A Multicriteria Decision Support Method for Assessing Circular Economy Pathways of End-Of-Life Products

By

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Declaration of Authenticity and Author's Rights

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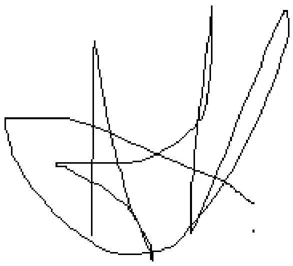
Signed:  Date: 11/09/2024

Aineias Karkasinas

To all those who have supported me, both knowingly and unknowingly, my deepest gratitude.

“Αγαπητοί φίλοι, στις παραμονές των εκτελέσεων, στις παραμονές από κάθε μάχη, μαζευόμαστε και κουβεντιάζαμε. Και λέγαμε: εάν εσύ ζεις, μη με ξεχάσεις. Εάν εσύ δε σε βρει το βόλι, όταν συναντάς τους ανθρώπους στο δρόμο, θα λες καλημέρα κι από μένα. Κι όταν πίνεις κρασί, θα πίνεις κρασί κι από μένα. Κι όταν ακούς τον παφλασμό των κυμάτων, θα τον ακούς και για μένα. Κι όταν ακούς τον άνεμο να περνάει μέσα από τα φύλλα, κι ακούς το θρόισμα του ανέμου, θα το ακούς και για μένα. Κι όταν χορεύεις, θα χορεύεις και για μένα!

Μανώλης Γλέζος, a quote from "ΑΚΡΩΝΥΜΙΑ" Ιούνιος 2017

“Dear friends, on the eve of executions, on the eve of every battle, we gathered and talked. And we said: If you live, don't forget me. If the bullet misses you, when you meet people on the street, greet them from me, too. And when you drink wine, drink wine for me, too. And when you hear the sound of the waves, you will hear it for me, too. And when you hear the wind passing through the leaves, and you hear the rustle, you will hear it for me, too. And when you dance, you will dance for me too!”

Manolis Glezos, a quote from "ΑΚΡΩΝΥΜΙΑ" June 2017

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The contributions of many have shaped this journey. No goal of mine could ever be achieved in isolation.

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Abstract

This study delves into the pressing need to reduce the environmental impact of human activities, accentuated by ongoing economic expansion and a burgeoning global population. The *Circular Economy* (CE) paradigm, promoting sustainability, is based on concepts like remanufacturing, recycling, and reuse to minimize waste and promote resource efficiency. The primary research question of this thesis is the exploration of holistic evaluation methods for *End-of-Life* (EoL) pathways for a core disposition problem, incorporating both quantitative and qualitative measures. The study aims to develop a method for evaluating available EoL pathways based on multiple criteria from the environmental, economic, social, and technical domains.

By integrating various established tools and introducing new ones, this research presents an innovative method for EoL decision-making. The *Hierarchical Attribute Liaison Graph* (HALG) and the *Bill of Materials* (BoM) were used to capture the product's structure. The *ease of disassembly Metric* (eDiM) was used to quantify the effort needed to replace critical components. Then, through economic and environmental analysis of multiple remanufacturing scenarios, the Circular Economy Design Analysis (CEDA) graph was created. The CEDA was used to illustrate to the decision maker the remanufacturability of the product under analysis. After the practitioner's input was captured across multiple decision clusters, the *Multi-Criteria Decision Aid* (MCDA) *Preference Ranking Organisation Method* (PROMETHEE) was used to rank the available EoL pathways. Some of the EoL pathways were eliminated due to solution constraints captured by the proposed method based on the partitioner's input. The proposed method was rigorously evaluated through feedback from the industry and validated through two utterly different case studies.

The proposed method is the first to introduce a visualization tool for depicting a product's design remanufacturability based on the economic and environmental aspects of multiple pre-defined remanufacturing scenarios. Furthermore, this study's insights significantly broaden the understanding of EoL decision-making, demonstrating the proposed method that holistically addresses a core disposition problem while considering the practitioner's input at each stage.

Keywords: End-Of-Life Decision-Making, Multi-Criteria Decision-Making, Cores Disposition, Circular Economy, Remanufacturing, Remanufacturing Assessment, *Preference Ranking Organisation Method* (PROMETHEE)

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1 Introduction

This chapter presents some introductory information for this thesis. It provides the background and motivation for the research, formulates the research question, and describes the aim and objectives of this work. Finally, the thesis outline is presented.

1.1 Background and Motivation for the Research

One of the most pressing and complex challenges that humanity faces is mitigation of the impact of human activities on planet Earth (*United Nations Environment Programme (UNEP), Global Environment Outlook 6 Report*, 2019), as those increasingly influence the Earth's climate (Parry et al., 2007). The demand for continuous economic growth on a planet with finite resources, coupled with a rapidly increasing population, exacerbates this challenge, leading to resource scarcity and significant environmental impacts. Thus, a clear issue of resource scarcity and other types of environmental impact due to economic activity is raised, and a need for changing the approach to economic growth by utilizing the available resources is highlighted (OECD, 2011). To better illustrate this problem, the planetary boundaries concept was developed by Johan Rockström and a group of 28 internationally renowned scientists (Rockström et al., 2009). Through their work, the safe operating planetary boundaries were defined for nine different types of environmental impact and the present condition was captured as illustrated in Figure 1.1. Within this approach, one of the key impact categories is climate change. Climate change '*refers to the significant and long-term changes in the patterns of weather and temperature in the Earth's atmosphere, caused by human activities such as burning fossil fuels and deforestation, which lead to an increase in greenhouse gas concentrations and global warming'* (Intergovernmental Panel on Climate Change, 2014).Using the systems boundaries approach,, climate change is quantified using both atmospheric CO2 concentration and radiative forcing as global-scale control variables (Rockström et al., 2009). It becomes evident from this quantification that that the impact of climate change exceeds safe operational limits and may lead to irreversible damage to the ecosystems.

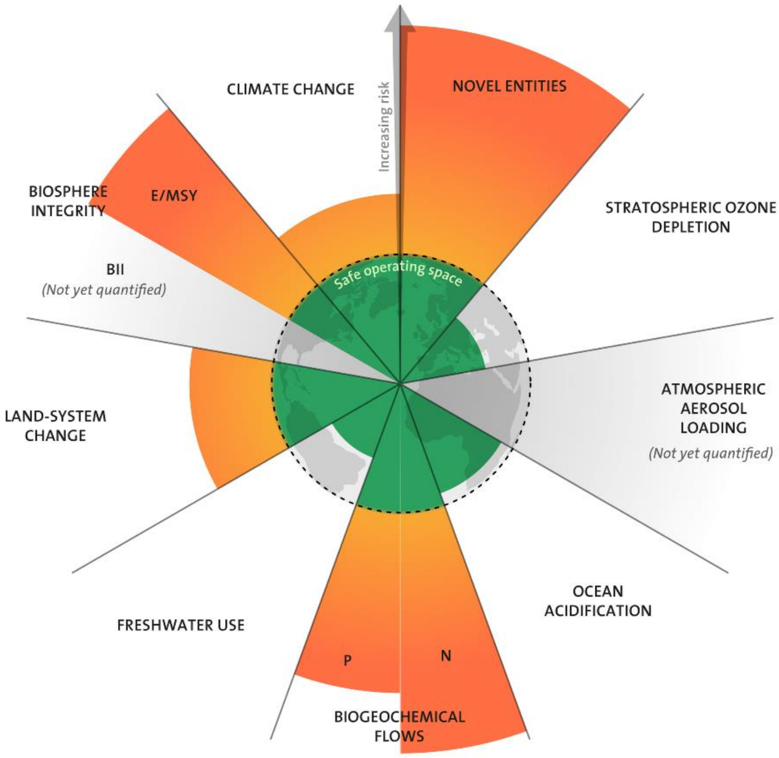


Figure 1.1: Planet boundaries approach (Rockström et al., 2009)

Although the system boundaries assess nine different environmental categories, it notably does not include resource scarcity among the impact categories. Resource scarcity '*refers to the condition in which the demand for a particular natural resource exceeds its supply, or when the supply of a natural resource is limited or insufficient to meet the demand for it'* (Bardi, 2014). With the global population constantly increasing, predictions suggest that over the next fifty years, there will be a need for ten times more resources than are needed today if technology remains unchanged (Kar, 2015). Moreover recent reports highlight that the demand for natural resources will continue to increase while the supply of these resources will become more restricted due to the depletion and degradation of ecosystems (IRP et al., 2019).

To address these interconnected issues, the concept of sustainable development was developed based on the Brundtland Report of 1987 (Brundtland, 1987). Sustainable development requires that the needs of the present are met without compromising the ability of future generations to meet their own needs (Brundtland, 1987).This concept evolved into the broader term sustainability, which maintains the essence of sustainable development.. Thus, sustainability refers to utilizing the resources in a manner that is consistent with the regenerative planet boundaries and secures growth for future generations. Sustainability has gained significant interest in many sectors of society, and there is a constant effort to integrate it in all value-creating activities of those sectors (*United Nations Environment Programme (UNEP), Global Environment Outlook 6 Report*, 2019). This commitment is further reinforced through the UN's 17 goals of sustainable development, which aim to strengthen the means of implementation through global partnership against specific positive impact targets.

In alignment with these sustainability goals, the Circular Economy (CE) concept was developed. The term originates from industrial ecology and environmental economy, and some of its elements are adopted from other principles as well (Ghisellini et al., 2016a). The core objective of CE is to create a sustainable system in which resources are kept in use for as long as possible through ‘loops’, and waste is minimized (Merli et al., 2018). A “circular EoL pathway” refers to the processes within the CE framework where products or materials are recovered, repurposed, or reused at the end of their lifecycle to minimize waste and resource consumption**.** Key enablers of CE include remanufacturing, which recovers products and materials during their end-of-usage (EoU) stage and utilizes them to produce new products or materials (Tjahjono & Ripanti, 2019). Other CE loops include recycling, focusing on material recovery (Yken et al., 2021) and reuse, which focuses on direct reuse of the product with minimal work needed to be done to be operational again (Harala et al., 2023). CE provides the discussed EoL pathways as an alternative to the traditional linear economy-related disposal of products after their usage, which is a highly unsustainable EoL pathway (Sariatli, 2017).

To effectively transition to a circular economy, companies must adapt by fundamentally transforming their business models, products, and service(Sariatli, 2017). This transformation requires a variety of support mechanisms, especially for SMEs, which often lack the resources and capabilities to implement circular practices independently(Cant et al., 2021). Scholars have identified that decision-making support is critical for companies to successfully complete the discussed transition, as it helps them navigate the uncertainties and de-risk the adaption of a circular business model (Sitcharangsie et al., 2019). Given the multidisciplinary nature of EoL decision-making, which involves multiple stakeholders, a collaborative approach among experts from various sectors is essential (Ziout et al., 2014). At the core of this process are disposition decisions, which determine the appropriate EoL pathway for returned products and are crucial for the success of EoL management.

The concept of *core disposition* within remanufacturing plays a critical role in CE. A "*core disposition problem*" refers to the challenges associated with determining the appropriate course of action for "cores" (Lund, 1985). A *core* is the used product or component that serves as the raw material for remanufacturing. The disposition process involves deciding whether a core should be remanufactured, recycled, or scrapped. These decisions are complex due to multiple factors such as quality assessment difficulties, uncertainty in demand for remanufactured products, variability in the condition of cores, cost considerations, environmental regulations, and logistics issues. As will be discussed in greater detail in the literature review chapter, EoL decisions, such as core disposition, are often primarily based on financial aspects, with other factors such as environmental and social considerations being underrepresented. Effectively addressing the core disposition problem requires improving EoL decision-making through a comprehensive and holistic approach that addresses these multiple factors. The research described in this thesis is conducted in response to the need for more informed and holistic EoL decision-making. Through a comprehensive review of state-of-the-art literature and industry feedback, the following gap was identified: '*There is a need for a holistic approach that simultaneously addresses the economic, environmental, technical and social aspects of EoL decision-making.'*

The proposed method has the potential to transform the way EoL decisions are made by creating a more informed decision-making process. This approach will demystify EoL decision-making and assist decision-makers in successfully adopting a CE business model. It will help decision-makers address questions such as, "What EoL pathways should this batch of cores follow?", "Is this product suitable for applying a CE business model?", and "How do my company's preferences and inputs into the decision model affect the optimal EoL pathway solution?".

1.2 Research question

Based on the above considerations, the following research question was formulated to guide the conducted research:

How can the performance of EoL pathways for a core disposition problem be quantitively and qualitatively assessed in a holistic manner?

1.3 Aim and Objectives

The research documented in this thesis is motivated by the lack of a method that simultaneously assesses the environmental, economic, social and technical aspects of the available EoL pathways and provides decision support to the decision-makers while considering multiple constraints arising from the actual practice. The aim of this work is thus *to facilitate circular EoL pathways selection for a returned batch of cores by supporting the decision-maker with a method that evaluates the available EoL pathways based on their environmental, economic, social and technical performance while considering feasibility solution constraints, is fully customized to the practitioner's input and unique requirements and provides a ranking of the available EoL pathways.*

To attain the research aim, the following objectives were defined:

Objective 1: Investigate and analyse the current state-of-the-art decision support methods applied for the EoL product's disposition problem.

Objective 2: Identify the key factors and the critical solution constraints impacting the decision to select an EoL pathway to a core disposition problem.

Objective 3: Design and implement a tool that facilitates the assessment of a product's remanufacturability by linking the product design's environmental impact and economic performance.

Objective 4: Design, implement and evaluate a method that holistically addresses the core disposition problem by quantifying the environmental, economic, social and technical performance aspects while considering the solution constraints input from the decision-maker.

The aim of the research is achieved through the development of a novel method that will support the decision maker to conduct a well-informed decision on which EoL pathway should a return batch of cores follow based on environmental, economic, social and technical aspects.

1.4 Scope of research

The research described in this thesis focuses on providing holistic decision support in a core disposition problem in an industrial context. For the method to be holistic, the environmental, social, economic and technical aspects have been included in the study. Nevertheless, the proposed work is confined to the following boundaries:

- The method only focuses on key components rather than all potential components for reasons of practicality, applicability and utility. In both case studies, five *key components* were selected by the method's practitioner.
- The method provides results that aid the decision-maker in solving an EoL batch of cores disposition problem through social, technical, economic and environmental analysis. The decision support focuses on the product-level and does not consider component-level decision-making support, such as which parts to replace and when.
- The proposed method considers as possible EoL pathways only the following: reuse, remanufacture, recycling, and disposal. A discussion on why the proposed method selected these EoL pathways as potential solutions to the EoL decision problem is included in Chapter 3.
- The proposed method, when applied, requires a new product to be purchased for the EoL pathways of recycling and disposal since the focus is the satisfaction of the customer's need. Such practice sets the boundaries for the new product to be identical to the old one or, at the very least, significantly similar so there can be a comparison among the different EoL pathways.
- The environmental impact for the components and the remanufacturing process is based on the guidelines of conducting a simplified LCA. Additional embodied emissions on the processes that stem from the company's economic activity have not been modelled.

- The decision factors impacting the results of the proposed decision support method have been selected based on industry feedback and literature research, as described in section 3.11. A lean version of the most important has been chosen for the method to be as sector-agnostic as possible. Consequently, the proposed method requires support from an expert to be tailored for its first application from the practitioner. This boundary relates to the direct application environment of the proposed method and was also highlighted by industry experts during the method evaluation stage.

1.5 Thesis outline

This section describes the thesis outline summarised. More specifically, the structure of this thesis is composed of the following:

Chapter 2 includes the state-of-the-art literature review conducted for this research. The critical terms of sustainability, circular economy and decision support for EoL are discussed. The literature synthesis results in identifying the gaps that highlight the importance of the conducted research and its deliverables.

Chapter 3 thoroughly describes the methodology used for developing the proposed method. Additionally, the key elements of the proposed method are discussed and presented in detail as well the justification for their selection.

Chapter 4 includes a detailed description of the evaluation process for the proposed method. The developed method is assessed against utility, accuracy, and applicability criteria.

Chapter 5 describes the application of the proposed method to the first case study. It explains in detail all the steps of applying the developed method from a practitioner’s point to the lighting industry using a luminaire as the product analysed.

Chapter 6 describes the second application of the proposed method in the Oil and Gas industry. The product analysed was a 20-litre bladder accumulator.

Chapter 7 concludes this thesis by discussing the proposed method and presenting the research's conclusions. The research novelty of the proposed method is presented alongside reflections, the knowledge contribution and a description of the advantages and limitations of the work. Finally, future research recommendations are suggested, and the concluding remarks provide a synopsis of the presented thesis.

2 Literature Review

This chapter describes the literature review conducted for this research. The multidisciplinary nature of this study is expressed through the main areas of interest: Sustainability, Circular Economy (CE), End of life (EoL) Management, a sub-category of Product Lifecycle Management (PLM), and Decision Support (DS), a sub-category of Decision Making (DM). Although the relationship between sustainability and circular economy is ambiguous in the literature, this research adopts the argument of Geissdoerfer that a subset relationship, where CE is contained inside the field of sustainability, seems more appropriate since it can maintain diversity while providing a variety of strategies for policymakers to apply (Geissdoerfer et al., 2017). Figure 2.1 illustrates the areas considered in this review and their relationship based on the adaptation above regarding sustainability and circular economy. The aim of this study has driven the literature review to focus on the meeting point of Circular Economy, EoL Management, and Decision Support. Thus, the final area of application in which knowledge is added is in the field of EoL decision support for solving a core disposition problem and promoting circular economy through holistic quantification of the EoL pathways' performance.

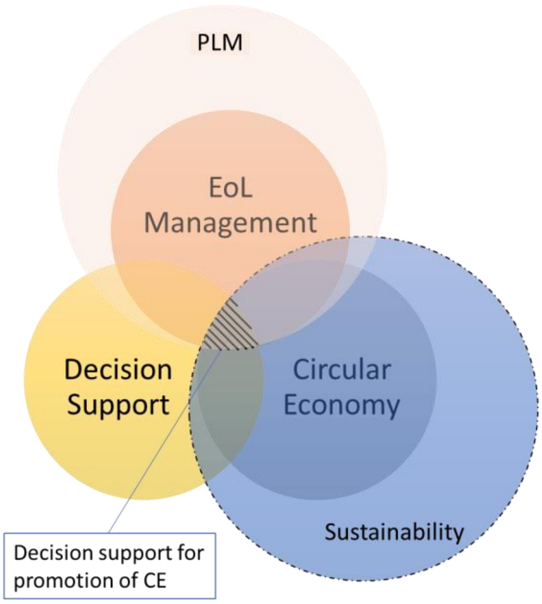


Figure 2.1: Research areas included in the critical review

First, an overview of sustainability is presented in 2.1, where the concepts and definitions are discussed alongside the role of sustainability in the business world. This study focuses on EoL multicriteria decision-making, with EoL as a sub-part of Product Lifecycle Management, introduced in section 2.2.

Then, the circular economy and its definition and applications to the business world are presented in section 2.3. Section 2.3.1 describes the concepts and definition of circular economy, while 2.3.2 describes the most used EoL pathways in literature and industry. A description of the circular economy Business models (CEBM) is presented in 2.3.3, and finally, the similarities and differences between sustainability and circular economy, as well as their relationship, are discussed in 2.3.4. The next key area of interest for this work, Decision support for EoL, is discussed in 2.4, with an overview of the Decision Making (DM) methods and approaches being presented in 2.4.1. The next sections describe the DM factors of influence on the EoL and their distribution across the existing literature. An analysis of 41 related articles is presented in those sections, while 2.4.4 and 2.4.5 discuss the one-factor and multi-factor approaches to EoL DM, respectively. In section 2.4.6, remanufacturing evaluation, a key process for EoL DM, is discussed. In this analysis, the keywords used for identification of the related work in academia are "End of Life decision making", "remanufacturing decision making", "EoL disposition", and "EoL", with those keywords not being a strict inclusion or exclusion criterion. The literature gaps are identified in section 2.5, and the chapter's summary is presented in section 2.6.

2.1 Sustainability

The term sustainability origins from the French verb *soutenir*, "to hold up or support" (Brown et al., 1987) and, in modern times, describes a broad discipline with various implications for the human world. Originally, sustainability was used in forestry, where the term expressed a form of controlled production since it stated that the amount of wood harvested from a forest should not exceed the volume that grows again (Geissdoerfer et al., 2017), with written references found from the 18th century (Von Carlowitz, 1732). The concept was modernised much later when used to express the ability of nature to regenerate itself and was mostly applied in the ecology sector. Nowadays, sustainability receives significant academic and industrial interest and stands out as one of the key themes of future development (Hay, 2015). It aims to tackle the problem of exceeding the finite resources of our planetary resource system

(Steffen et al., 2015) or, in simple terms, to utilise the resources without compromising their availability for future generations. The great interest in sustainability and its crucial role in prosperity for people and the planet has led to the *2030 Agenda for Sustainable Development*, a 17- Sustainable Development Goals agenda adopted by all United Nations Member States in 2015 (DESA, 2016). Those goals are associated with a broad spectrum of fields, providing the opportunity for academia and industry to explore different solutions and applications that extend beyond the theoretical development for achieving those goals. Those applications aim to support businesses with sustainability integration to their main objectives, such as meeting their customer needs, increasing or accessing new markets, designing better products and complying with the newly introduced legislative restrictions.

