamic segments of the oral care market, little innovation has been occurred on the packaging of toothpaste, considering the fact that the market is still dominated by the tube, a packaging device that was initially launched in the beginning of the past century. Developing a sustainable design for this type of packaging entails redesigned physical and graphics features so that the packaging has less impact on the environment but allowing it to keep its durability while being transported or stacked on shelves. If, on the one hand, design is to be involved in the production process packaging, optimizing the use of materials and the production process through innovation based on sustainable development, on the other hand, it is also required that design promotes a meeting between aesthetic, practical and symbolic factors for the creation of packaging that arouses empathy in consumers, sensitizing them for a new paradigm based on ethical, social and environmental issues. From this perspective, DfE, an inherent constituent of the DfX paradigm, has surged to develop environmentally compatible products and processes to reduce lifecycle impacts while preserving performance standards and value for money, encompassing all life cycle phases from material extraction, manufacturing, transportation, usage and end-of-life.

The literature review has revealed a main gap that should be addressed and a significant under-exploited potential to capture greater value in toothpaste containers that could be radically improved by compounding action and innovation across the global value chain. Currently there are no solutions on the market that address a zero-waste packaging concept combined with a reuse system for toothpaste that, therefore, avoids it to be thrown once it is empty. Accordingly, the full characterization of the problem was described, featuring the need to shift from the current linear business model of the toothpaste tube into a circular product concept through a fundamental packaging redesign.

This research adopts the methodology proposed by Slack et al. (2007) which was further extended to a multi-methodology approach, across the five pillars of the product design. The first two stages, which comprised concept generation and concept screening, allowed to translate the problems into design requirements. The research conducted revealed that the majority of customers are willing to switch to a sustainable alternative, however they are reluctant on abandoning a familiar format to which they are already accustomed, especially regarding the type of paste, which should preferably be a gel. It also realized the need for a container composed of a malleable and flexible material, a characteristic that will allow it to have a better performance in the other technical requirements pointed. Such material is required to be robust and able to be reused through multiple washes, since hygiene is an attribute valued by the consumer especially given the product we are dealing with, that is required to be well preserved and fresh. By being malleable it will also allow the toothpaste squeeze and therefore the possibility to control the dosage applied for each use. The ability to choose the toothpaste that is used within the container is also valued by users as many consumers already have their toothpaste brands of choice, whether for the taste, the feeling of freshness it provides or even for being suited to particular medical conditions.

Hence the selected concept which meets the majority of design requirements is based on the squeeze mechanism that combines both research queries. The solution is based on a CBM with a hybrid model where the toothpaste tube is a container made of recyclable materials that can be washed and refilled and therefore reused with toothpaste bought separately. This design stands on the ease of reuse, disassembly and recycling, rather than the continuous extraction of resources on a take-make-dispose system. Silicone has become very popular as an alternative to plastic over the years and it was the chosen material to make up the main container. This high-end material is safe, nontoxic, non-allergenic and non-reactive, eco-friendly, easy to shape and manufacture, extremely durable and resistant, possessing a long lifespan up to 30 years. Taking this in consideration, the tube is made of soft and squeezable BPA free food grade silicone that only dispense its contents when the silicone body is pressed. Each container includes a polypropylene flip cap and a dispenser valve to protect from leaks, spills or drops. The Toothpaste Refills hold the same amount of toothpaste of a regular tube of 75 ml, packaged in water-soluble and biodegradable film. This edible food-grade film is dissolves completely in water and naturally breaks down into water and carbon dioxide. It does not persist in the environment, contaminate the recycling stream nor contribute to micro-plastic pollution. These refills are relatively water and impact sensitive, which invalidates the use of solely paperboard to carry them. The best solution that combines the desired unique properties of keeping the liquids in but the microbes out, and a strong but lightweight container are Tetra Pak food cartons which are easy to transport and fully recyclable.

The last two stages of the design process comprised an environmental and financial project appraisal that defines the starting point for launching the product. The results obtained in the LCA prove that the new solution proposed has the potential to replace the current traditional toothpaste systems, by demonstrating a very significant reduction in the environmental impact generated. This impact showed that its impact is 80% lower than the impact caused by the laminate toothpaste tube, the most commonly used today, which allowed to confirm the environmental viability of the new system proposed. The financial analysis concluded that there is a great potential for growth in the market, which is also complemented by a positive NPV and an IRR that exceeds by far the minimum attractive rate of return, which demonstrate that there is reasonable financial justification to move forward with the project.

As far as the methodology of design process is concerned, it is concluded that every project has needs that are unique and factors such as the objective of the project, the available information and the provided accessibility and timing constraints which may affect the order and flow of the designing phases. The design proposal derived from this process, seem to achieve the objectives set on the design brief. However, it is worth noting that the simultaneous satisfaction of all requirements is usually not feasible and constitutes a major challenge in the design process, as there may be conflicts emerging from the interactions between several features.