2.1.1 Definitions of sustainability and approaches

The concept of sustainability has attracted such great academic interest that more than 300 definitions of 'sustainability' and 'sustainable development' have been developed to express the term in a plethora of disciplines that are directly or indirectly linked to it (Johnston et al., 2007). Sustainable development was defined based on the Brundtland Report of 1987 as *"...development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland, 1987) as a policy concept introduced to acknowledge the limitations in resources by nature against humanity's constant development and growth. Although scholars (Johnston et al., 2007) have highlighted the importance of using the term 'sustainable development' against simply 'sustainability', the second term has prevailed. Sustainability refers to utilising the resources without compromising their availability for future generations and is a broader term with a more long-term focus. Although this definition seems to describe the term adequately, the link between the utilisation of resources and availability for future generations is vague and reveals a slight shift in the concept's meaning. Other scholars have argued that this change from the original definition may obscure the contradiction between long-term sustainability and short-term welfare (Kuhlman & Farrington, 2010). The original definition of sustainable development, cascading to sustainability, offers a widely accepted explanation of the term across multiple sectors and is based on two pillars: the environment and the development concerns (Gibson et al., 2001). This definition lacks a way to operationalise sustainability for businesses and a means for capturing its social aspect as well.

Consequently, the need for a more practical definition was raised in the business environment. The first answer to this problem came from the sustainability guru, John Elkington, who stated that companies should commit to social and environmental concerns the same focus they commit on economics in an attempt to provide the foundation for corporate social responsibility from an operational stance (Elkington & Burk, 1989). Other scholars proposed different approaches that included seven dimensions of sustainability by analysing the environment of sustainability and adding cultural and political points of view (Gibson et al., 2001). This approach was named the triple bottom line (TBL) and led to the establishment of the three pillars of sustainability (3Ps): profit, people, and the planet.

Since the problem of the definition of sustainability not being easy to operationalise has been resolved through its extension to the three pillars of sustainability, the second main issue with the definition occurs. According to the Brundtland Report, the key to sustainability lies in the fact that it does not compromise the ability of future generations to meet their own needs. Since for any present growth, some loss of natural resources is inevitable (Kuhlman & Farrington, 2010), a debate sparked in academia whether these resources' loss can be substituted through capital or such an approach demines the term of sustainability to its core. This debate resulted in the creation of *weak* and *strong* approaches. The *weak sustainability* approach, which the economists highly accept, argues that weakly sustainable development does not diminish across generations (Brekke, 1997) and expresses the ability of a nation to maintain its capital at a constant level (Ayres et al., 2001). On the contrary, the *strong sustainability* approach, which the ecologists mostly agree with, requires that quantities of several types of capital, such as economic, ecological and social, should be independently sustained since the natural resources cannot be substituted by capital (Ayres et al., 2001).

This work focuses on providing decision support for promoting a circular economy. It utilises multiple decision factors and sub-factors weighted by the practitioner and ranks the available EoL solutions based on their preferences. Thus, the economic dimension of sustainability plays a vital role in this study. At the same time, the practitioners operationalise the proposed method for identification of the best suited EoL pathway to their case. Most of the time, the primary decision driver is the generation of profits. As a result, in this study, we follow the *weak* approach.

2.1.2 Sustainability in the business world

Sustainability in the business environment was initially introduced through legislation concerning the environmental impact of industrial activities. Nowadays, international organisations such as the United Nations (UN), in an attempt to transform our world for the year 2030 based on the principles of Sustainable Development, have identified the 17 Sustainable Development Goals (SDG) for reaching a sustainable future (DESA, 2016). Those goals include, across many more, the end of poverty, zero hunger, good health and wellbeing, gender equality, affordable and clean energy, industry, innovation and infrastructure, responsible consumption and production, sustainable cities and communities and climate action. The UN conducts progress reports to monitor the development of those goals (Rosenthal, 2021). It becomes evident that the goals follow the 3Ps approach to sustainability, while some are related to the industrial dimension of sustainability.

Organisations such as the UN demand industrial activities to include sustainability as a crucial part of them, and consumers also highlight the importance of sustainability, generating changes to the market. The great impact of industrial activities on the environment and society has been highlighted multiple times in academia (Abdallah et al., 2012; Montoya, 2015). Sustainability has been identified as an approach to social responsibility for enterprises (Mena et al., 2019), which focuses on simultaneously delivering economic, social, and environmental benefits (Huang & Rust, 2011). Although these sustainability concerns initially targeted mostly the focal companies (Seuring & Mu, 2008), it did not take long for a sustainability-centred approach to cascade towards the supply chain of those companies. Thus, areas such as Sustainable Supply Chain Management (SSCM), Green Supply Chain Management (GSCM), Product Lifecycle Management (PLM) and End of Life Management (EoL), and Circular Economy (CE) have emerged to support activities and processes related to the sustainable development of an organisation. Many are operationalised in conjunction with others within the organisational boundaries for optimum results, such as GSCM and CE (Kazancoglu et al., 2018).

2.2 Product Lifecycle Management (PLM)

For this research, particular interest shows the PLM approach, which, despite the variety of definitions in the literature, there is consensus about its key aspects, which are captured by the following captions (Karkasinas & Rentizelas, 2019):

'A strategic business approach that applies a consistent set of business solutions that support the collaborative creation, management, dissemination, and use of product definition information'

'Supporting the extended enterprise (customers, design and supply partners, etc.)'

'Spanning from concept to end of life of a product or plant.'

'Integrating people, processes, business systems, and information.'

These captions reveal that PLM is a holistic strategic business approach that extends across all of the product's life stages and integrates multiple resources. Scholars have argued that PLM systems are key to achieving a more sustainable paradigm across the product's life (Duque Ciceri et al., 2014). A key stage of the product's life is the EoL stage, where the product is disposed of. Scholars focusing on that stage developed a sustainable business model that delivers economic growth while limiting the environmental impacts, the Circular Economy business model (Cong et al., 2019).

Figure 2.2 illustrates the stages described in the literature by different authors and varying perspectives. Some scholars put more weight on the stages until the production/ manufacturing stage of the product (Abramovici, O. Sieg, 2002; PTC, 2008), while others included more lifecycle stages (W. Liu et al., 2009; Ramani et al., 2010; Stark, 2005).

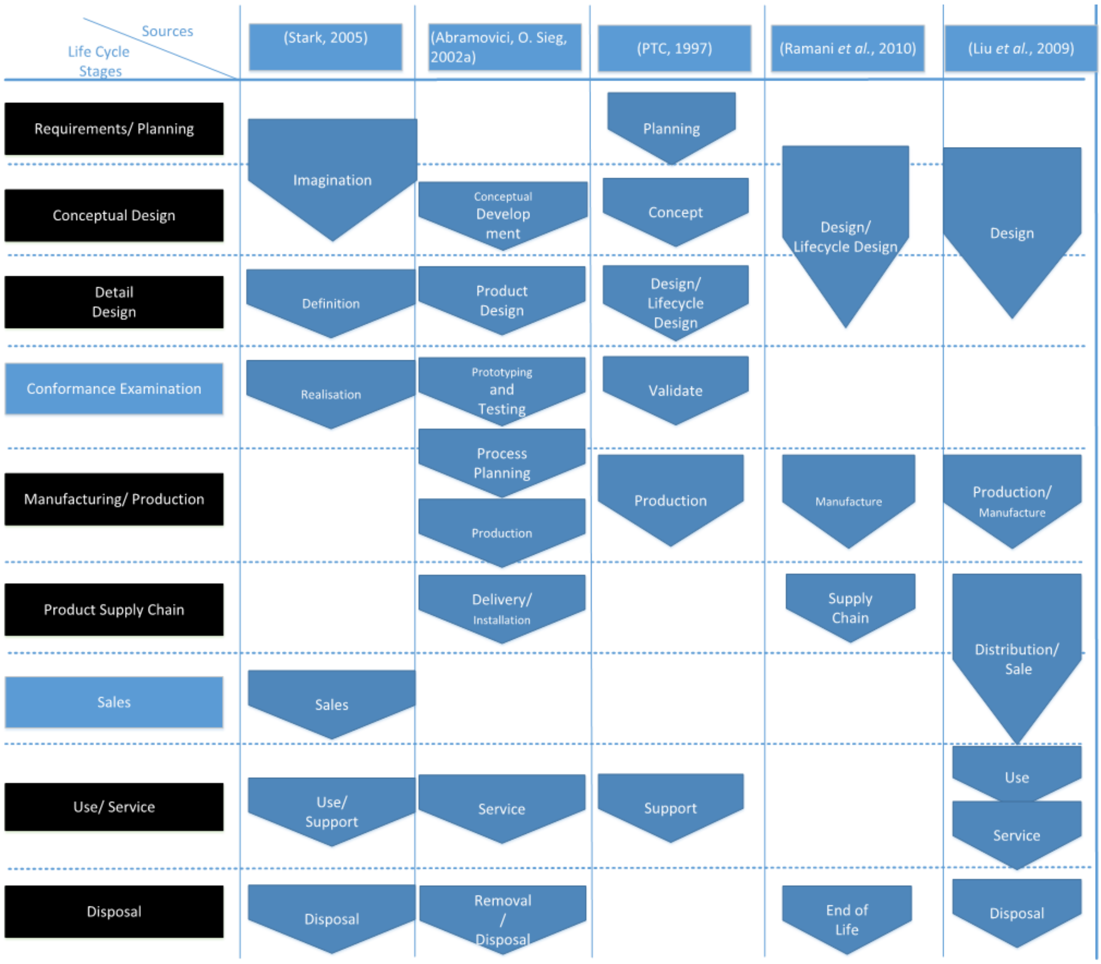


Figure 2.2: Product Lifecycle Stages (Karkasinas & Rentizelas, 2019)

Based on the studies above, the most used term for the 'End of Life' (EoL) stage is 'disposal'. In this work, the term EoL refers to the stage in which a product no longer satisfies its function for the last user at end-use. Additionally, this work focuses on more EoL pathways than just disposal; thus, a deeper dive into the possible EoL pathways is needed. Section 2.3.2 presents an analysis of the most common EoL pathways.

The relationship between sustainability and circular economy has been described as '*conditional*', '*beneficial*' and '*trade-off*' (Geissdoerfer et al., 2017). A *conditional* relation defines circularity regarding a sustainable system as a critical condition, a solution for the transformation, or a necessary but not sufficient condition (Bakker, CA. et al., 2014; Läpple, 2007; Nakajima, 2000; Rashid et al., 2013). *Beneficial* relation underpins the importance of CE for sustainability to a system as one of the solutions, but without a CE being a condition (Allwood et al., 2008; Deselnicu et al., 2018; Garetti & Taisch, 2012). Finally, *Trade-off* refers to CE providing a degree of sustainability under the cost-benefit lens, and that correlation may even be negative (Andersen, 2007; Kirchherr et al., 2017; OECD, 2009). In this study, we adopt the *conditional* approach relation between CE and sustainability since we consider that a CE business model must be applied at some extent for transformation to a truly sustainable system.

2.3 Circular Economy

As discussed previously, CE is a means of operationalisation for sustainable development (Ghisellini et al., 2016a; Murray et al., 2017). Previous scholars have argued that although sustainable development is depreciating in interest due to its vagueness (Van den Brande et al., 2011), CE continues to gain interest from multiple stakeholders (Bovea & Pérez-Belis, 2018; Cayzer et al., 2017; Cong et al., 2019; Geissdoerfer et al., 2017; Sitcharangsie et al., 2017; The Ellen MacArthur Foundation & Company, 2014; C. Yang et al., 2016).

CE was developed as a sustainable alternative to the "take-make-dispose" (Ness, 2008) linear economy model, which led to material scarcity and volatilisation of raw material prices alongside significant environmental impacts due to the continuous demand for raw materials (The Ellen MacArthur Foundation, 2013a; Zhijun & Nailing, 2007) and is depicted in Figure 3. The origins of the inspiration for CE can be traced to Industrial Ecology (IE) (Bocken et al., 2017; Ghisellini et al., 2016b), where the importance of closing the loops of material flaws has a key role in the area (Lüdeke-Freund et al., 2019).

The concept of a circular economy has been around for centuries, but the modern understanding and application of the term began to take shape in the 1970s and 1980s. The origins of the circular economy can be traced back to the works of thinkers such as Buckminster Fuller, Walter Stahel, and David Pearce (Pearce & Turner, 1990; Stahel & Reday, 1976), who advocated for a shift away from the traditional linear "take-make-dispose" model, as illustrated in Figure 2.3, of the economy towards a more regenerative and sustainable model.

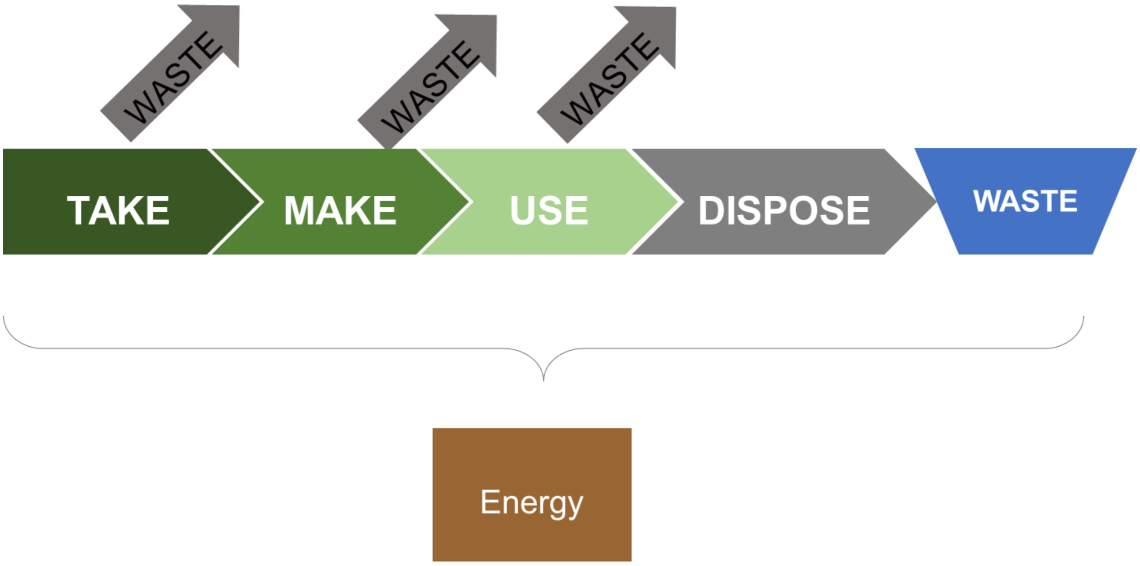


Figure 2.3: Take-make-waste (Linear economy model)

On the contrary, CE aims to achieve exceptional resource efficiency of any resource input in a system by conservation of the resources and circulation through closed loops among the various stages of the product's lifecycle (Guldmann, 2016a).

In CE, the value of a product is sustained for as much as possible, and that value could be embedded in the material, energy, labour or capital (Oakdene Hollins Ltd, 2015). CE expands through all the life stages, from the designing phase to the EoL; thus, it is highly aligned with the principles of PLM with an operational focus on the EoL stage, as depicted in Figure 2.4.

2.3.1 Concept and definitions of Circular Economy

The circular economy originates in industrial ecology and environmental economy, with elements adopted from other principles as well (Ghisellini et al., 2016a). It is expressed in the literature mainly through its three key 'actions', namely '3Rs', which are: *Reduction*, *Reuse* and *Recycle* (Yong, 2007; Zhijun & Nailing, 2007). CE has been widely implemented in the Chinese economy, much before getting traction in the Western economies, and was promoted as a '*top-down national political objective*'.

Two of the primary accelerators were resource scarcity and the vast development rate of the economy. On the contrary, in Europe and US, it is the public that, through multiple organisations, pushed for transitioning from the linear economy to a more sustainable CE, thus following a '*bottom-up*' approach. This led to CE being used mainly to design environmental waste policies in western societies (Ghisellini et al., 2016a).

The definition of CE is "a generic term for the reducing, reusing and recycling activities conducted in the process of production, circulation and consumption" according to Chinese law (*Circular Economy Promotion Law of the People's Republic of China.*, 2008). EMF (The Ellen MacArthur Foundation, 2013b) defined CE as *'an economy that is restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times.'* The main difference between those two definitions is that the Chinese approach to CE acts as an umbrella term that includes multiple industrial activities, while in post-industrialisation Europe, the approach is from an economic point of view (Ghisellini et al., 2016a). Even though the definitions have slightly different approaches, the goals are the same and expressed through the '3Rs' with the addition of *economic prosperity* as another dimension from the European approach, an addition that academia has widely accepted (Kirchherr et al., 2017).

2.3.2 Circular Economy EoL pathways

Although CE can be adequately described through the 3Rs approach, scholars have suggested other approaches, including more strategies for minimising environmental impact and closing the loops. Those approaches tend to add related terms starting with the letter 'R'; one of the most holistic is described as the '9R' framework (Potting et al., 2017). The main CE loop categories are also distributed across multiple lifecycle stages. Figure 2.4 illustrates a generic CE model integrated with the '9R' approach (Potting et al., 2017) to depict the possible circular loops linked to the appropriate lifecycle stage. The main contribution of this illustration is the link between the design phase, from requirements planning to detail design, where CE must be considered for successful implementation.

The 9Rs express the key pathways for the circular economy while they are taxonomised across three main categories. The first group refers to pathways with a limited adaptation of the CE principles, focusing on the *useful application of materials*. The next group and further on the ladder of transition from a linear to a circular economy, focused on the *extension of the lifespan of the product.* The pathways allocated to this group, such as repair and remanufacture, are the key aspects of a circular economy business model, where the product stays functional for as long as possible. Implementing those CE pathways requires the company to allocate much more resources to the CEBM. Finally, the last group of strategies for the implementation of CE is *smarter product use and manufacture*. At this stage, strategies focused on the product's functionality, the ownership model and manufacturing efficiency are implemented. Such strategies are focused on the design stages of the product.

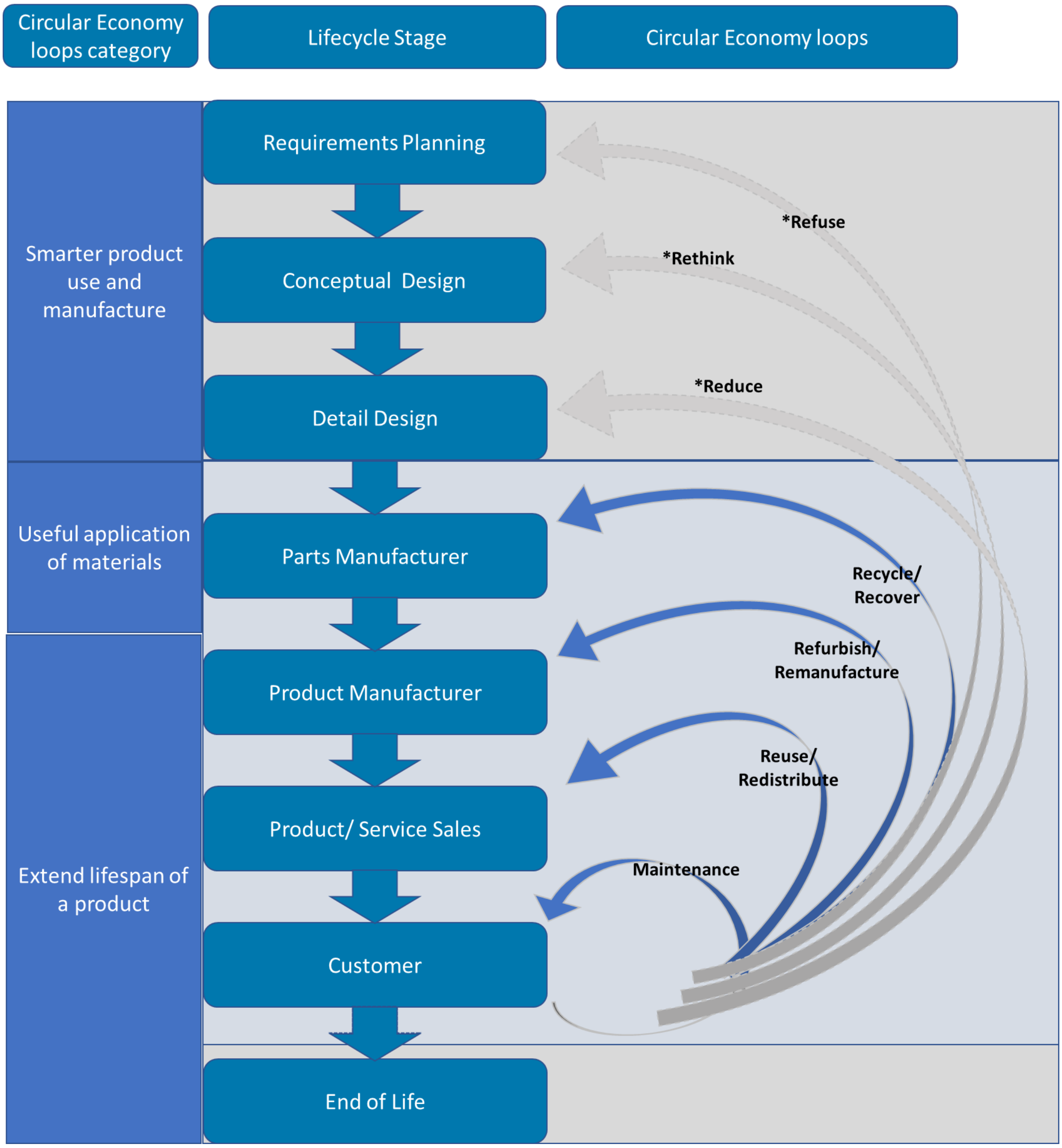


Figure 2.4: Circular economy model, integrated with the '9R' approach

Of course, not all EoL pathways are circular. From the field of Product Recovery Management (PRM), another classification for EoL pathways emerges based on whether the EoL pathway fulfils the criteria to be considered a Product Recovery Strategy (PRS). According to Thierry (Thierry et al., 1995), these criteria are: collecting the product after its usage stage, reprocessing the product, and then redistributing the processed product. This classification has been used to group the EoL pathways related to the CE (Alamerew & Brissaud, 2019).

Table 2.1 is created based on the literature and contains the most used EoL pathways, their definition, and whether the EoL is considered circular, which of the PRS strategy criteria the EoL pathways fulfil. The aim of Table 2.1 is to provide an overview of the applied EoL pathways independently of whether those are considered circular or not. Based on Table 2.1, it becomes evident that some EoL pathways have similarities and may even overlap, while others cannot strictly be considered as EoL pathways but strategies for EoL products. For instance, refuse, rethink and reduce are strategies for EoL products that are a part of the '9R' framework. These strategies can be implemented through the detailed design phase, and their utilisation will highly impact the EoL pathway of the product.

Table 2.1: Most used EoL pathways in the literature

EoL pathway	Product Recovery Strategy (PRS)			Definition
	Collection of after usage stage products	**Reprocessing of recovered products**	**Redistribution of the reprocessed products**	
Reconditioning	X	X	X	The rebuilding of a product to specifications of the original manufactured product using a combination of reused, repaired and new parts (Alamerew & Brissaud, 2019)
Disassembly	X	X		A reversal process in which a product is separated into its components and/or subassemblies by non-destructive or semi-destructive operations which only damage the connectors/fasteners (Vanegas et al., 2014)
Dismantle	X	X		A not-reversible product separation process in which a product is separated into its components (Vanegas et al., 2014)
Refurbishment	X	X	X	Restore an old product and bring it up to date (Alamerew & Brissaud, 2019)

Repair		X		Repair of defective product so it can be used with its original function (Alamerew & Brissaud, 2019)
Salvage	X	X	X	Salvage means an operation conducted in whole or in part to reclaim any product or material (*Https://Www.Lawinsider.Com/Dictionary/Salvage*, 2023)
Incineration	X			Incineration of material with energy recovery (Alamerew & Brissaud, 2019)
Resale	X	X	X	Resale is the sale of items that were previously purchased (*Https://Dictionary.Cambridge.Org/Dictionary/English/Resale*, 2023)
Reuse & redistribution	X	X	X	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function (Alamerew & Brissaud, 2019)
Recycle	X	X	X	Process materials to obtain the same (high grade) or lower (low grade) quality (Alamerew & Brissaud, 2019)
Remanufacture	X	X	X	The process of returning a used product to at least original performance specification from the customers' perspective and giving the resultant product a guarantee that is at least equal to that of a newly manufactured equivalent (BSI, 2009; W. Ijomah, 2002)
Disposal (landfill)			X	Landfilling is defined as the disposal, compression and embankment fill of waste at appropriate sites (Vaverková, 2019)
Demanufacturing	X	X	X	Demanufacturing focuses on evaluating the economic and environmental implications of material recycling, part reuse, shredding and landfill options (Johnson & Mccarthy, 2014)

(Repair &) Maintenance		X		The combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function (CEN/TC, 2018)
Cascading and repurposing	X		X	Cascading and repurposing refer to multiple uses of biological materials, first exploiting the functionalities of these materials as components and finally recovering energy, along the process of increased entropy (The Ellen MacArthur Foundation, 2013b)
Biochemical feedstock extraction	X	X	X	Organic residuals can be processed via biomass conversion, composting, or anaerobic digestion, which is a "process in which microorganisms break down organic materials, such as food scraps, manure, and sewage sludge, in the absence of oxygen (The Ellen MacArthur Foundation, 2013b)
Recover	X			The action or process of regaining the possession of the lost value of a product (Corum, 2016)
Repurpose	X	X		Use parts of discarded product in a new product with different function (Alamerew & Brissaud, 2019)
***Refuse**				Make product redundant by abandoning its function or by offering the same function with a radically different product (Alamerew & Brissaud, 2019)
***Rethink**				Make product use more intensive (e.g. by sharing product) (Alamerew & Brissaud, 2019)
***Reduce**				Increase efficiency in product manufacture or use by consuming fewer natural resources and materials (Alamerew & Brissaud, 2019)
Note: X indicates which of the Product Recovery Strategy (PRS) principles apply to the particular EoL pathway				

Table 2.1 shows that while some EoL pathways (or strategies) promote sustainability, it doesn't necessarily mean that they are circular. The strategies of refuse, rethink, and

reduce mentioned earlier are good examples. Those strategies promote sustainability while not closing any loops or satisfying the three PRS criteria, so they cannot be considered circular. Understanding the available and potential EoL pathways is crucial for this work since the proposed method promotes CE EoL pathways against traditional ones, such as disposal. The proposed method used the information from Table 2.1 to identify the most appropriate EoL pathways for the developed decision support method since the table presented all the available EoL pathways and specified which PRS criteria they satisfied for each of them. Finally, the following section focuses on the circular economy business models.

2.3.3 Circular Economy Business Models (CEBM)

Applying a CEBM requires a great extent of partnerships and cooperation between multiple companies and customers for successfully closing the loops (Lüdeke-Freund et al., 2019), and the specific roles of each relative stakeholder is an area that needs further research (Lakatos et al., 2016). Although the servitisation CEBM seems to be gaining momentum, scholars claim that it is more attractive to companies with products that are defined by a high cost of operation; thus, their customers will benefit from the high maintenance services they are supported with (Accenture Strategy, 2014). For products that don't satisfy those criteria, multiple other CEBM can close the loops generated through the product's lifecycle, and each of those is classified based on its unique characteristics.

Researchers proposed a new taxonomy of the CEBM by introducing two key dimensions: (i) the customer value proposition & interface and (ii) the value network, which is the degree of circularity of companies from a business model perspective (Urbinati et al., 2017), as illustrated in Figure 2.5. Some of the key CEBM that were identified were focused on a) the reverse supply chain processes and greater cooperation with the upstream suppliers, b) the transition to a lease model for the product, c) a greater degree of cooperation between companies and customers and, d) a usage-specific payment service. Finally, the authors utilised a group of eight experts in the field of CE to classify 62 companies into four categories and validate their proposed taxonomy. Those CEBM groups may include various ways of implementing the same principles and, according to the authors, can be taxonomised in the categories presented in Figure 2.5.

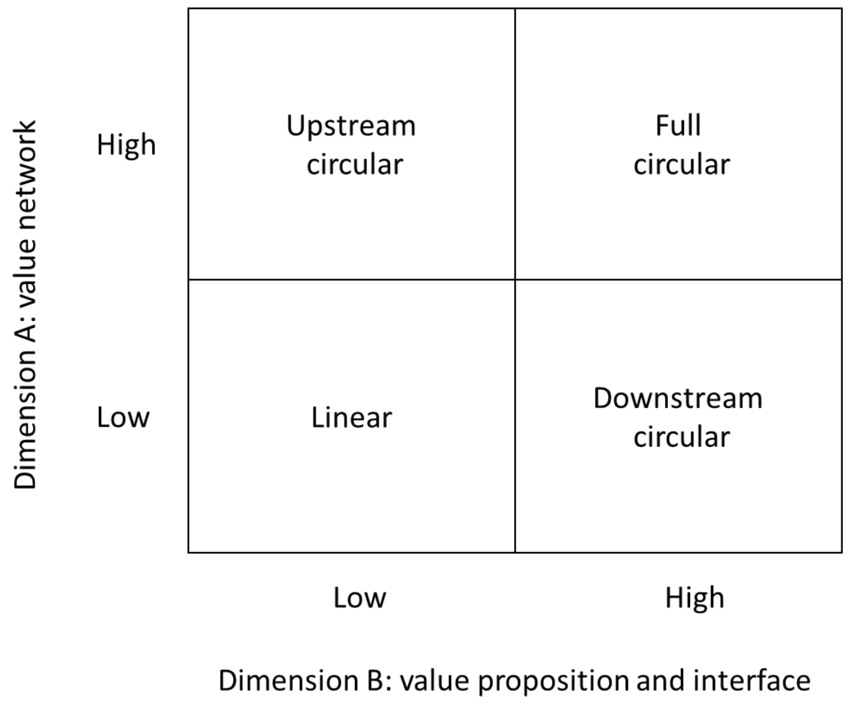


Figure 2.5: The four modes to adopt CEBM principles -adopted from (Urbinati et al., 2017)

Lewandowski (2016), in their research, used the well-established business model canvas as the main structure for identifying and taxonomising the CEBM. The main classification criteria used are depicted in Figure 2.6 and were used for the classification of 26 different CEBM. For further detail on those CEBM models and how they are defined, the reader is advised to study the work of Lewandowski (2016).

Regenerate	Optimise	Virtualize
Share	Loop	Exchange

Figure 2.6: Classification criteria for CEBM, adopted from Lewandowski (2016)

Lewandowski (2016) concludes that most of the identified circular business models can be reflected in the ReSOLVE framework developed by the Ellen MacArthur Foundation (2015) and that the literature has already identified multiple adoption factors, evaluation models and design and managerial tools that circular business models need to be operative. On a similar note, Lüdeke (2019) highlighted the importance of CEBM by first classifying 26 CEBM into the six main circular categories: repair and maintenance; reuse and redistribution; refurbishment and remanufacturing; recycling; cascading and repurposing; and organic feedstock business model patterns. Those patterns have been established through the Ellen MacArthur Foundation (2013b). In their research, for each of those categories, they provided a morphological box that contained related CEBM. This representation was able to depict that for each of the major circular loops, there are many CEBM available for closing the loops, which could provide some creative applications of CEBM (Lüdeke-Freund et al., 2019).

Their proposal aligned with the conceptual framework gap to support practitioners transitioning from a linear to a CEBM since previous studies on CEBM develop bespoke solutions with limited transferability (Lewandowski, 2016). Another critical gap identified regarding the CEBM is the need for clear arguments on why a company should apply a CEBM (Bocken et al., 2016) and address the lack of context sensitivity in the publications, which biases the proposed CEBM (Lüdeke-Freund et al., 2019). Thus, any proposed work on the area should provide insight into the suitability of a product for applying a CEBM, which includes remanufacturing as a viable solution and provides the base for an unbiased argument on the real impact of the application of a CEBM.

2.3.4 Sustainability and Circular Economy

This section discusses the similarities and differences between sustainability and the circular economy, two concepts that still have not been made explicit in the literature, constraining the efficacy of their application and usage (Geissdoerfer et al., 2017).

The main similarities between the two concepts are based on the multidisciplinary approaches needed to integrate financial and environmental aspects in their value creation for each of the collaborating stakeholders (Geissdoerfer et al., 2017). Other similarities stem from the need to adopt regulation and incentives as core implementation tools and the potential cost, risk, diversification, and value co-creation opportunities (Geissdoerfer et al., 2017). For a deeper dive into the similarities, the reader can study the work in detail (Geissdoerfer et al., 2017).

Although the similarities between the two concepts seem to create the image of two very similar terms, their differences are significant. To begin with, CE aims to close loops, thus minimising resource input to the system, while sustainability is open-ended with a variety of goals to achieve. An excellent example of this multidisciplinary aspect of sustainability is the establishment of the 17 UN sustainable development goals. Sustainability focuses on its three main pillars: the environment, the economy and society (Geissdoerfer et al., 2017). On the contrary, CE focuses hierarchically on the financial system and how it can benefit the main economic actors. Finally, CE has a much more 'operative' perception of responsibilities since it focuses on private businesses and regulators, while sustainability shares its responsibility with the broader community and is not clearly defined.

2.4 Decision support for End-of-Life

As illustrated in Figure 2.1, the proposed work is the meeting point of Circular Economy, EoL Management and Decision Support. Therefore, the closest field to this work is the decision support for EoL, focusing on CE pathways. Thus, this section will present a detailed analysis of the decision support for EoL to provide a good overview of the state-of-the-art literature and identify gaps for further development.

One important difference is the distinction between decision-making and decision-support. *Decision-making* is the process of selecting a course of action from among several alternative options based on a set of criteria or goals. It involves analysing information, assessing risks and benefits, and weighing the potential outcomes of each option before making a final choice (Hammond et al., 1998; Simon, 1960). On the other hand, *decision support* refers to tools and techniques that are used to assist decision-makers in the decision-making process. These tools may include data analytics, simulation models, expert systems, or other computer-based systems that provide information and recommendations to decision-makers to help them make more informed and effective decisions (Sharda et al., 2014). In other words, decision support provides decision-makers with relevant and timely information to facilitate better decision-making, while decision-making is the actual process of selecting the best course of action based on the information and insights provided by decision support.

This literature review used the snowball approach, also known as snowball sampling or snowballing, which entails starting with a set of initial relevant sources and then using the reference lists of those sources to identify additional relevant sources. This process is repeated recursively, with each new source serving as a potential entry point for identifying additional relevant sources. The snowball approach has been selected since it is particularly useful in cases where the research topic is niche or where the relevant literature is difficult to find through traditional search methods. The difficulty in finding related literature occurred due to the cross-sectional nature of the research. Additionally, extra caution was exercised while applying the snowball approach since it can lead to sample bias if there are gaps in the original set of relevant sources or if there is a high degree of interconnectedness among the sources. Each new source was critically evaluated based on its quality and relevance to the scope of this work.

During the approach, some keywords were identified and used to identify the related work in academia. Those were "End of Life decision making", "remanufacturing decision making", "EoL disposition", "EoL", “core disposition”, and “product recovery management”. These keywords were not a strict inclusion or exclusion criterion but were used to identify the relevance of the new sources. In the conducted literature review, 41 articles were identified as the most relevant to the scope of work, while the snowball approach in the literature review was adopted.

Figure 2.7 allocates the number of related works to the year of publication. Additionally, it demonstrates the average number of factors considered when conducting EoL decision support or making per publication. The identified factors based on the literature and industry feedback were financial, technical, environmental, social and legal.

According to Figure 2.7, there is a steady incline in the number of related publications as the interest is, on average, growing and peaked in 2016. In 2018 and 2019, there was a decline in the number of related publications. The research engine Scopus was used to test if that was the case regarding the field of *EoL decision-making*. A query for journal articles, limited to *Engineering*, and the publication period was from 2014 until 2023, containing “End-of-life” and “decision-making” keywords, was conducted. The 83 results of the search and their publication year are illustrated in Figure 2.7. Although the scope of the articles is unsuitable for the literature review conducted for this research, the allocation of the publications across the years confirms that publications were limited between 2017 and 2019. Additionally, in Figure 2.7, it is evident that the interest is growing and surpassing its peak in 2016.

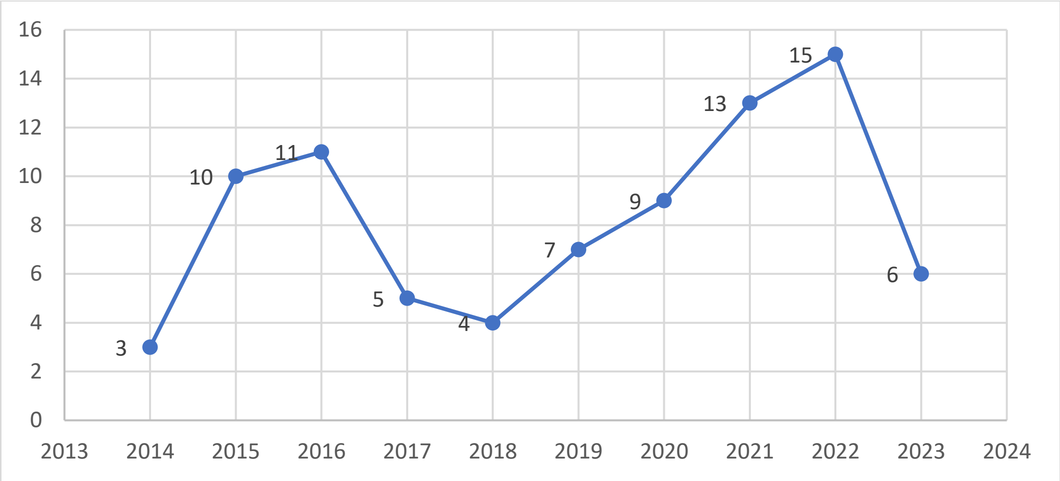


Figure 2.7: Publication per year in the SCOPUS query

Focusing again on Figure 2.7, in 2020 work that was conducted during 2019, pre-COVID-19 was published, while in the following years, 2021 and 2022, there was a decline which follows the pattern of COVID-19 publications, where a substantial decrease of non-COVID-19 research accompanied the dramatic rise in COVID-19 publications (Raynaud et al., 2021). A comparison between Figure 2.7 and Figure 2.8 reveals that this literature review does not share the growth in interest in the field after 2020, which was revealed through the previous SCOPUS search. This is because the scope of the literature review limited the selection of related publications that were analysed in depth.

Interestingly, based on Figure 2.8 and the average usage of factors per publication, expressed through the orange line, we recognise that EoL decision-making and support is a multifactor problem requiring input from many factors. The number of factors adopted varies from two to four on average, although the number of publications per year is too small to draw confident conclusions.

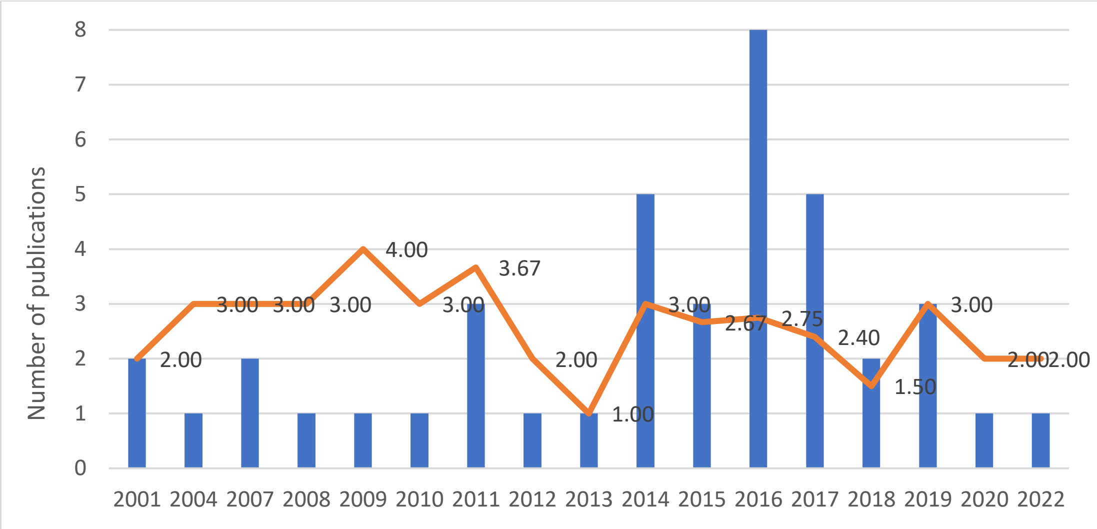


Figure 2.8: Average number of factors based on examined publications per year (orange line- average number of factors for publications)

The logical assertion we arrive at is that EoL decision support and decision-making is a multidimensional problem that previous publications addressed through the adoption of multiple financial, technical, environmental, social and legal factors. Those factors are in the broader areas of sustainability, circular economy and EoL decision-making, which we will describe in greater detail in the following sections.

2.4.1 Decision-making methods & approaches

One of the key aspects of the literature analysis was identifying methods and approaches previous scholars have followed to provide decision support in the EoL stage. Table 2.2 reports the findings of 41 papers published between 2001 and 2022 that assess EoL options in their decision-making.