The main limitation of this research was the inability to produce a physical prototype that could even be tested by a focus group. This step would be essential in validating the product with potential consumers, which could lead to fine tuning and adjustment of the product's characteristics.
As mentioned in the first part of the research, an equally important factor, which plays an important role in consumer behaviour and constitutes a significant selection criterion among many competitive products, is the cost. The economic assessment was not a primary objective of this thesis but it could be studied further as well it would help in a more detailed verification of the viability of launching of a new innovative product onto the market.
Future work that is suggested involves further experimental testing through the development of a physical prototype, initially using new technologies such as 3D Printing and, in a second phase, the creation of molds during the extrusion injection molding processes. In this way, the results would certainly be more reliable and objective as users would be those who would empirically provide feedback to the design process giving solutions to more detailed data.
In conclusion, this dissertation has contributed to filling out the literature gap on the zero waste toothpaste packaging by adopting the methodology proposed by Slack *et al.* (2007). Additionally, this research has contributed to a sustainable solution in reducing the excessive volumes of plastic waste which are threatening life as we know on planet Earth.

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Appendix A

-- START --

Product Development for the Toothpaste Packaging 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 "Product Design of a Zero Waste Toothpaste Packaging" being pursued at Instituto Superior Técnico - University of Lisbon (Portugal).

Billions of toothpaste plastic tubes end up in the landfill yearly, leaving out a significant under-exploited potential to capture greater value by compounding action across the global value chain. What zero-waste means? I believe waste is a design flaw. The present survey aims at unveiling the possibility of developing a fully specified prototype of a zero-waste toothpaste packaging within the frames of the Circular Economy and Eco-design.

All the information provided is confidential and only used for the matter of the present study.

The survey you are about to start is divided into three sections: I - Consumer Insights; II - Product Information; III - Consumer data.

Thank you for your contribution.

* Required

I - Consumer Insights

1. Are you aware that the majority of toothpaste tubes contain 11 layers of plastics, polymers and resins and therefore are not recyclable? *

- ○ Yes
- ○ No

2. Knowing this info, is it a problem for you? *

Meaning if this is something that bothers you and you want to see changed, or if it doesn't affect you.

- ○ Yes
- ○ No

3. Are you familiar with any environmentally conscious toothpaste alternatives in the market? *

- ○ Yes
- ○ No

4. If Yes, please specify from which brand or in what format.

____

5. Select the reasons you think may prevent you from adopting sustainable toothpaste solutions when compared to the current toothpaste option you are using (in case you are already using select that option).

- ☐ Expensive solutions
- ☐ Not available in common supermarkets
- ☐ Poor product quality
- ☐ Lack of market information
- ☐ Absence freshness and cleanliness feeling
- ☐ Resistance to change
- ☐ Comfortable with current toothpaste option
- ☐ Not specialised for specific oral conditions (such as sensitive gums or teeth, etc)
- ☐ I am already using a sustainable toothpaste
- ☐ Other: ______________________________

II – Product Information

1. **What are your thoughts on the following zero waste toothpaste solutions? ***

5 zero waste toothpastes are displayed below:

1. Edible pod that melts in your mouth - The gel toothpaste foams up as you brush and the soluble film dissolves.
2. Solid toothpaste tabs - chew until completely broken up, then brush as normal.
3. Toothpaste powder - Simply wet your toothbrush and dip it into the powder.
4. Solid toothpaste - Slide the toothpaste stick on the bristles of your toothbrush and then brush your teeth as usual.
5. Cream toothpaste in a glass jar - Dip your toothbrush into the jar to apply the paste.

	Tried it already	Willing to try	Not willing to try
Edible Pod	◯	◯	◯
Toothpaste Tabs	◯	◯	◯
Powder Toothpaste	◯	◯	◯
Solid Toothpaste	◯	◯	◯
Glass Jar Cream	◯	◯	◯

2. In case you are not willing to try, can you specify why?

(Long-answer text)

---

3. Please rank these options from most to least favourite. *

	Edible Pod	Toothpaste Tabs	Powder Toothpaste	Solid Toothpaste	Glass Jar Cream
1st option (Most favourite)	◯	◯	◯	◯	◯
2nd option	◯	◯	◯	◯	◯
3rd option	◯	◯	◯	◯	◯
4th option	◯	◯	◯	◯	◯
5th option (Least favourite)	◯	◯	◯	◯	◯

4. How do you rate the importance of each criteria when selecting and handling a toothpaste and respective packaging, from 1 to 5 (1 = not important, 5 = very important attribute).