Table 2.2: Literature focused on EoL decision-making

	Decision Aspects					**Methods**		
References	**Economic**	**Technical**	**Environmental**	**Social**	**Legal**	Quantitative	Qualitative	Mixed
Murayama and Shu (2001)	-	X	-	-	-	FMEA		
Lee et al. (2001)	X	X	X	-	-	MIP, LCA		
Bufardi et al. (2004)	X	-	X	X	-	MCDM (ELECTRE)		
Jun et al. (2007)	X	X	-	-	-	MIP, Pareto (optimal)		

Mergias 2007	X	X	X	X	-	MCDM (PROMETHEE)		
Chan (2008)	X	-	X	X	-	GRA		
Wadhwa et al. 2009	X	X	X	-	X	Fuzzy logic, TOPSIS		
Lee et al. (2010)	X	X	-	-	X	MIP		HALG
Ghazalli and Murata (2011)	X	X	X	-	X	NN, AHP		CBR
Ma et al. (2011)	X	X	X	-	-	2 step HR	And/or graph	
Dhouid 2011	X	X	X	-	X	PROMETHEE	2-tuple linguistic model, choquet integral interaction	
Jun et al. (2012)	X	X	-	-	-	MINLP, GA		
Mckenna et al. (2013)	X	-	-	-	-	Factors Sensitivity, LCA		
Ondemir and Gupta (2014a)	X	X	X	-	-	MIP		
Shokohyar et al. -2014	X	-	X	-	-	MINLP, GA, Pareto		
Ziout et al. (2014)	X	X	X	X	X	AHP, PESTEL		
Ondemir and Gupta (2014b)	X	X	X	-	-	MIP		
(Johnson & McCarthy, 2014)	X	-	-	-	X	Integrative optimisation model (Integer Programming)		
Qian et al. (2015)	X	X	-	-	-	LCA		
Yang et al. (2015)	X	X	X	-	-	MIP		HALG
Kwak (2015)	X	X	X	-	-	Pareto, MIP		
Pazoki and Abdul-Kader (2016)	X	X	-	-	-	MINLP, Sensitivity Analysis		
Kwak and Kim -2016	X	X	X	-	-	MIP		
Liu et al. (2016)	X	X	-	-	-	GA (NSGAII), Pareto		
Yang et al. (2016c)	X	X	X	-	X	GA		
Meng et al. (2016a)	X	X	X	-	X	MIP, Fuzzy logic, MCDM (PROMETHEE)		
Meng et al. (2016b)	X	X	X	-	-	LCA		
Li et al. (2016b)	-	-	X	-	-	LCA		
Karaulova and Bashkite (2016)	X	X	X	-	-	LCA	TRIZ	
Meng et al. (2017a)	X	X	X	X	-	GA (NSGAII), Pareto		
Meng et al. (2017b)	X	X	-	-	-	PHM		
Mashhadi and Behdad (2017)	X	X	-	X	-	MIP, Clustering Algorithm		
Cho et al. (2017)	X	X	-	-	-	GA, ASCA		
Steeneck and Sarin (2017)	X	-	-	-	-	MIP		
Omwando et al. (2018)	X	-	-	-	-	Fuzzy logic		

Alamerew (2018)	X	-	X	-	-	MCDT		
Wang et al. (2019)	X	-	-	-	-	MIP		
Farahani et al. (2019)	X	X	-	-	X	MINLP, QMIP		
Yang et al. (2019)	X	X	X	X	X			PHFSs
Garvey et al. (2020)	X	-	X	-	-	LCA	DA	
Quéheille et al.(2022)	-	-	X	-	X	LCA		

Legend

ACSA = ant colony search algorithm
AHP = analytical hierarchy process
CBR = case-based reasoning
DA = Decision Analysis
ELECTRE = ÉLimination Et Choix Traduisant la REalité ("Elimination and Choice Translating Reality")
FMEA = Failure mode and effect analysis
GA = Genetic algorithm
GRA = Grey Relational Analysis
HALG = hierarchical attributed liaison graph
IP = integer programming
LCA = life cycle assessment
MINLP = mixed integer non-linear programming
MIP = mixed integer programming
NN = The nearest neighbourhood algorithm
NSGAII = Non-dominated Sorting Genetic Algorithm
PESTEL = political, economic, social, technological, environmental, and legal
PHFSs = picture hesitant fuzzy sets
PHM = proportional hazard model
PROMETHEE = Preference Ranking Organisation METHod for Enrichment of Evaluations
Q-MIP = Quadratic Mixed Integer Program
TOPSIS = Technique for Order of Preference by Similarity to Ideal Solution
TRIZ = Theory of Inventive Problem Solving

Table 2.2 reveals that EoL decision-making is a multicriteria decision problem that usually considers more than one aspect. Additionally, almost all of the published work analysed used at least one quantitative approach (98%), one qualitative approach at a percentage of 15%, and at least one mixed method at 10%. This reveals that all published work focuses on quantifying the EoL decision-making process, but qualitative and mixed approaches seem to be understudied. This categorization is based on the primary methodological approach of each method, but some methods could use a combination of qualitative and quantitative techniques. Additionally, some methods in the quantitative category may involve subjective judgments or qualitative data interpretation. Therefore, the classification may not always be clear-cut, and there could be some overlap between the categories. Of the quantitative methods used, the most common is mixed integer programming (MIP). HALG and TRIZ are the most common methods regarding mixed and qualitative methods, respectively.

According to Table 2.2, the main method categories used in the literature are the *Optimization algorithms* (ACSA, GA, GRA, MINLP, IP, MIP, Q-MIP), *Decision-making methods* (AHP, CBR, DA, ELECTRE, NSGAII, PROMETHEE, TOPSIS, TRIZ), *Environmental impact assessment methods* (LCA, PESTEL), *Statistical methods* (PHFSs, PHM, NN), *Graph-based methods* (HALG) and *Risk analysis methods* (FMEA, PHM). This categorization is not strict since some methods may fall under multiple categories.

In the optimization domain, GA, IP, MINLP, MIP, and Q-MIP are mathematical techniques that can handle different types of problems, including continuous or discrete decision variables, linear or nonlinear objective functions, and uncertain or complex systems. These methods help to systematically evaluate alternatives, identify optimal solutions, and improve decision-making processes. Scholars used those optimization methods and techniques to find solutions for the best EoL pathway by programming the related parameters and defining the necessary decision variables (Farahani et al., 2019; Johnson & McCarthy, 2014; Meng et al., 2016).

Among the decision-making methods, AHP and DA provide a structured approach to EoL decision-making. AHP handles qualitative and quantitative data and can address multiple criteria and uncertainties (Z. Ghazalli & Murata, 2011b; Ziout et al., 2014). More specifically, Ghazali used the AHP integrated with the case-based reasoning (CBR) method to gather information and retrieve the most relevant case of previous EoL decision-making and provide EoL decision support to a component level (Z. Ghazalli & Murata, 2011b). Ziout used AHP to identify all the relevant stakeholders in an EoL decision-making problem and focused on a product level, identifying and clustering the multiple decision factors. The application of DA has a more qualitative focus (Ziout et al., 2014). Previous scholars identified that future trends in the methods used for EoL decision-making would include the usage of GA or other metaheuristics and increased usage of subjective weighted methods, such as AHP, to limit the inaccuracy of the assumptions made through corrections made by experts (Sitcharangsie et al., 2017). The applications of other Decision-making methods, such as the PROMETHEE, will be discussed in detail in the following sections, where the articles are studied based on the decision-making factors they applied.

FMEA is a risk analysis method that helps identify potential system failures and prioritize the most critical failure modes. Scholars used FMEA to support decision-making between direct reuse and remanufacturing based on approaches addressing the reliability of the product’s components (Murayama & Shu, 2002). Other research used another risk analysis method, the PHM, to provide quality-driven EoL decision-making focused on profit maximization from component recovery (Meng et al., 2017b).

The most frequently used illustration representation method was the HALG, which can demonstrate the product's structure and the connections between components at a component level.

2.4.2 Decision-making factors of influence on the EoL

Previous sections of this chapter have highlighted the relationship between sustainability and circular economy and the business models that can be applied to implement those principles. The more focused literature review on decision-making and support for a circular economy provided additional insights into the factors influencing decision-making for EoL. As discussed before, remanufacturing is one EoL pathway that requires significant resources. Thus, EoL decision-making is dominated to a great extent by those decisions when the viability of remanufacturing as a potential EoL pathway is tested. Due to the complexity of decision-making in remanufacturing, the clusters of decision factors applied in this decision are extensively studied in this research.

According to the literature, the clusters of factors that impact EoL decision-making while considering remanufacturing a viable pathway are the following: financial, environmental, technical, legislative and social (Dhouib & Elloumi, 2011; Johnson & McCarthy, 2014; Meng et al., 2016, 2017a; Sitcharangsie et al., 2019). The conducted studies developed different approaches regarding EoL decision-making based on, amongst others, the type of decisions they support, the factors under consideration, and the level of decision-making.

Figure 2.9 uses a Venn diagram to illustrate those clusters of decision factors during EoL decision-making, including remanufacturing in their available EoL pathways. In this illustration, the clusters are all considered of equal interest. The area covered by all clusters is the area of EoL decision-making that integrates all those clusters simultaneously.

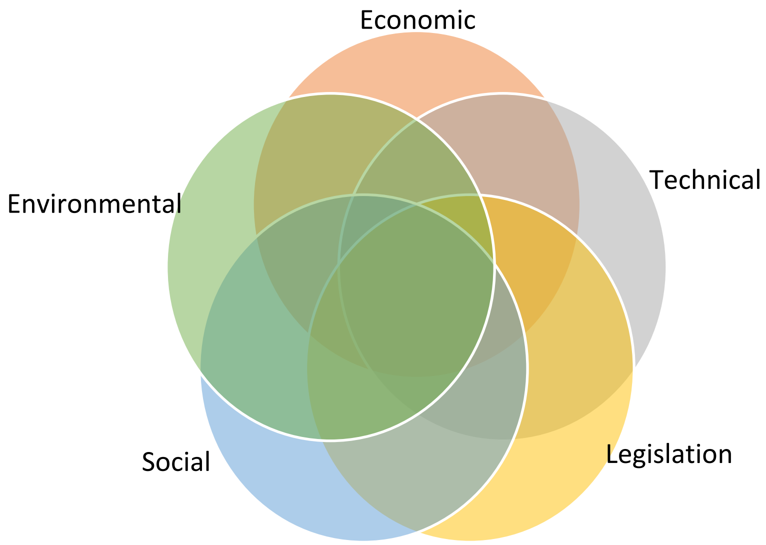


Figure 2.9: Clusters of factors that impact decision-making in the EoL

The next session uses the five factors of interest to analyse the related literature and determine when remanufacturing is considered a viable EoL pathway, what the state-of-the-art is, and what opportunities lie within the literature gaps.

2.4.3 Decision-making factors literature distribution

Although previous work has identified the main decision factors that impact the EoL decision support approaches, it did not quantify the research conducted in the field. This section analyses articles whose main contribution was a decision support method or framework aimed at the EoL stage of products.

As depicted in Figure 2.10, two numbers were calculated for each influential factor based on the 41 reviewed articles; the percentage of the articles in their approach was based solely on a factor (illustrated in orange) and the percentage of articles that included a factor in a multifactor approach (illustrated in blue).

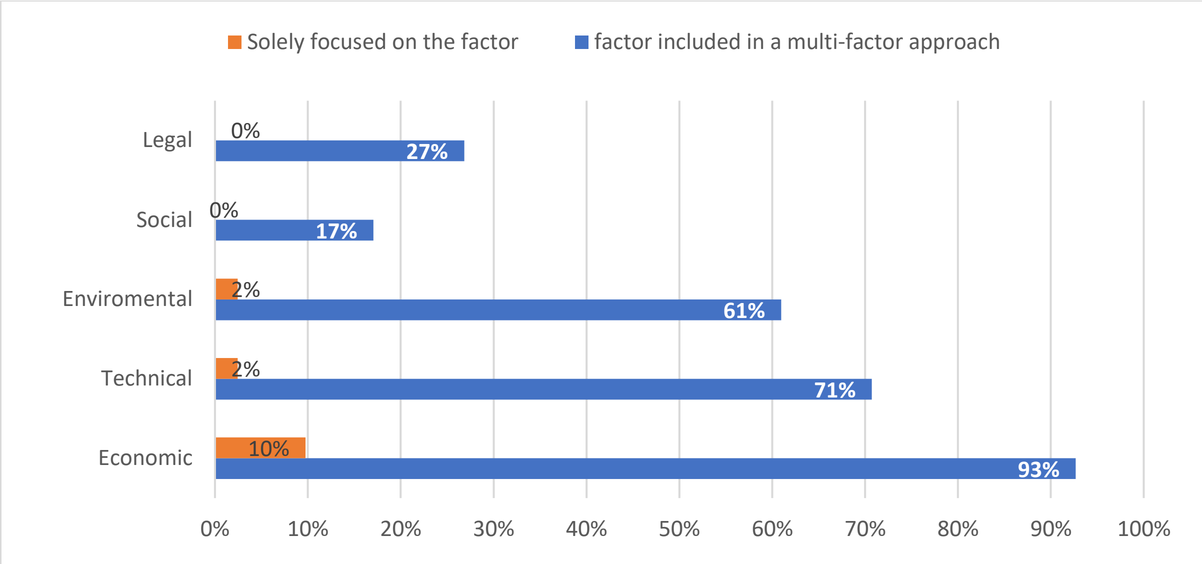


Figure 2.10: EoL decision support literature distributed across factors of influence

It becomes evident from the analysis illustrated in Figure 2.10 that articles following a one-factor approach are not common since most of the published work includes at least one more factor in their study. No work has been focused solely on the legal or social aspect of EoL decision support. Additionally, only 17% of the articles analysed in this literature review consider social aspects as part of their decision-making process. Previous scholars have also identified the lack of research on EoL decision-making focused on social aspects and legislative aspects (Alamerew & Brissaud, 2019).

According to past research, technical concerns are the most dominant for considering remanufacturing as a viable EoL pathway, while social and legal aspects are mostly neglected (Chaowanapong et al., 2017). Based on Figure 2.10, that statement is partially confirmed since, after the economic aspect where companies focus on the profitability of remanufacturing, the following concern is the technical aspects of it. Additionally, social and legal aspects are much less researched in the literature.

The articles that consider environmental aspects as part of their decision-making process are equal to 61%, which does not reflect the significance of the environmental factors in the EoL decision-making and support.

2.4.4 One factor approach in the EoL decision-making literature

Approaches based solely on economic aspects are more common, and their primary goals can differ from energy savings to maximisation of profits. Mckenna et al. (McKenna et al., 2013) studied the energy savings in the German automotive sector by using LCA data to quantify those savings when Direct Secondary Reuse (DSR) was the selected EoL. The chosen decision factors for their work were monetary, demand and supply factors. Wang et al. proposed an integrated quantitative decision model to evaluate the financial traits of a component in its EoL when direct Secondary Reuse was also a viable solution (Wang et al., 2019). By focusing exclusively on economic factors, they obtained the optimal acquisition cost to retrieve EoL products for component reuse. Both of these studies have investigated the practical application of the DSR pathway from a financial perspective, even though they have employed LCA methodologies in their research. This appears to be a recurring trend in the existing literature, as direct reuse entails minimal resource allocation and reduces the effort required to refurbish returned cores. Consequently, it can be observed that the decision-making process regarding direct reuse is primarily centred around financial considerations, rather than involving a multidimensional approach. As we shall delve into in the subsequent literature analysis, this distinction becomes more evident when one explores EoL pathways beyond the exclusive focus on direct reuse

Omwando et al. (2018) devised an adaptable decision support system utilizing a fuzzy inference approach to investigate the remanufacturability and comparative analysis of a set of EoL products(Omwando et al., 2018a). Their primary focus lies in optimising profit associated with remanufacturing a product within the chosen product family.

In a related vein, Steeneck and Sarin (2017) delved into a comprehensive examination of the remanufacturing production process for a product. Their research was motivated by the critical role that production economics plays in facilitating optimal decisions at the EoL stage, particularly for Original Equipment Manufacturers (OEMs) engaged in the production of both new and remanufactured products. Notably, their contributions extended to modelling the production economics of remanufacturing, which serves as a valuable tool for tactical decision-making at the EoL. Furthermore, their work incorporated crucial financial considerations, such as the quantity of demanded cores and pricing, into a dynamic framework. These studies have been captured in Figure 2.10 through the orange colour, which is equal to 10% of the total literature analysed.

Focused on only one aspect, other scholars studied remanufacturing solely from the technical perspective by using a reliability model to provide decision support for EoL products (Murayama & Shu, 2002). The lack of solely technical-focused studies reveals that although previous work has claimed that technical concerns are the most dominant for considering remanufacturing as a viable EoL pathway (Chaowanapong et al., 2017), they are usually addressed in alignment with economic factors. Other technical factors could be focused on the complex task of assessing the product's remanufacturability. This remanufacturing evaluation requires a multifactor approach, which will be discussed thoroughly in the following section.

From an environmental perspective, LCA is academia's primary method of analysis (Sitcharangsie et al., 2019). Based on LCA data for vehicles in China, scholars developed scenarios that represented different technological levels of recycling ELVs and proved that by improving engine remanufacturing, the higher recovery of materials would enhance the recovery of resources (Li et al., 2016). Garvey et al., identifying the need for better integration of LCA into the decision-making for EoL products, developed a framework that integrates LCA and supports decision-making through the environmental lens (Garvey et al., 2020). Their approach reinforces the communication of the decision-makers with the LCA practitioners by combining the goal and scope of developing the LCA with information from the decision-making process, thus maximising the LCA value and addressing the financial aspects of the decision-making process.

Finally, based on the analysis illustrated in Figure 2.10, no published articles provide decision-making support from solely a social or legislative perspective.

2.4.5 Multi factors approach in the EoL decision-making literature

Based on Figure 2.10, it becomes evident that the plethora of previously published work examines more than one decision factor simultaneously, with almost all of them considering economic factors. Although the financial aspect is crucial, Figure 2.10 proves, as suggested by previous works (Sitcharangsie et al., 2019), that EoL decision support is considered a multicriteria decision-making (MCDM) problem; thus, MCDM methods are used to resolve it.

Significant interest lies in the combinations of the factors adopted to develop the MCDM approaches proposed by previous works. Both Figure 2.10 and Figure 2.11 are based on Table 2.2. Figure 2.11 depicts the combinations of the different approaches studied in the conducted literature review. Figure 2.11 contains both the case when the combination of the selected factors is "*strict*" (for instance, only Econ-Techn factors are used in the approach and depicted in orange colour and solid line) and "non- strict", when the selected factors combination is part of a larger combination (for instance, Econ-Techn factors plus some other factor(s), and depicted in blue colour and dotted line). Thus, a "*strict*" combination of factors in this research is a combination that only includes the specified decision factors and no additional decision factors. A "*non-strict*" combination includes the selected combination of factors, while it may include additional factors as well.

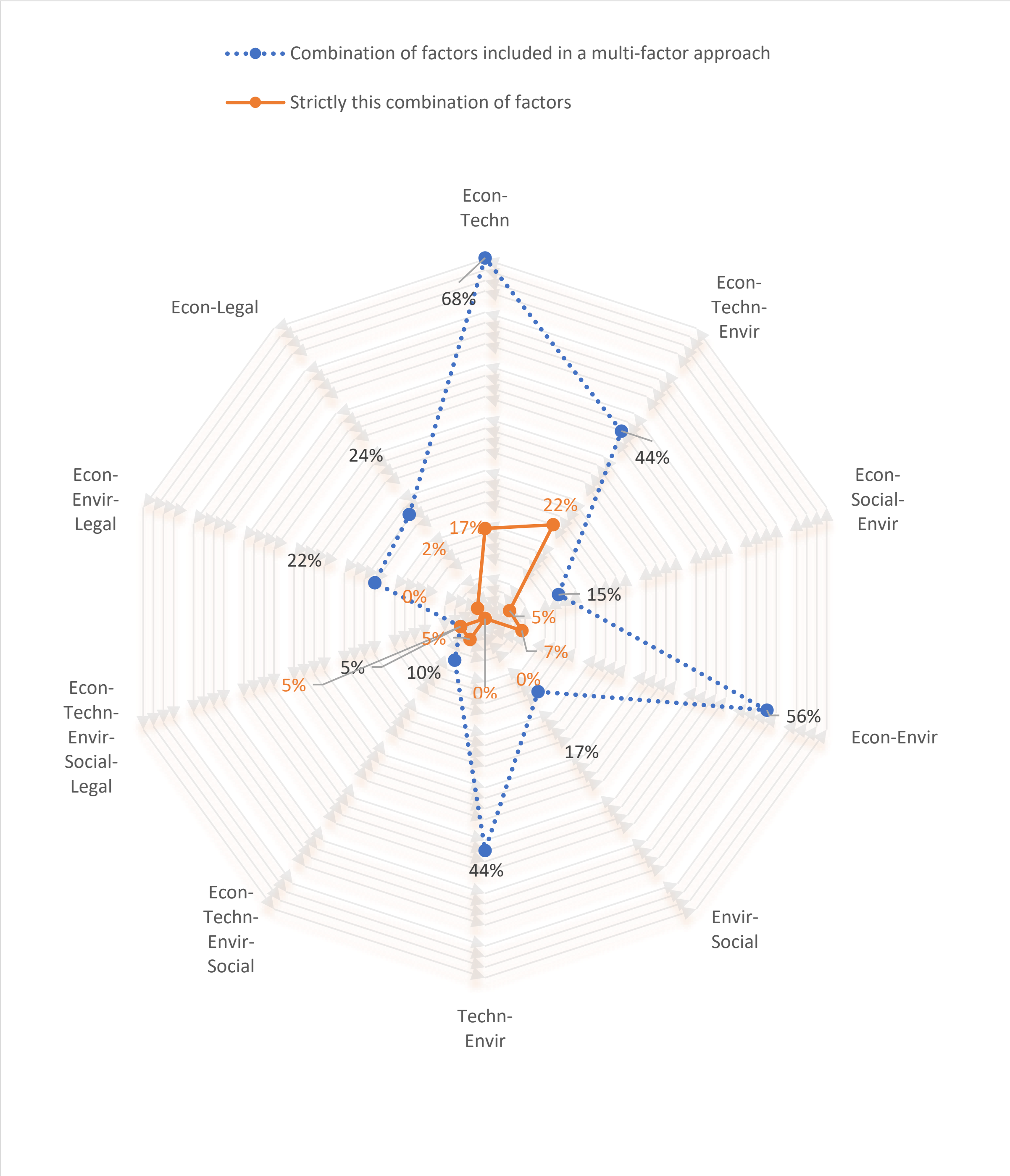


Figure 2.11: EoL decision support literature with a combination of factors of influence

From Figure 2.11, there are multiple conclusions to be drawn. Firstly, it becomes evident that the most common *strict* combination (depicted with a solid orange line) is the *Econ- Techn- Envir* adoption of factors with no adoption of any other factor. This approach accounts for 22% of the total articles studied. The second most popular strict approach is the *Econ- Techn*, which accounts for 17%. Those two strict approaches are the most common in literature in EoL decision-making and reveal that the financial motive is the most crucial and is directly linked with the technical feasibility and environmental impact of the solution under review. The strict combination of *Econ-Envir* accounts for 7% of the total articles, and 5% are the combinations of *Econ- Tech-Social* and *Econ- Tech- Envir- Social- Legal – Envir,* which includes all factors. Moreover, 2% of the total articles follow a strict *Econ- Legal* approach where the article focuses on conforming to the EoL decision process with the environmental regulations. An interesting outcome of Figure 2.11 is that it reveals which strict combinations of factors have not been identified at all in the selected literature. For instance, no studies focused strictly on an *Envir- Social* approach were identified, which might be explained by the limited interest from the industry in such an approach that does not consider financial factors.

Moreover, no strict approaches were identified in the *Econ- Envir- Legal* combination or *Tech- Envir* combination, although both of them include the very popular economic and technical factors clusters. Although such an observation seems unusual, the reason behind this is that the studies that do consider those approaches frequently apply some technical or economic aspect to their analysis respectively. Thus, due to their critical importance, most publications studied in this review also include those factors.

When the focus changes to the *non-strict* combination of factors (depicted with a dotted blue line), the *Econ- Techn* is the most common, used in 68% of the total articles. The second most common is the *Econ- Envir* combination, with 56% inclusion in the total articles. The *Econ- Tech- Envir* and *Tech- Envir* account for 44%, revealing once again that most EoL decision-making approaches include a technical analysis in their methodology.

As discussed, sustainable development was initially expressed through the ‘3Ps’, namely ‘*profit-people-planet.’*. Figure 2.11 illustrates that research that includes those three initial pillars of sustainable development accounts for only 15% of the literature. On the contrary, any combination containing economic, environmental, and technical aspects has been studied significantly more than any other combination. Previous work in the field has identified the need for more research with multiple objectives, specifically the combination of economic, environmental, and technical factors (Sitcharangsie et al., 2019).

While remanufacturing presents a viable option for end-of-life (EoL) product management, the social and legal dimensions of decision-making in this context have received limited scholarly attention. There is a notable gap in the literature for a comprehensive approach that integrates various aspects of EoL decision-making. Legal considerations primarily manifest through prescribed recovery rates or similar benchmarks (Dhouib & Elloumi, 2011; Zakri Ghazalli & Murata, 2011; Johnson & McCarthy, 2014). These rates are typically enforced through legislation like Extended Producer Responsibility (EPR) regulations and directly influence landfilling, recovery, or recycling limitations. Consequently, they act as constraints when selecting the optimal product EoL pathway.

Finally, based on Figure 2.11, it is evident that a comprehensive approach, which encompasses all the aforementioned factors, is represented in merely 5% of the total articles examined in this review. This observation underscores a conspicuous deficiency in holistic decision-making pertaining to End-of-Life (EoL) considerations. Furthermore, the subsequent sections delve into studies that employ identical aspects and factor combinations, offering a more detailed examination to unveil further gaps within the existing literature.

2.4.5.1 Economic- Technical- Environmental (Econ- Techn- Envir) aspects

Previous studies focused on the *Econ- Techn- Envir* aspects and adopted methods that provide a more holistic solution to the problem. Lee et al. (2001) use Mixed Integer Programming (MIP) and an LCA approach based on the now-outdated Eco-Indicator 99 to provide a multi-objective methodology for determining the optimal EoL pathway for used products. Their MIP approach included different scenarios of objective functions with the aim to: a) minimise the environmental impact through maximisation of reusable components, b) minimise economic deficit, c) minimise the time for disassembly and deficit, d) minimise the time for dis-assembly and minimise environmental impact, e) minimise environmental impact and deficit (or maximise surplus), f) minimise the time for disassembly, environmental impact and deficit (or maximise surplus) (S. G. Lee et al., 2001). Although such an approach considers multiple objectives, it limits the practitioner to predetermined scenarios for those key objectives while it does not weigh the factors that will impact the decision model; thus, it does not provide the practitioner with the ability to develop their own, bespoken decision model. Moreover, the Eco-Indicator 99 is an outdated method that does not provide accurate environmental quantification for precise decision-making. Additionally, through MIP, the visualisation of the EoL decision problem is limited. Methods such as the Hierarchical Attributed Liaison Graph (HALG) have been used to provide a qualitative representation of the product's structure (Yang et al., 2015). Yang et al. (2015) additionally used quantitative usage of the conditional probability of quality to estimate the expected profit for each EoL pathway. Their work did not provide the possibility for weighting decision factors individually, while their method highlighted the need for a visual aid to support the EoL decision-making process and the practitioners (Yang et al., 2015).

On a similar note of visualisation of the EoL decision problem, Ma et al. (2011) focused on providing decision support for the EoL stage by addressing the main decision objectives of the Disassembly Process Planning: a) the disassembly level, b) the disassembly sequence and, c) EoL pathways selection. Thus, they linked the EoL decision problem to the Disassembly Process Planning and used an extended AND/OR graph and then a two-phase algorithm to provide decision support. One of the key contributions of this work was the introduction of solution constraints to the EoL decision problem, although the solution remained aimed at the economic aspects. Based on the author’s comments, some limitations of this work were the limited solution constraints that were considered and the method’s suitability for complex products (Ma et al., 2011). Thus, the need for a suitable method for complex products and a deeper analysis of the possible solution constraints has been highlighted.

Quality uncertainty of the returned products is a key parameter for successful EoL decision-making, as other studies have also suggested (Farahani et al., 2019; Ondemir & Gupta, 2014a, 2014b; S. S. Yang et al., 2015). While previous studies provided EoL decision-making based on the condition of the product, Ondemir and Gupta claimed that optimal recovery decisions can be made without any preliminary disassembly or inspection operations when sensor-embedded products (SEPs) are used (Ondemir & Gupta, 2014b). The SEPs collect data related to the product's usage stage that impacts its lifecycle and minimise the uncertainties related to its quality condition. Other studies have based their quality assessment solely on the OEE of the equipment and an analysis of the lifetime left in the product (Karaulova & Bashkite, 2016). Such an approach lacks the inspective aspect for the quality of the returned cores that had been highlighted before. For instance, other researchers suggested that when a grading system is adapted prior to remanufacturing, profitability can increase regardless of the quality distribution (Yanıkoğlu & Denizel, 2020).

Other scholars linked the quality of the cores with the financial gain and developed a novel quality grading method for PCs that supported the decisions of the acquisition price, the disposition of the cores and their remanufacturing cost by considering the quality of the returned cores as a continuous variable (Farahani et al., 2019). Through a bidirectional feedback loop and a mixed integer non-linear programming model, the remanufacturing cost was used to determine the minimum required quality grade for which remanufacturing of the cores would be profitable.

Karaulova and Bashkite (2016) developed a Lean and Green Manufacturing tool based on TRIZ that validates the selected EoL strategy without implementing a take-back approach. They used an enhanced Remanufacturability Assessment Method previously developed by Du et al. (2012), which focused on assessing the *Econ-Techn- Envir* aspects to support remanufacturing. This work differs from the ones above due to the strong focus on the remanufacturability of the returned cores, which satisfies the *technical* and *economic* aspects but does not deliver a detailed *environmental* analysis, which may include an LCA of the remanufactured products and a clear quantification of their environmental impact.

In the same context, Kwak and Kim (2016) claimed that product remanufacturability is key to the success of remanufacturing since a remanufactured product should provide greater economic and environmental value than a brand-new product. Although that might be the de facto principle, some researchers have highlighted the possibility that this may not always be true due to the limited efficiency of the remanufactured product, obsolescence or the environmentally demanding remanufacturing process (Boustani et al., 2010; Gutowski et al., 2011; Intlekofer et al., 2010). Additionally, as discussed in the previous paragraphs, using outdated methods such as Eco-Indicator 99 or a very light approach to environmental impact quantification may result in findings with high uncertainty and limited significance. Thus, a method that quantifies environmental impacts and profitability in detail while considering technical aspects, such as product remanufacturability, is needed. To tackle this, researchers estimated the relative advantage between a remanufactured product and a new one through a multidimensional assessment based on three key objectives: unit production cost, environmental impact, and net profit (Kwak & Kim, 2016). The main contribution of their approach was the link between the timing of remanufacturing as an EoL pathway and its profitability and environmental impact on physical and technical obsolescence. This approach was based on the dynamic relationship between the technical characteristics of the returned cores and remanufacturing, highlighting the need for obsolescence to be a crucial EoL decision-making factor. Their proposed work provides insights on the environmental impact at a product level only, while it lacks visualisation aids for the EoL decision maker, a need previously highlighted in the literature from an LCA and a decision-making perspective (Laurin et al., 2016).

Several salient conclusions have emerged in light of the analysis conducted on the previously mentioned studies. Firstly, it has been underscored that adopting a weighted factors approach is imperative. Addressing quality uncertainty can be accomplished by integrating embedded systems and sensors or, alternatively, by implementing inspection and grading systems that consider critical performance indicators, such as the product's lifespan. Furthermore, it is vital to factor in solution constraints when confronted with intricate decision-making challenges. Lastly, in assessing environmental and financial impacts, it is essential to employ contemporary methodologies that enable the precise quantification of these parameters, all while considering technical factors such as obsolescence.

2.4.5.2 Economic- Technical- Environmental- Legal (Econ- Techn- Envir- Legal) aspects

Prior research has predominantly focused on the economic, technological, and environmental aspects of EoL decision-making, with some studies incorporating legal considerations. For instance, Ghazalli and Murata (2011) conducted a survey to identify the decision factors or attributes that influence the EoL pathways, where legal factors emerged as prominent among the survey participants. Consequently, these legal factors were integrated into the decision-making process. To assess the significance of these decision factors, the study employed a combination of AHP, CBR, and the NN algorithm. However, the study exhibited limitations stemming from the reliance on a survey methodology, as the limited participant pool may not have provided a comprehensive perspective. Additionally, environmental impact assessment relied on secondary data and assumptions from prior studies (Ghazalli & Murata, 2011), potentially undermining the validity of the environmental analysis, a limitation previously noted by various researchers (Kwak & Kim, 2016; S. G. Lee et al., 2001). Furthermore, at the product design level, the study did not evaluate the remanufacturability of the design, thus lacking a direct correlation between product design and its suitability for remanufacturing.

Kwak (2015) addressed the legislative-driven remanufacturing planning using a bi-objective MILP, considering technical, environmental, financial, and legislative aspects. In this context, the legal aspect primarily served as a constraint, driven by set recovery target rates for returned products, akin to the Extended Producer Responsibility (EPR) approach (Johnson & McCarthy, 2014). An intriguing outcome of this approach was its applicability beyond EoL considerations, potentially aiding the DfR principles for the specific product. This convergence of decision-making tools for sustainability requirements at the product's conceptual stage and EoL decision-making underscores their interchangeability (Chunhua et al., 2020).

Moreover, as the method targeted a product family, it offered the capacity to estimate the remanufacturability of the entire product family, thereby supporting remanufacturing portfolio planning. These observations underscore the critical role of assessing product remanufacturability in EoL decision-making, an imperative reiterated in the literature through the development of *remanufacturing evaluation* methods, as discussed in the subsequent section.

Similarly, other researchers have employed group decision approaches to address the EoL decision-making for electric vehicles (Yang et al., 2019). Their approach is product-specific, while it does not provide the decision maker with any intermediate steps before presenting the final solution to the MCDM problem. They consider the evaluation of the EoL alternatives a multicriteria decision-making problem that is directly analysed under four key dimensions: economic, technical, environmental and social, while indirectly, legal aspects are captured through the environmental regulations (Yang et al., 2019). Despite employing 19 criteria within these dimensions, the study predetermined the weight for each criterion through industry experts rather than allowing each method's applicant to determine the weights individually. Notably, the proposed method does not offer visualization of the decision-making process or the impact of each decision criterion.

2.4.6 Remanufacturing evaluation

As identified in previous chapters, assessing the feasibility of each step of the resource-intensive remanufacturing process is crucial before committing to it (Goodall et al., 2014). This feasibility assessment is often referred to as remanufacturing evaluation or remanufacturability. According to Fang et al. (2015), remanufacturing evaluation is a 'comprehensive analysis and assessment of products from technical performance, economic benefits, environmental impact and other factors to determine whether they have remanufacturing values'.

Other studies claimed that remanufacturing evaluation or remanufacturability is the response to one of the key challenges in remanufacturing, the high variability of EoL products (Liu et al., 2016). Goodall et al. (2014) consider remanufacturability as a product characteristic, while other scholars highlight that effective support can be provided to the product designer through it for improving the design of a new similar product (Omwando et al., 2018b). Ke et al. (2016) link remanufacturability to the usage characteristics of the EoL product, thus adding another dimension to the term.

Remanufacturability is key in EoL decision-making since one of the most paramount aspects of remanufacturing is the answer to the question of whether a product is worth being remanufactured or not, thus assessing its suitability for supporting decision-making in the field (Gu et al., 2015; Z. Liu, Jiang, et al., 2016). To explore the literature on the subject, scholars have adopted the economic, environmental, and technical aspects of sustainability and emphasised the importance of remanufacturing evaluation by allocating previous work among those pillars (Zhang et al., 2021). Among the 51 journal articles that were analysed by Zhang (Zhang et al., 2021) in their systematic literature review, 9.8% addressed remanufacturability evaluation from solely a technical perspective, 27.5% from an environmental, 19.6% from a financial and the rest of 43.1% from a comprehensive perspective that included all those lenses. Based on the authors, even though the higher number of the proposed evaluation methods does consider the three key aspects of sustainability, many of the analysed methods cannot be fully integrated into production decision-making models, making them inapplicable to reality and providing headroom for improvement due to their complexity (Zhang et al., 2021).

Although the backbone of remanufacturing evaluation has been defined, there is a lack of practical decision-making tools to assist designers or decision-makers in making well-informed decisions while considering the remanufacturability of a product (Zhang et al., 2021). The need for practical and empirical case studies from the industry is also emphasised as a much-needed source for improvement of the versatility and practicality of the developed methods (Zhang et al., 2021).

2.5 Key findings and research gaps

A recurring theme in the literature under consideration is the imperative for more informed decision-making regarding EoL processes. This necessity spans from overarching decisions concerning adopting CEBMs within companies (Bocken et al., 2016) to granular operational choices regarding the weighting of various factors influencing the remanufacturing of returned products.

Despite numerous publications focusing on remanufacturing, there remains a conspicuous absence of a comprehensive decision-making framework. Such a framework would serve as a valuable tool for firms, particularly SMEs, in determining their involvement in remanufacturing endeavours and optimizing the efficacy of these activities (Bagalagel & ElMaraghy, 2021; W. L. Ijomah et al., 2005). Assessment of the benefits of implementing each available EoL pathway will support the practitioner in high-level EoL decision-making and provide them with quantifiable data to de-risk any decision and help them make an informed decision.

Among the various EoL pathways, remanufacturing emerges as the most intricate product recovery strategy. This complexity arises from the requirement that remanufactured products must attain, from the customer's perspective, Original Equipment Manufacturer (OEM) performance specifications while simultaneously providing warranties equivalent to those of new products (Paterson et al., 2017). The tasks involved in the remanufacturing process encompass activities such as quality testing of returned cores, evaluating remanufacturability, and considering a range of decision factors. A significant research gap is a need for a method that holistically addresses the decisions of multiple activities that compose the remanufacturing function (Sitcharangsie et al., 2019).

Similarly, current EoL decision-making approaches primarily focus on economic and technical factors (David Stewart & Ijomah, 2011). The review presented here highlighted the need for a holistic approach that uses an inclusive methodology to assess and evaluate EoL pathways recovery strategies from an integrated point of view by considering technical, economic, environmental, legal, and social aspects simultaneously since such methods are lacking in the literature.

The need for a systematic evaluation of remanufacturability is a recurring theme underscored by the synthesis of the extant literature. Remanufacturability represents essential information concerning the viability of remanufacturing a particular product, furnishing decision-makers with critical insights. Moreover, it provides a valuable avenue for enhancing product design in accordance with Df'X' principles, where 'X' encompasses remanufacturing, sustainability, circular economy, repair, and related considerations. Approaches aimed at incorporating remanufacturing into product development processes should encompass an evaluation of the product's suitability for remanufacturing, alongside projections of its financial and environmental implications, and establish a clear linkage between this assessment and the product design phase.

Even in cases where a more holistic approach that considers multiple aspects has been adopted, scholars have underscored the importance of incorporating solution constraints pertaining to EoL pathways (Meng et al., 2016). A comprehensive examination of the existing literature and its synthesis has illuminated prior efforts in this domain (Sitcharangsie et al., 2019). Nevertheless, it has been observed that these previous methods lack the requisite flexibility and direct applicability to accommodate the preferences and input of practitioners on a case-by-case basis, should such adaptability be desired. These findings underscore the necessity for an EoL decision support method that integrates solution constraints and can adjust to the specific product and the practitioner's preferences.

Another discussed area of interest is the visualisation of the EoL decision process, which aids in supporting the practitioner in acknowledging the factors of influence. Tools such as LCA have been used to capture the environmental impact of remanufactured products or processes. Integration of such tools with visually-aided decision-making tools is challenging, and limited work has been done in this direction. Therefore, an ideal proposed method should incorporate visualization tools that facilitate a deeper understanding for practitioners regarding the product's structure, decision parameters, and the outcomes associated with the recommended EoL pathway.

The literature indicated that a weighted decision factors approach is needed for tailoring the multiple and EoL decision parameters to the practitioner's preferences. This finding denotes that an ideal proposed decision support method should require weight allocation to each decision factor or group of decision factors.

Drawing upon the identified key findings and research gaps in the existing literature, the primary objective of this research is to rectify the following deficiencies in the domain of scientific knowledge:

Providing a holistic approach to EoL decision-making requires simultaneous consideration of economic, technical, environmental, social, and legal aspects. Previously published work addresses some of those aspects, but as proven, limited work has been published addressing all the aspects simultaneously.

Gap 1: *Therefore, there is a need for a holistic approach that simultaneously addresses the economic, environmental, technical and social aspects of EoL decision-making.*

The process of EoL decision-making necessitates the inclusion of weighted decision factors, which can be subject to variation based on practitioner preferences and the availability of EoL pathways or technical solutions. These factors may also act as constraints when their fulfilment proves challenging.

Gap 2: *Hence, there is a need for an enhanced end-of-life (EoL) decision-making approach that specifically addresses the key gap of incorporating practitioners' preferences, an aspect often neglected, especially when navigating solution constraints.*

In cases where remanufacturing stands as one of the viable EoL pathways in core disposition problems, its evaluation becomes pivotal due to the extensive resource requirements and inherent uncertainty. An effective EoL decision-making process necessitates the visualization of a product's remanufacturability, integrating economic and environmental aspects. Although environmental impact assessment methods like LCA are commonly employed for estimating the carbon footprint of EoL products, there is a noticeable absence of research endeavours that incorporate these methods into remanufacturing assessments, thereby aiding decision-makers in comprehending a product's remanufacturability and utilizing this information to bolster EoL decision-making.