	1	2	3	4	5
Hygienic	◯	◯	◯	◯	◯
Easy to dispense	◯	◯	◯	◯	◯
Retains shape	◯	◯	◯	◯	◯
Reasonable cost	◯	◯	◯	◯	◯
Attractive container	◯	◯	◯	◯	◯
Leak proof	◯	◯	◯	◯	◯
Squeezable	◯	◯	◯	◯	◯
Pleasing taste	◯	◯	◯	◯	◯
Environmentally friendly	◯	◯	◯	◯	◯
Resolve dental problems	◯	◯	◯	◯	◯
Portability	◯	◯	◯	◯	◯
Keep product well preserved and fresh	◯	◯	◯	◯	◯

III - Consumer Data

1. Please select your age gap.

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

2. Please indicate your gender.

Female	Male	Prefer not to say
◯	◯	◯

3. What is your country?

(Short-answer text)

____

Appendix B

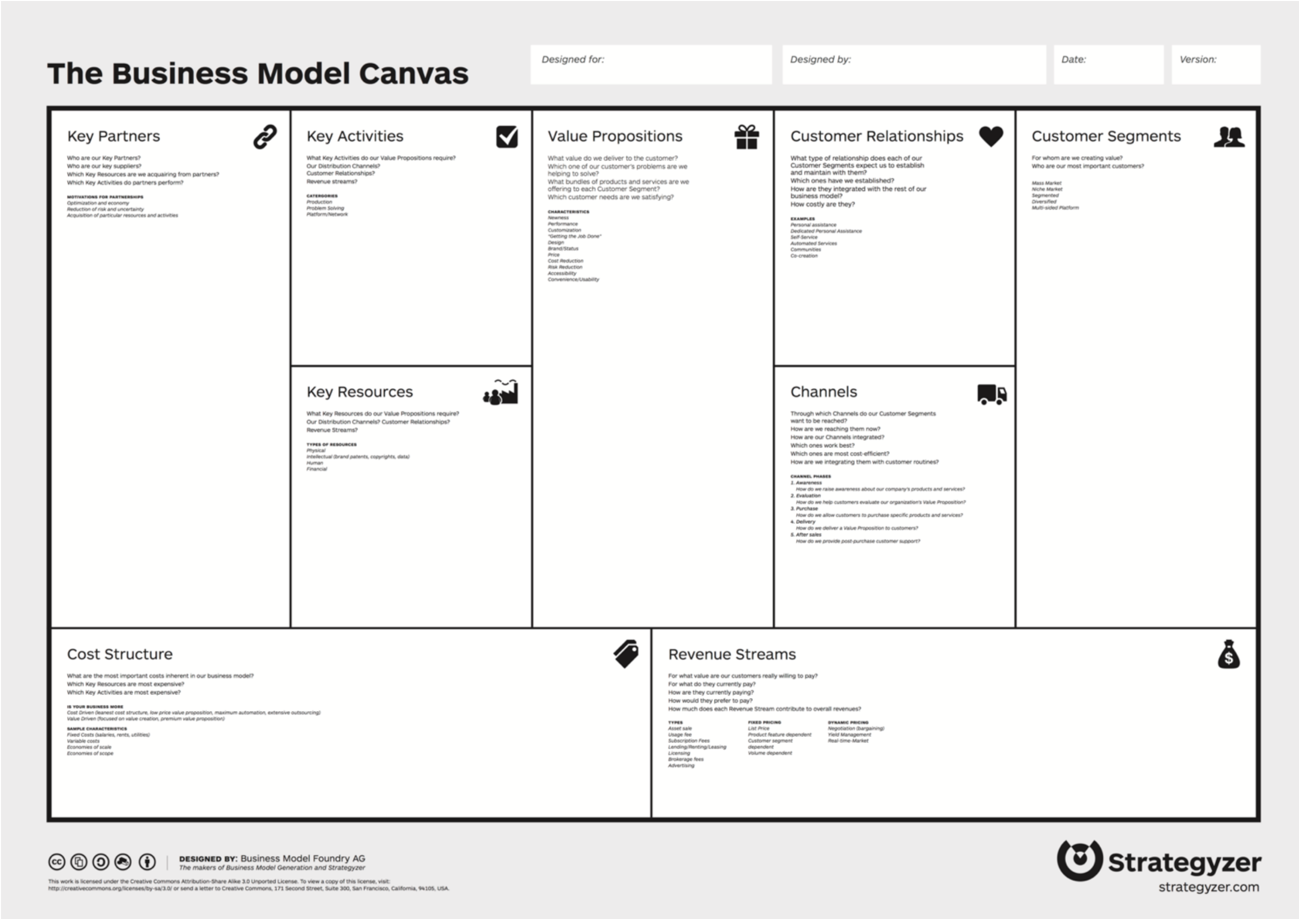

Figure B1 – The Business Model Canvas by Osterwalder and Pigneur (2010).