Gap 3: *Thus, there is a need for a method that assesses the remanufacturability of a product's design from an environmental and economic point of view and visualises the results to support informative EoL decision-making.*

These three research gaps will be addressed through the proposed work that will be presented in the following chapters, with the final method contributing to the body of knowledge in the area of EoL decision-making.

2.6 Chapter Summary

This chapter presented an extensive review of the existing literature on the thematic areas relevant to the scope of this study. Initially, an introduction to the themes of sustainability, product life cycle and the circular economy was presented. Next, the EoL pathways were identified and discussed. The following stage was an in-depth analysis of the decision-making literature focused on the previously discussed EoL pathways that mainly concentrated on the application of sustainable and circular solutions. The literature review was synthesised to identify and discuss the key gaps in the existing literature. This discussion resulted in identifying the gaps the developed method will cover and how it will contribute to the knowledge in the related areas.

3 Method description

Chapter 2 provided an in-depth review of the existing literature about sustainability, circular economy and decision support. This review identified a gap in the lack of a method that supports decision-making in a product’s EoL stage since current methods consider financial factors, environmental and social impact, and technical aspects in isolation or in some combination but do not address them all simultaneously. Therefore, Chapter 3 introduces a novel method to provide decision support in the product’s EoL stage by ranking the available EoL pathways based on the decision-maker's inputs and preferences. The proposed method intends to promote circular economy application by deeply understanding each EoL pathway's impacts while addressing the solutions' financial, environmental, social, and technical aspects.

In Chapter 3.1, a high-level analysis and the introduction of the method are presented alongside the main tools selected or developed in this thesis. Then, each tool is discussed in detail in their allocated subchapters. Chapter 3.2 includes the structural analysis of the products and is followed by section 3.3, which introduces the ease of Disassembly index (eDiM). Chapter 3.4 describes the remanufacturing scenarios approach adopted by the proposed method, while chapter 3.5 presents the environmental analysis completed for this study. The financial model is presented in Chapter 3.6, and the developed Circular Economy Design Analysis (CEDA) tool is discussed in Chapter 3.7. The decision factors and the methodology that identified them are presented in chapters 3.8 and 3.9 and supported by chapter 3.10, which includes an analysis of the data collected from a questionnaire filled out by industry experts. Finally, the multicriteria decision-making method is discussed in chapter 3.11, and the chapter is summarised in section 3.12.

3.1 Introduction to the proposed method

The method proposed in this research addresses gaps identified in the existing literature and incorporates feedback from the industry through real-life case studies and discussions with experts. The goal is to bridge these gaps and integrate industry insights to assist decision-makers in determining the optimal EoL pathway for a batch of returned products after their EoU stage. The ranking of EoL pathways is guided by the weights assigned to decision factors and the constraints of the solutions, which are identified at various stages of the method's application.

The method operates differently depending on whether it is being applied for the first time or in subsequent instances. The differences arise from the need for initial calibration and the use of MCDM tools to ensure successful implementation in the first application. Due to its complexity, the initial application requires support from an expert to guide the practitioner through the method's steps.

For any subsequent application of the method on the same product, only step 0, the capture of core quality from step 3, and step 4 are necessary, as other inputs remain unchanged. This streamlined process allows for quick reapplication, enhancing the method's agility, ease of use, and speed—key attributes for industrial environments.

Furthermore, the initial application of the proposed method provides the practitioner with comprehensive decision support, covering aspects such as remanufacturability and other critical external parameters like solution constraints and decision factor weights.

When the method is reapplied, the focus shifts to selecting the best EoL pathway for a specific batch, given that product design information has already been analysed in a prior application.

The outputs generated by the method offer multiple information sources for the practitioner, as the method concurrently:

- Provides an in-depth structural analysis of the product using the HALG and evaluates the time required for disassembly and reassembly through the eDiM (step 1). This combination of tools represents a significant innovation of the proposed method, as it has not been previously utilised in the literature.
- Assesses the financial viability of implementing a circular solution during the product's EoL stage (step 2).
- Conducts a detailed environmental analysis of the product and available EoL pathways using LCA (step 2).

- Offers a comprehensive assessment of the product's design suitability for remanufacturing through the CEDA graph. This approach, which evaluates remanufacturability based on key remanufacturing scenarios, is a unique innovation of the proposed method and is discussed in more detail in Section 3.7 (step 2).
- Identifies the primary decision drivers for adopting a circular business model and their relevance to the decision-making process (step 3).

Finally, the method provides a ranking of available EoL solutions after the EoU stage of a product, considering multiple factors referred to as "solution constraints" (steps 3 and 4). This holistic approach to addressing EoL decision-making for returned batches of cores, along with the novel integration of existing tools to deliver decision support, constitutes the key innovation of the method. The novelty is also highlighted in **Error! Reference source not found.** with dotted rectangles that pinpoint the most novel aspects of the method.

3.1.1 Step by step implementation of the method

The proposed method is presented in a clear, step-by-step manner to ensure it is repeatable by others. Each technique used is justified on a high level and for a deeper justification on its selection the reader should refer to the relevant section in the chapter. The method's steps are illustrated in **Error! Reference source not found.**, where a step-by-step application of the proposed method is provided.

In greater detail and based on **Error! Reference source not found.**, the method's application begins in Step 0, with product selection for implementation. At this stage the practitioner is the person who will make the decision of which product will be analyses though the proposed method.

Step 1

If this is the first application of the method for a specific product, Step 1 (depicted in **Error! Reference source not found.**) involves the practitioner inputting data related to the product's structure, such as the BOM and details about the connectors, as discussed in the referenced section 3.2. The outcome of this step includes the creation of the HALG, which visualizes the connections between components and their hierarchical levels, and the eDiM, which estimates the time required for disassembly and reassembly of each component at every hierarchical level.

This stage demands substantial input from the practitioner to successfully develop the HALG for the selected product. Additionally, applying the eDiM methodology to the connections identified in the HALG will quantify the time needed for each disassembly and reassembly operation. Due to the complexity and importance of this step, expert support is recommended for the practitioner during the first application of the method to ensure accurate execution and minimize the risk of errors in the input data.

Moreover, the integration of HALG with eDiM represents a novel aspect of the proposed method, offering a unique approach to analysing product structure and assembly requirements.

Step 2

This step (depicted as step 2 in **Error! Reference source not found.**) involves conducting an environmental and economic assessment of the product. The input data for this step consists of details about the processes that will be applied during remanufacturing. This data is then used to develop detailed remanufacturing scenarios based on the product's key components need to be replaced. For each scenario, the cost and environmental impact are estimated using reasonable assumptions and refined cost modelling techniques.

Due to the complexity of this step, expert support is needed during its initial application. The practitioner's role will primarily involve accurately capturing the remanufacturing process and gathering the relevant data. The expert will then use this input to develop a simplified LCA to quantify the environmental impact and apply cost modelling techniques to estimate the costs associated with each remanufacturing scenario.

The cost and environmental impacts of each remanufacturing scenario are then visualized on the CEDA graph. This graph highlights the suitability of the product's design for implementing a circular business model focused on remanufacturing. A more detailed analysis of the CEDA graph, which is a significant novelty of the proposed method, can be found in Section 3.7.

Step 3

After the creation of the CEDA graph, the next step (depicted as Step 3 in **Error! Reference source not found.**) focuses on developing the decision-making model. In this step, the practitioner provides two key inputs: the decision factors and the quality of the returned batch.

The practitioner provides input to decision factors relevant for their EoL decision-making problem, which are captured through the method's predetermined factors. The practitioner must assign weights to these factors based on their preferences. Depending on the assigned weights, some factors may act as solution constraints. The decision factors are categorized into 'soft' and 'hard' approaches to achieve this differentiation.

In the 'soft' approach, a decision factor is included in the decision-making process by simply assigning a weight to it, reflecting the practitioner's input. In contrast, the 'hard' approach involves the practitioner's input serving as a solution constraint for one or more EoL pathways, thereby restricting the available options for the returned batch. For example, the environmental impact of an EoL pathway is considered a 'soft' decision factor, with a weight assigned to each pathway based on the practitioner's input. On the other hand, legislation represents a 'hard' decision factor since it can exclude certain options, such as disposal, from being viable EoL pathways if recycling is mandated by law, as illustrated in the case study in Chapter 5.

The other critical input from the practitioner is focused on the pre-screening process. This process, detailed in Section 3.11.1.2, is responsible for assessing the quality of a returned batch of cores. The main dimensions of quality considered are functionality and aesthetics. Based on the practitioner's input, the pre-screening model can be tailored to fit their specific EoL decision-making needs.

Expert support is necessary during this step to mitigate errors due to potential uncertainty in the practitioner's inputs. This support is required only during the initial application of the method, as the decision model, with its weighted factors, must be customized to align with the practitioner's preferences. After the first implementation, provided that the company's decision profile remains unchanged, the only action needed in this step would be to provide input to the pre-screening process regarding the quality condition of any subsequent batches in the future.

Based on the analysis of the cores' quality and the decision model established by the practitioner during the initial application, the method can be reapplied to produce the final results, as outlined in the subsequent and final step. For these reapplications of the proposed method, expert guidance or support is no longer necessary, and the practitioner can confidently apply the method independently.

Step 4

Finally, Step 4 (depicted in **Error! Reference source not found.**) involves applying the developed decision model. This step utilizes all the outputs from Step 3 as inputs and feeds them into the chosen MCDM method, the Promethee II full ranking method. The Promethee method has been selected over other methods due to its ease of use, its ability to be highly tailored to match the practitioner's preferences, and the availability of the Visual Promethee software, which further supports the visualization and interpretation of results for the practitioner. For a more in-depth analysis of why the Promethee method was chosen, refer to Section 3.11.4.3.

The Visual Promethee tool, used to develop and visualize the decision model, provides the final output of the proposed method, which is the ranking of the available EoL pathways. In addition to ranking the solutions, this method offers a comprehensive analysis of how each EoL pathway performs across the decision criteria clusters: technical, financial, environmental, and social.

Steps 3 and 4, which encompass the development and application of the proposed MCDM method, are the primary contribution of this research. The holistic approach adopted by the method, along with the integration of well-established tools such as the HALG and eDiM to create new tools like the CEDA graph, provides multidimensional decision support for EoL core disposition problems. This integration is where the novelty of this research lies.

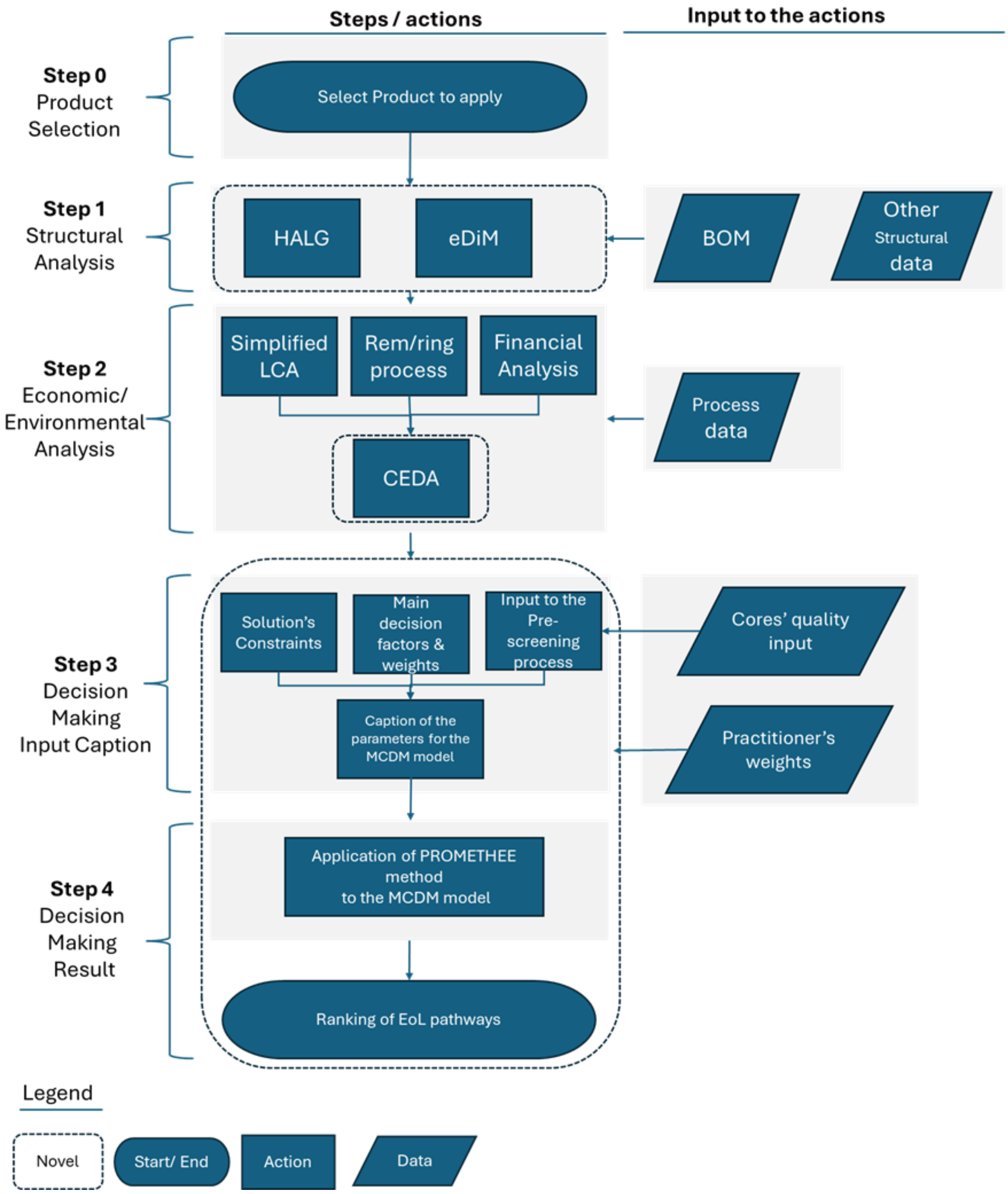


Figure 3.1: Step by step application flowchart for the proposed method

3.2 Structural analysis of the product

The proposed method aims to identify the best EoL pathway for a returned batch of similar products by considering the practitioner's decision factors and other inputs, such as the product's structure and condition. The value of the enclosed components and the efforts to obtain them are usually used to identify the level of disassembly of a product. More specifically, previous research identified that for deciding the level of disassembly for a product, there are three main factors: i) economic, ii) engineering, and iii) environmental (Sitcharangsie et al., 2019). The proposed method follows a hierarchical approach to the product's disassembly, capturing each of the factors mentioned above without answering the question of what the optimum level of disassembly is but rather the question of what the cost is to dis- and re-assembly a component of a specific level, financially and environmentally, and how the product's engineering reflects that.

As illustrated in Figure 3.2, this chapter describes the structural analysis performed on the product to identify the interconnectors and the hierarchical levels of the dis- and re-assembly process. The proposed method requires input on the materials, components, and their quantities through the BOM as well as information on the interconnections and their time for dis- and re-assembly through eDiM (Vanegas et al., 2018). The BOM and the interconnections information are used for the creation of the HALG (Dong et al., 2006), which, in addition to the eDiM, provides the components replacement scenarios. Later, on the method, remanufacturing scenarios are made based on the key components being replaced with identical or similar ones.

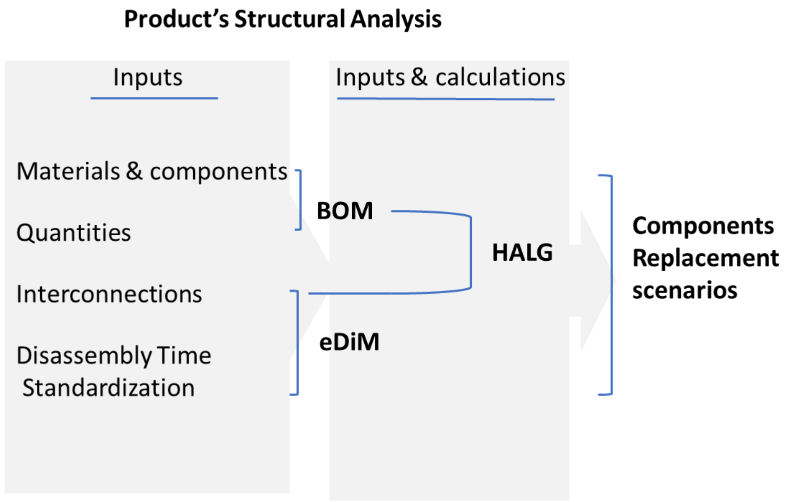


Figure 3.2: Adopted structural analysis in the method

The data emerging from the components replacement scenarios are utilised in pre-screening, which estimates a specific batch's remanufacturing cost and environmental impacts. Those data from the replacement scenarios are used in the MCDM Promethee II method and may also act as solution constraints, as presented in 3.11.2. The following chapters will present each of the aforementioned tools and methods in greater detail.

3.2.1 *Methods of product's structural depiction*

3.2.1.1 Bill of Materials (BOM)

The BOM lists the raw materials, components, assemblies, and quantities needed to manufacture a final product (M. Liu et al., 2014). It has a hierarchical format, with the end product positioned at the diagram's top. The BOM aims to achieve successful communication between the manufacturing partners and has been widely accepted by the industry and academia (Lambert & Gupta, 2002).

The main advantages of BOM are the wide acceptance of the industry, the ease of use, the effectiveness in structure representation, and the hierarchical approach to product composition. One of the main drawbacks of BOM is that it does not capture the interconnections between the components for each hierarchical level, limiting the amount of information for the disassembly process. This limitation of BOM can be overcome by using connection diagrams (Lee et al., 2010), which focus on the successful caption of the interconnection of the components. The proposed method uses BOM as an input to the HALG diagram, which is then used as input to multiple stages of the method.

3.2.1.2 Hierarchical Attributed Liaison Graph (HALG)

For identification of the hierarchical levels, the proposed method utilises the HALG (Dong et al., 2006), which can represent the structure of the product in levels and the interconnections between each component from the same level without the need for two different diagrams (Lee et al., 2010). Therefore, the HALG has a crucial advantage against more traditional methods of structural representation such as the BOM or the connection diagram since by capturing the interconnections between the components, a time of dis- and re-assembly can be allocated to that connection. That time is captured graphically, resulting in a more profound understanding of a product's dis- and re-assembly process and which components require the same amount of effort to reach. This advantage is critical for this study since the method utilises this connection caption to identify costs and time needed for each component replacement and uses this information for estimation of various variants further down the process, such as the environmental impact of the remanufacturing process. An example of how the methods were applied is presented in Figure 5.6, which presents the HALG of the first case study of the proposed method, an industrial-sized luminaire named ‘Strathclyde’. In Figure 5.6, the components are represented with a circle and the assemblies with a rectangle, while each line represents an interconnection between components or even assemblies and levels.

The conducted research developed a methodology demonstrating how a multilevel BOM aids in creating a HALG. The process begins with the BOM identifying all components of the product. The practitioner then uses the BOM's levels to establish the initial hierarchical levels of the HALG. Following this, the practitioner draws connections between the components, which helps verify that the correct levels have been established and the components are appropriately allocated. Finally, to validate that the final and accurate HALG is developed for the chosen product, the practitioner should refer to product drawings or rely on their experience.

Previous studies have used the HALG to identify the disassembly levels for end-of-life decision-making based on financial or environmental criteria or both (H. B. Lee et al., 2010). Those studies illustrated that the remanufacturing strategy could be modified by applying environmental criteria, such as environmental regulations. Additionally, they proved that a hierarchical approach to EoL decision-making is highly effective and that effective structural representation is key for identifying the value/ cost relation of the dis- and re-assembly process. Drawing upon the findings of previous studies, the proposed methodology combines HALG with the eDiM – a recognized measure to quantify the time required for both disassembly and reassembly of each interconnection. A detailed discussion of eDiM is presented in the subsequent section. The combination of the two tools is a novelty of the proposed method since there is no similar prior work in the literature, further enhancing the body of knowledge in the sector.

3.3 Ease of disassembly (eDiM)

The metrics designed to assess the effort required for disassembly and reassembly can be categorized into two primary groups: a) absolute metrics, encompassing parameters like time, and b) relative metrics, which include factors like effectiveness, as delineated in prior research (Afrinaldi et al., 2008).

This research uses eDiM to estimate the disassembly and reassembly time for each of the cores being processed. eDiM, an absolute metric since it expresses time, is based on the Maynard Operation Sequence Technique (MOST) (Zandin, 2002) and provides a clear and comparable index that describes the easiness of replacing a component in a returned core.

eDiM was developed by a European Commission fund and the Joint Research Centre (JRC) to create a standardised metric to capture the difficulty level of disassembly. This tool can be widely used across remanufacturers to estimate the time needed to replace each component. Thus, this method results in a confident estimation of the labour costs, often the primary cost source when reconditioning a core.

eDiM is based on a calculation sheet that includes the main actions when disassembling a component, their sequence, and additional information such as the tools used. The input data categories are covered in the following expressions found in the literature (Peeters et al., 2018; Vanegas et al., 2018).

Equation 1, Equation 2 and Equation 3 are used to capture the effort and time needed to replace a component, and the whole metric is counted in seconds (s). The equations and the total eDiM method have been validated through industrial case studies (Peeters et al., 2018) and publications (Vanegas et al., 2018).

Disassembly:

Equation 1: eDiMD

$$eDIMD = tool\,change + identification + manipulation + tool\,positioning + disconnection + removal;$$

Reassembly:

Equation 2: eDiMR

$$eDIMR = addition + tool\,change + identification + manipulation + tool\,positioning + fastening;$$

Total:

Equation 3: eDiM

$$eDIM = eDIMD + eDIMR$$

Equation 3 represents the total eDiM for replacing a component.

The eDiM's application for the proposed method is illustrated through the case studies found in chapters 5 and 6. In those, we use the product information and the data related to task completion as input data found in the MOST operation sequence technique, which is widely used in the industry for setting the standard time that a worker should complete a predefined task.

While eDiM is a notable methodology addressing ease of disassembly and reassembly in industry, it is not the sole method recognized by international standards. Vanegas et al. (2018) compared various disassembly time calculation methods. They highlighted the U-effort technique by Sodhi et al. (2004) and the approach by Desai and Mital (2003) particularly focused on supporting Design for Disassembly. Conversely, methods like the one by Philips (Boks et al., 1996a) prioritize the computation of End-of-Life (EoL) costs. Kroll's methodology (Boks et al., 1996b; Hanft & Kroll, 2012; Kroll et al., 1996) is grounded in MOST, aiming primarily to facilitate design for recycling. A comprehensive comparison of these disassembly methodologies, sourced from Vanegas et al. (2018), is provided in Table 3.1.

Table 3.1: Disassembly methods comparison adopted from (Vanegas et al., 2018)

METHOD	CALCULATION APPROACH	ADVANTAGE	LIMITATIONS
U-EFFORT	Based on properties of connectors	Objective: based on product properties	Only disconnection time accounted for
			High modelling effort for new connectors
DESAI & MITAL	Factors affecting disassembly are evaluated with MTM	Flexible: based on time and motion analysis	Preparatory tasks not included
			Based on MTM, which is seen as impractical
KROLL	Base time for fasteners and difficulty scores based on MOST	Flexible: based on time and motion analysis	Can lead to excessive detail
			Subjective difficulty rates
PHILIPS	Database with actual disassembly times	Straightforward: based on direct measurements	Limited insights for DfD
	Facilitates addition of disassembly tasks		Product-specific

One of the main benefits of using the eDiM is that its databases are widely accessible. Moreover, academia has verified eDiM, providing a robust solution for unambiguously estimating the effort and time for dis- and re-assembly. Additionally, case studies demonstrate the method's applicability to multiple industrial products and validate its reproducibility and repeatability. Finally, transparency and great easiness of use by the operators provide a fail-proof basic formula for manufacturers and surveillance by upper managers (Vanegas et al., 2018).

Another advantage of utilising this method is categorising the dis- and re-assembly tasks into six categories that provide additional analysis on the most resource-consuming tasks and the product design itself. The categories are presented in Table 3.2 and have been selected based on research from Vanegas (2018), where they identified, based on previous researchers, the main disassembly tasks and their research context.

Table 3.2: eDiM Disassembly task categories, adopted from Vanegas (2018)

Disassembly Task Categories	Description
Tool change	Picking up/ putting back a tool (including adaptation and preparation time)
Identify connectors	Identifying the location, type and kind of tool needed for that connector
Manipulation	Includes the time needed for manipulating the product to access or identify a connector for further actions
Positioning	The time needed for positioning the tool on the connector properly
Disconnection	The time needed for performing the task of disconnection of a connector
Removing	includes the time needed for removing the unfastened components and placing them in the trays/ bins

The disassembly categories that eDiM is composed of provide an excellent base for identifying the main ‘bottlenecks’ during the dis- and re-assembly process. This categorisation can further develop the remanufacturing process and its optimisation. Finally, the categorisation is also used to illustrate to the upper management the time spent by the operators in the dis- and re-assembly process, providing them with a deeper understating of where the time is spent and aiding them in identifying hidden costs of the process.

3.4 Components replacement scenarios

As illustrated in Figure 3.2, all the structural analysis steps result in component replacement scenarios. The product's structure has been studied at this final stage, and the time and cost for replacing each main component can be calculated.

One of the most crucial decisions in applying the proposed method is the selection of the ‘key’ components for the correct functionality of the product, as interpreted by the customer. For instance, a component with no vital role in the product's effectiveness, such as a component linked to its aesthetics, might be ‘key’ to the product’s functionality, according to the customer’s perspective. Thus, any such component is considered a ‘key component’, and only the replacement of those components is examined in the component’s replacement scenarios. The key components express exceptional value for the product and provide the foundations for all the analysis of the proposed method since, during the component replacement scenarios, only crucial components can be replaced while the rest remain in their position if feasible and will be directly reused.

For a key component, the status could be a ‘0’ or ‘1’, with ‘0’ translating to ‘no replacement needed’ and ‘1’ to ‘replacement needed’. Since each component can have only two possible statuses, the number of the total components’ replacement scenarios equals 2^n, where n is the number of the identified key components. For each of the 2^n scenarios, the proposed method calculates the environmental and financial costs and feeds those findings to the next steps of the proposed method, such as the pre-screening process and the MCDA method applied.

3.5 Environmental Assessment of the product

One of the essential drivers for this research is the application of more sustainable solutions, expressed through the implementation and promotion of circular economy business practices such as remanufacturing of used EoL products. This research addresses the prevailing challenge wherein numerous remanufactured products, at their end-of-life (EoL), are either discarded or recycled for raw materials, leading to a loss of their intrinsic value (Zhang et al., 2019). The study advocates for the remanufacturing or direct reuse of products, as these practices advance the principles of the circular economy (Zhang et al., 2020).

While the utilization of CE EoL pathways—such as direct reuse, remanufacturing, recycling, and upcycling—is frequently perceived as the most environmentally efficient EoL approach (Z. Ghazalli & Murata, 2011a; Zakri Ghazalli & Murata, 2011), the method introduced in this study calls this widespread belief into question. To achieve this, the proposed method conducts an exhaustive environmental assessment of the remanufactured products and incorporates various operational and technical elements, including obsolescence and the quality of the returned cores. Consequently, the method offers a detailed environmental impact assessment for each

EoL pathway, aiming to deter 'greenwashing' with definitive outcomes. Additionally, the proposed method to ensure utmost transparency in the environmental analysis adopts a carbon footprint measure for the product in focus, executing a Life Cycle Assessment (LCA) in compliance with the ISO 14040:2006 standards (Finkbeiner et al., 2006).

3.5.1 Life Cycle Assessment (LCA)

The LCA is a well-established methodology for capturing a product's environmental impact. Depending on its application, the LCA can also be built to focus solely on expressing the environmental impact through the carbon footprint. Existing research suggests that enterprises increasingly recognize the value of gauging their carbon footprint by measuring direct carbon emissions (scope 1) and at the product level. Such assessments serve as pivotal benchmarks, informing and shaping organizational environmental strategies (Brohé, 2017). LCA provides quantitative analysis, through a systematic approach, of the environmental impact of a product during its lifecycle as defined in ISO 14040. The emissions captured in an LCA could be focused on air, water, land, and resource consumptions, and their environmental impact is expressed through the adverse impacts on the areas of analysis, such as the ecosystem, natural resources and human health (Finkbeiner et al., 2006).

LCAs aim to create an inventory of direct and indirect environmental data that describe a process or a product and evaluate the flow of materials, resources and emissions and their impacts identified during the product's life cycle. In the 1970s, LCAs mainly focused on energy consumption and raw materials consumption, and their application lacked a common, comprehensive theoretical framework (Guinée et al., 2011). In the 1990s, LCAs were first used for marketing and communication (Brohé, 2017). Following their wide application across multiple industries, the issue of data transparency and reproducibility of results occurred. This issue was tackled through ISO 14040, which aimed to limit any risks regarding bad practice or manipulation of information, provide transparency to the LCAs and the data used, and demonstrate the LCA results in a structured and verifiable way.

This study follows the best practices of the ISO 14040 series for conducting an LCA, as illustrated by the case studies in Chapters 5 and 6. Additionally, in an effort to limit the cost, time and access to secondary data from the product's supply chain, the 'simplified approach' of an LCA is applied. This approach is based on the same extensive assessment of the environmental impact of a product through its life cycle with accuracy and aims to minimise the resources used in the LCA, such as cost and time (Christiansen et al., 1997). As identified, the key success of the simplified LCA lies in the correct goal and scope definition phase, where the system's boundaries can be selected in a matter that is relevant to the goal of the LCA study (Kun-Mo Lee & Inaba, 2004). The simplification of the LCA stems from the fact that data collection from 2nd tier suppliers was not possible in any of the case studies and that the main focus of the environmental impacts is the carbon emissions equivalent as the main expression in the CEDA analysis and the decision-making model. Additionally, the speed and agility of a simplified LCA align perfectly with the aim of the proposed method to be implemented in the industry for quick and reliable decision-making support in a fast-paced environment.

Four phases constitute the simplified LCAs provided herein: a) Goal and Scope definition, b) Life Cycle Inventory Analysis (LCI), c) Life cycle impact assessment (LCIA) and d) life cycle interpretation. These phases are illustrated in Figure 3.3, and each will be described in greater detail in the following paragraphs.

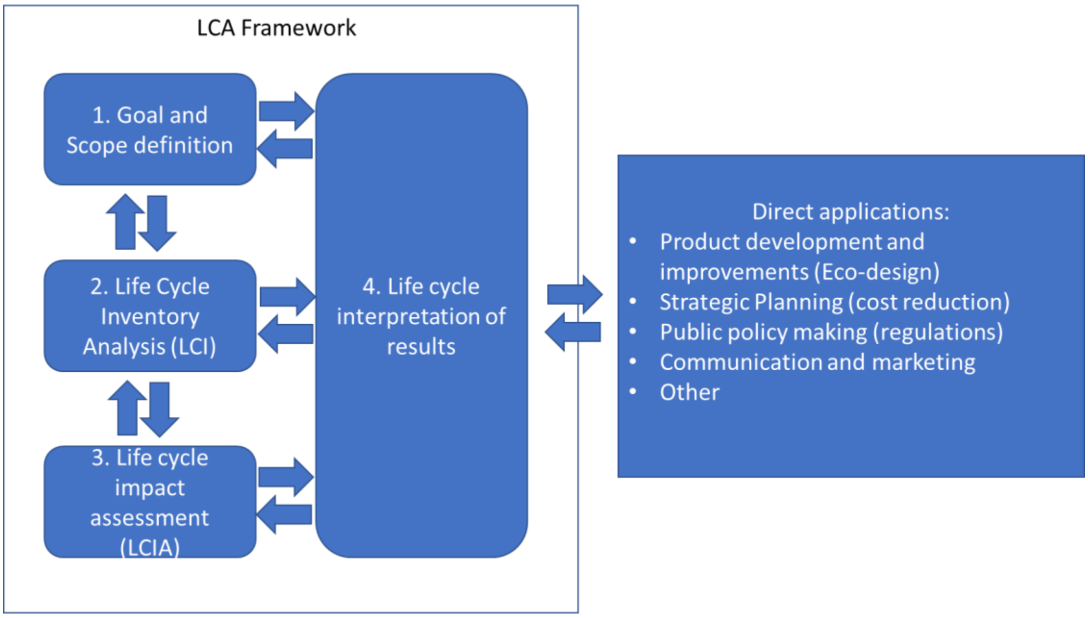


Figure 3.3: Phases of an LCA adopted from ISO 14040: 2006

3.5.1.1 Goal and Scope

In any LCA, the foundational step entails defining its objective and scope. This step seeks to discern the assessment's rationale and intended audience. Within the framework of the method presented, the stimulus for performing an LCA on a given product is to ascertain its environmental impact at a component level. Subsequently, the gathered environmental data from the remanufacturing process is harnessed to compute the environmental repercussions of various remanufacturing scenarios, each contingent on component replacements. This LCA study has practitioners as a target audience implementing the proposed method within an industrial context. The overarching objective is to give these practitioners critical insights into the environmental impacts of the remanufacturing process, the product itself and its EoL pathways. This, in turn, aids the application of a decision-support mechanism that categorizes EoL strategies for a collection of products at their End of Usage (EoU) phase, predicated on many determinants.

3.5.1.2 Functional Unit

The functional unit in every LCA allows the quantification of the function defined during the scope of the LCA. It expresses the performance of the functional outputs and provides a reference between outputs and inputs. For instance, in a place trip, the function could be defined as 'transportation of 100 passengers'; thus, the functional unit would be the environmental impact per passenger since the scope clearly defines a connection between the mean of transportation and the number of passengers. Functional units provide a better understanding of the environmental impact of a product by allowing comparison between similarly defined functions, even if some parameters might be different, as long as the key parameters are the same. As described from the scope of this LCA, no comparative study between one or more similar products will take place. Thus, the functional unit for the LCA in the proposed method is one unit of the selected product. In the case study presented in Chapter 5, the selection unit is one *'Strathclyde'* luminaire, and in the case study of Chapter 6, an accumulator.

3.5.1.3 System boundaries

Another crucial stage for the LCA is the definition of the system boundaries, which includes a description of the upstream and downstream processes within the study's scope. In our approach, the boundaries of this simplified LCA are dictated from the 'cradle to grave' approach, as depicted in Figure 3.4.

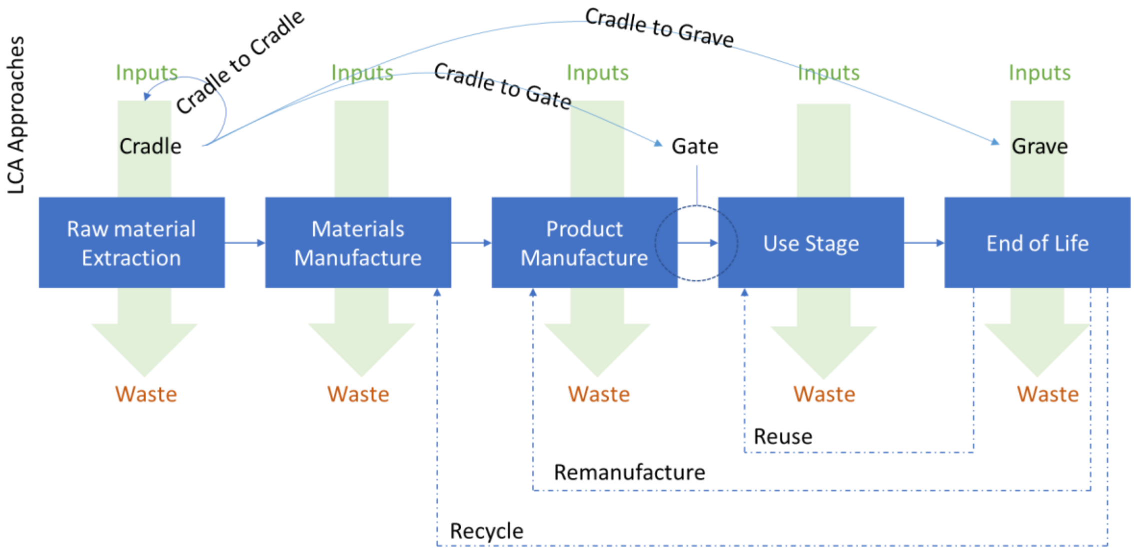


Figure 3.4: LCA Approaches

Through a 'cradle to grave' LCA approach, the study considers the stages of raw material extraction, production of basic materials and components, transportation, usage, and EoL stages of the product. This approach was followed due to the inclusion of the EoL pathway, which is a vital part of the study since it provides a quantitative analysis of the actual environmental impact of each available EoL pathway.

According to Figure 3.4, another LCA approach is the 'cradle to gate', which does not consider the Usage or EoL stages. The usage stage is important to this study due to the potential obsolescence of the product. However, its environmental impact is not extensively analysed since this research does not aim to study the product's design and efficiency but runs a remanufacturing feasibility analysis and EoL decision support for the best EoL pathway. Another reason for this decision is that this is precisely the same, irrespective of the EoL scenario selected. In greater detail, the proposed method considers that the customer, during the usage stage, will need the same amount and type of products, regardless of whether those are new or remanufactured. Thus, the final products being assessed through the proposed method must satisfy the same customer needs in quality and quantity.

Finally, another LCA approach is the 'cradle to cradle', where a full ecological loop has been completed. Such an approach is not in the scope of this study since the products of this study will be placed back into the usage stage or be recycled/ disposed, and their suitability for becoming raw materials for other products is not assessed.

3.5.1.4 Data category

The data used to conduct an LCA can be direct, based on measurements from the process directly, or indirect, based on existing life cycle inventory (LCI) data. The proposed method used data from well-known databases such as Ecoinvent 3.6. The use of widely accepted datasets provided the analysis with all the information needed to construct the LCAs and calculate the remanufacturing processes' environmental impact. Moreover, these datasets allow the assessments to be transparent and reproducible. The databases are crucial for the validation of the study's environmental claims. A key reason for this is the development of the Circular Economy Design Analysis (CEDA) graph, which links the environmental impact to the cost of a remanufacturing scenario. Then, it allocates each remanufacturing scenario to four zones based on the threshold values created through a new identical product. Finally, since the approach was a 'simplified LCA', some realistic assumptions have been made regarding the manufacturing processes and the materials where no data were available based on feedback from the case studies collaborators. The assumptions are discussed in the relevant chapter for each case study. Finally, the simplified LCA is expressed regarding carbon footprint, reflecting the Climate Change impact category.

3.5.1.5 LCIA method of choice

The LCIA method of choice was the ReCiPe Midpoint 2016 V1.04 / World (2010) because it provides 18 midpoint impact categories, with Climate Change to be the one in focus. Climate change is expressed in kilograms of Carbon emissions equivalent ($kgCO_2$ eq). The other 17 categories of environmental impact are stratospheric ozone depletion, ionising radiation, ozone formation & human health, fine particulate matter formation, ozone formation & terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resources scarcity, and water consumption.

3.5.1.6 Results Analysis

To deliver the results for each LCA, the backbone of the study was creating a detailed process tree that captured all the inputs and outputs per process for each component of the assemblies. The process tree is a crucial step of each LCA, as stated in the ISO 14040: 2006, and before proceeding to the LCA, data related to the process tree were verified by the collaborating industrial partners. The results were expressed through the climate warming environmental impacts, quantified in kilograms of Carbon emissions equivalent ($kgCO_2$ eq) for more straightforward quantification. Nevertheless, the use of midpoint methods provides the industrial partners with some insights into their products for other environmental impact categories, such as Marine ecotoxicity and, more importantly, a clear depiction of the distribution of the environmental impact to the components of their assemblies.

For an overview of the LCA result in this study, we utilise the tool provided by SimaPro that illustrates the product's network. The network demonstrates all the essential processes and uses a cut-off value, which the user can alternate. The thickness of the lines in the network diagrams represents the environmental load of the selected flow according to the chosen method of analysis, as depicted in Figure 5.12 and Figure 6.7 from the case studies. This tool provides an excellent overview of the distribution of the environmental impact per component and process to the practitioner and supports their knowledge of the impact of the product under investigation.

The next tool utilised by SimaPro software is the selected product's impact assessment (LCIA). When used under the ReCiPe 2016 Midpoint (E) V1.04 / World (2010) E / Characterisation method, the impact assessment tool provides a range of 18 different environmental impact categories that provide an overview for each component of each of those categories. Thus, the real impact of each component can be identified, and potentially valuable information can be drawn for developing more sustainable design solutions for new similar products or updating the design of an existing product by using another type of component. This illustration tool provides the practitioner with more information on the actual environmental impact of the products and builds more confidence in their knowledge, which can support any design decision in the future.

Another tool used is the process impact graph, which allocates the environmental impact caused by manufacturing the product to each of the processes applied to reach the end product. Similarly, with the impact assessment of the components, the method used is the ReCiPe 2016 Midpoint (E) V1.04 / World (2010) E / Characterisation method, and the aim is to provide the practitioner with a clear view of the process applied to manufacture the product and what the main contributors are. When this benchmarking exercise is presented to the practitioner as a by-product of the proposed method, the greater knowledge of the manufacturing process can spark design decisions that aim to achieve a better environmental result, potentially making the product even more remanufacturable in the future.

Finally, the data acquired through the simplified LCA study are used in the CEDA graph, which is a vital part of the proposed method. The CEDA graph integrates the environmental impact of remanufacturing scenarios with their financial impact and provides an excellent illustration tool of the product's remanufacturability. The CEDA graphs for the case studies are in Chapters 5.5 and 6.5, respectively.

3.6 Economic Analysis of the EoL Pathways

This research provides decision support for promoting a circular economy by investigating the suitability of each EoL pathway through the environmental, economic, social and technical lens. The economic analysis provided in the study is based on input from the literature, previous similar works, and input from the industry through the development of case studies. For each EoL pathway, the cost functions have been defined based on their main cost-related tasks, and each of those will be presented in greater detail in the following paragraphs. Each of the following cost functions refers to variable costs since they are directly and proportionally affected by the batch volume.

3.6.1 Direct Reuse costs

The direct reuse costs are related to the product itself as a whole, and they do not include component-level costs since direct reuse does not include dis- and re-assembly tasks. Thus:

Equation 4: Direct reuse cost

$$Direct\ reuse\ cost = cleaning\ cost + inspection\ cost$$

3.6.2 Remanufacturing cost

The cost of remanufacturing as an EoL pathway is analysed at product and component levels. The remanufacturing cost at a component level is a detailed analysis of all the costs related to the replacement, dis- and re-assembly of the component to the product. On the other hand, the remanufacturing cost on a product level aims to provide the final cost of remanufacturing the product by summing the costs of remanufacturing each key component and adding the final inspection cost of the product. Equation 5 and Equation 6 express the described approach:

Equation 5: Remanufacturing cost at the components level

$$\begin{aligned} Reman.Cost\ [Component] &= Cleaning\ cost + Comp.replacem.Cost + Disassembly\ cost \\ &+ reassembly\ Cost + Comp.recycle\ cost \\ &+ Comp.Disposal\ cost \end{aligned}$$

Equation 6: Remanufacturing cost at the product level

$$Reman.Cost\ [product\ level] = inspection\ cost\ [product] + \sum_{i=1}^{N} Reman.Cost\ [Component_i]$$

3.6.3 Recycling cost

For this research, the cost of recycling as an EoL pathway follows the same approach as remanufacturing costs, differentiating the product level from the component level. The cost of recycling at a product level is equal to the sum of the cost of recycling for each component. Since not all key components might be recyclable, the cost of disposal is also a part of the cost function if that is applicable. The costs Equation 7 and Equation 8 are described below:

Equation 7: Recycle Cost at the component level

$$Recyc.\ Cost\ [Component] = (-component\ weight * material\ price\ for\ recycling) + disposal\ cost\ of\ component$$

Equation 8: Recycle cost at the product level

$$Recyc.Cost\ [product] = \sum_{i=1}^{N} Recyc.Cost\ [Component_i]$$

The components' disposal cost is estimated based on the disposal rate for that material and the weight of the components as expressed below:

Equation 9: Disposal cost of component

$$disposal\ cost\ of\ component = component\ weight * disposal\ rate$$

This approach requires prior knowledge of which components are recyclable and which are not. When this information is obtained, the recycling cost per product is fixed, but the recycling cost for a batch is variable because it depends on the volume of the batch. Finally, the recycling cost is negative, thus is a revenue, since recycling rates are paid to the company from the recycling centres for the returned materials.

3.6.4 Disposal costs

Based on the previous paragraph, the disposal cost is the sum of the disposal of each component and is linked to the disposal rate for each material. Thus:

Equation 10: Disposal cost of product

$$disposal\ cost\ of\ product = \sum_{i=1}^{N} disposal\ cost\ of\ [Component_i]$$

The aforementioned cost functions expressed from Equation 4 to Equation 10 have been used to identify the cost related to each of the remanufacturing key component replacement scenarios, the CEDA graph, and the estimation of the average cost per product of the pre-screening process.

3.7 Circular Economy Design Analysis (CEDA)

One of this study's essential outcomes is the CEDA. Graphically, the CEDA is based on the economic and environmental analysis outcomes for each remanufacturing scenario. The CEDA graph illustrates a product's design suitability for remanufacturing, one of the key CEBMs.

The remanufacturing scenarios are based on identifying the product's key components, and each scenario is an alternative sequence of component replacement. A component has only two conditions, '*not to be replaced',* denoted by '0' and 'to be replaced', denoted by '1'. In this study, a component is replaced with an identical or similar component with the same cost, environmental, and technical characteristics. In a given product, let there be '*n*' key components. Each of these components can exist in one of two possible states, represented by the binary values '0' or '1'. The '0' state indicates that a component will not be replaced, while the '1' state signifies its replacement. Given this binary classification, the total number of possible combinations of component states is given by $N=2^n$. Thus, for any given n, the number of potential combinations or scenarios equates to *N*. For this function to be used as input to the rest of the tools used in this study, an Excel sheet was created with the limitation of a maximum of six key components in a product.

The calculation of the remanufacturing scenarios is crucial for developing the CEDA graph since each of those scenarios is a point on the graph expressed through Equation 11, where n_i represents the point of the remanufacturing i-scenario, x_i its cost and y_i its environmental impact.

Equation 11: Point in CEDA graph

$$n_i = (x_i, y_i)$$

The cost of the remanufacturing i-scenario is based on the economic model described in 3.6, and the environmental data (y_i) are sourced from the LCA described in 3.5.1. The goal of the in-depth environmental analysis of the product through the LCA is to get a detailed environmental impact estimation for each of the remanufactured scenarios. These estimations provide the practitioner data that aid them in understanding the true environmental impact of remanufacturing a product compared to buying a new identical one.

The points are plotted after estimating each remanufacturing scenario's environmental and cost impact. The LCA for the identified product provides the y_0, an estimation of the environmental impact of a new product expressed in kilos of carbon emissions equivalent ($kgCO^2$ eq). Then, its cost to the company, when new, provides the x_0 value. Thus, the set of comparison n_0 (x_0, y_0) has been defined. This set of values represents the boundaries for the four areas of analysis that will provide the practitioner with the visual aid for a better understanding of the product's suitability for remanufacturing.

Figure 3.5 includes a generic CEDA representation where the new product and its data are captured as n_0 (x_0, y_0). This set creates the borders for the four areas of interest: ' Sustainable area (win-win)', 'Unsustainable area (loss-loss)', 'Trade-off with economic preference' and '*Trade-off with environmental preference*'.

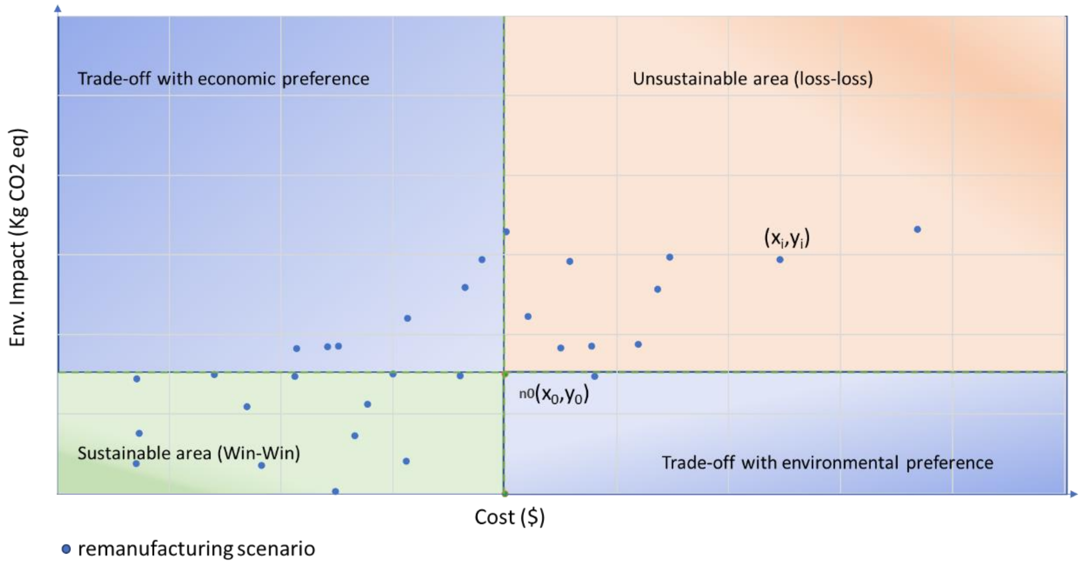


Figure 3.5: CEDA graph

In the sustainable area (win-win), remanufacturing scenarios are placed whose environmental and economic impact is less than the cost and impact of buying a new identical product (n_0). The greater the number of remanufacturing scenarios in that area, the more suitable the product's design is for remanufacturing. This is based on the fact that replacing its key components results in significant economic and environmental gains.

The unsustainable area (loss-loss) includes remanufacturing scenarios that are more expensive and environmentally impactful than buying a new identical product (n_0). When a product's CEDA is densely populated in this area, remanufacturing is unsustainable as an EoL pathway. Reasons for such a case could be the expensive replacement of components required, the intensive labour needed for dis- and re-assembling the product or fasteners that require cutting and welding for the key components to be accessed. A product with multiple scenarios in this area cannot sustain a CEBM since it doesn't provide the necessary value to be competitive against purchasing a new product.

The other two areas that constitute the CEDA graph are the trade-off areas. The first is the trade-off area with economic preference, where remanufacturing a product is profitable but environmentally more impactful than buying a new one. Such a scenario can occur when a key component dominates the product's total environmental impact. Replacing that component may result in a bigger environmental impact than buying a new one due to the remanufacturing process, transportation and auxiliary systems that may be used for adequately remanufacturing the product. On the contrary, a trade-off area with environmental preference refers to remanufacturing scenarios that will have a higher cost than buying a new product, but the impact will be less environmentally. Companies with strong environmental values and strict goals may still consider remanufacturing such products when the loss is not too significant to achieve their ecological goals, such as carbon neutrality or Net zero emissions.

The CEDA graph reveals a product’s suitability compactly for applying a remanufacturing EoL pathway that can be the base for a circular business model. It provides crucial information to the practitioner, both qualitatively and quantitatively. Qualitatively, the practitioner can identify in which area most of the remanufacturing scenarios belong, thus understanding the product’s design suitability for remanufacturing. Additionally, if they obtain CEDA graphs for other similar products, they can compare them to identify the best-suited product for applying a CEBM. The allocation of the remanufacturing scenarios across the four areas of interest provides the practitioner with a rough risk estimation of acquiring returned products with no data on their quality condition. The risks associated with core acquisitions can be mitigated through prior knowledge of the product’s design suitability for remanufacturing and a rough estimation of the key components that may need to be replaced.

Quantitatively, the CEDA graph can provide detailed cost and environmental impact for each remanufacturing scenario. A unique sequence of key component replacements defines these scenarios. When a scenario occurs, an estimation of the economic and environmental gains or losses can be used to plan maintenance strategies to limit those losses in the EoL stage of the products. Additionally, quantification of those dimensions gives the practitioner an idea of how remanufacturing is compared to buying a new product. Finally, the CEDA graph provides a prediction for remanufacturing scenarios with particular interest for future returned cores after their EoU stage. Replacement of one or more key components across the whole batch can be modelled both environmentally and economically; thus, decision-making is supported in a much more preliminary stage.

This in-depth knowledge of the product's design suitability for remanufacturing, one of the most common CEBMs, is a preliminary output of the proposed method before implementing the decision-making model that considers the additional social and technical decision pillars and the solutions' constraints.

3.8 Process of developing the proposed decision model

This section describes the methodological steps undertaken for developing the decision-making process of the proposed method, segregating the process into three distinct stages. Those are:

Stage 1: Identification of the Decision Model Elements

Purpose: The objective of this stage was to determine the variables that would constitute the decision-making model.

Methodology: As illustrated in Figure 3.6, the requisite data was amassed through a comprehensive literature review, supplemented by industry feedback acquired via questionnaires and interviews.

Stage 2: Organizing and Structuring of Decision Model Elements

Purpose: This phase aimed to delineate the interrelations between the decision model's elements and craft a systematic structure.

Methodology: A rigorous process was undertaken that included the creation of hierarchical relationships, the definition of interactions, the establishment of logical sequences, and the categorization of decision elements into discernible clusters. After analysing each decision factor and sub-factor identified in the first stage and considering the constraints associated with potential solutions, these elements were subsequently grouped into four decision clusters. The overarching objective was to devise a robust framework to seamlessly navigate the ensuing decision-making endeavours.

Stage 3: Application of the Structured Decision Model

Purpose: The previously structured decision model was put to practical use in this phase.

Methodology: The PROMETHEE II methodology was employed as a full-ranking decision method, and the Visual PROMETHEE software facilitated the visualization of the developed decision model.

For further details on the decision model, refer to 3.11. The developed model is highly adaptable to the practitioner's preferences. A concise overview of the entire decision model development can also be found in Figure 3.6.

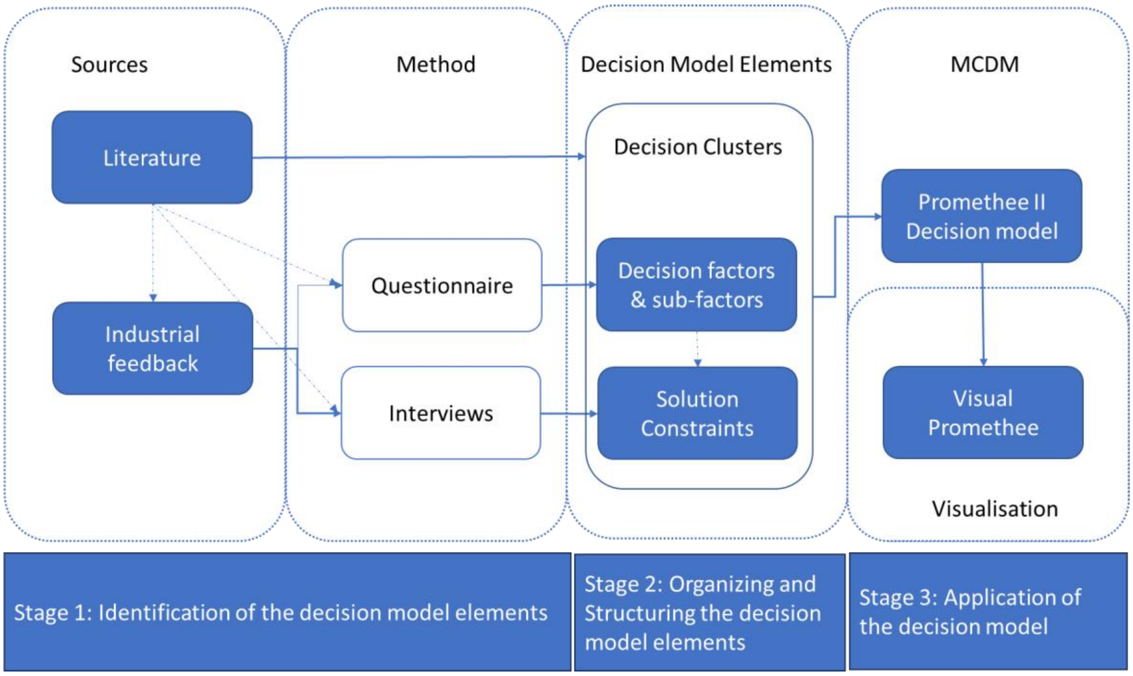


Figure 3.6: High-level depiction of the Decision Model development

One of the critical aspects of the proposed method is that it holistically studies the decision-making problem of the best available EoL pathway by considering the four main related decision pillars: environmental, economic, social, and technical feasibility criteria. Those pillars are the decision clusters that include multiple sub-factors which belong to this ‘umbrella’ term. The sub-factors are weighted based on the overall cluster’s weight, and each impacts the available EoL pathways differently. Additionally to the sub-factors, the proposed method includes the ‘solution constraints', which are decision factors that act as 'hard' and 'soft' solution constraints based on the practitioner's preferences.

Figure 3.6 shows that the four decision clusters have been identified mainly based on the literature. For the development and identification of the decision factors and sub-factors, additional industry input was captured through questionnaires that captured the initial findings from the literature and enriched them with industry input.

3.9 Decision clusters and factors

The main decision clusters that participate in the decision-making process in the EoL stage of products have been identified through literature. The gaps in integrating all four key decision clusters into one model that will support the selection of the best EoL pathway have been highlighted multiple times (Meng et al., 2016; Zhang et al., 2020). Each decision cluster will be analysed in greater detail in the following paragraphs.

One of the critical contributions of applying CE EoL solutions and remanufacturing is the strong social impact on the local communities. Remanufacturers provide economic and social stability in their local communities by directly creating jobs (Guldmann, 2016b; Sundin et al., 2016). Another social benefit of remanufacturing is the easier accessibility to high-end products due to reduced costs and prices. For example, electricity can be delivered to remote areas in Africa with a cost reduction of 30% by using remanufactured hybrid wind turbines and diesel systems (Sundin et al., 2016). This is an example of how applying CE solutions can generate a multidisciplinary positive impact. In this case, the remanufacturer creates jobs for the local community, provides an environmentally friendly EoL solution by extending the product's lifespan and minimising waste, provides easier access through the limitation of cost to a new customer and finally, harmonises the application of the selected EoL pathway with another community's needs by providing affordable electricity to remote areas of Africa. Thus, the social decision cluster has been created with the aim of capturing this aspect of EoL decision making.

The environmental decision cluster quantifies the equivalent carbon emissions by conducting an extensive LCA using the SimaPro 9.1 Software and the Ecoivent 3.6

database. This research utilises Midpoint indicators expressed in single environmental problems, such as climate change, which is the selected issue to express the environmental impact of an EoL pathway. Endpoint indicators also aggregate the results into three main categories: a) effect on human health, b) biodiversity, and c) resource scarcity. In this research, we chose to apply midpoint indicators instead of endpoint because we needed a single score method of environmental impact for the CEDA graph and the decision model, and due to the inherent uncertainty on the results when translating a midpoint method to endpoint (Tintelecan et al., 2020). The method of choice is the ReCiPe Midpoint 2016 V1.04 / World (2010), and the LCA results are expressed in average kilograms of carbon dioxide equivalent (kg CO_2 eq). The environmental impact quantification is based on the pre-screening process and the emissions estimation for each possible remanufacturing scenario.

Two key aspects of the economic decision factor are the total cost and the market demand for a specific product, as identified by discussions with industry experts. The total cost is a sum of multiple costs such as acquisition, logistics, reconditioning, and some non-variable costs added to the remanufacturing processes. The market demand is based on the predictions and estimations of the decision-maker, and its input is qualitative. The identification of the economic sub-factors was based on input from the literature (Sitcharangsie et al., 2017) and feedback from the industry while the method was developed.

The last decision cluster is the technical cluster, which is composed of many sub-factors that aim to identify the suitability of a specific product for each of the EoL pathways with a greater focus on remanufacturing. To identify the technical feasibility factors and sub-factors that play a role in the application of remanufacturing as a sustainable EoL pathway, the researcher created Table 3.3. Table 3.3 includes the groups of factors identified in the literature and the ones originating from the industry's feedback captured during the method's development phase. A questionnaire and discussions with industry experts captured the industry's feedback and later supported validating the findings. The questionnaire was created and distributed to four collaborating companies that perform remanufacturing activities at different levels. The questionnaire and its analysis are presented in greater detail 3.10.

Table 3.3: Decision factors identified

Source	Factors groups											
	Durability	Residual Value	Standardisation Of Components/ Interchangeable	Materials	Obsolescence	Market Demand	Disassembly Easiness	Testing Easiness	Cleaning	Legislation	Components Availability	Other
(Lund, 1984)	X	X	X	X	X	X						X
(Zhang et al., 2020)			X				X	X	X			X
(Omwando et al., 2018a)			X				X		X			X
(Chakraborty et al., 2017)							X					X
(Wu, 2012a)							X					
(Wu, 2012b)			X	X								X
Industrial feedback	*	*	*				*			*	*	

3.10 Questionnaire analysis for determining the decision factors

This section presents the results from the questionnaire distributed to the collaborating industries for feedback on the identified decision factors. Additionally, the final selection of decision factors is presented. As described before, the proposed method is fully customisable; thus, the decision factors (and sub-factors) here are the backbone of the method, while each practitioner can alter them based on their preferences and inputs. Each company had an introductory table with generic information, and then the participants were asked to answer the main questions.

The questionnaires were used as a research method to identify the main decision factors and to inform the decision model with key relevant factors from four decision clusters: environmental, technical, social, and financial. These factors are fully customizable to the practitioner's preferences. The questionnaire is not part of the repeatable process of the proposed method but was a research tool used to enhance the method's standards and to capture industrial feedback.The questionnaire format is based on a preselected list of decision factors per cluster. The questionee has to rate the prepopulated decision factors based on their importance and can also add new ones. If a prepopulated factor is not considered during the decision-making process, then the questionee can delete the factor from the list. The questionnaire can be found in Appendix A.

Finally, the questionee is also asked to classify the decision factors identified into the three main decision categories: operational (batch-focused), tactical (products design-focused) and Tactical/ Strategic (strategy-focused). This exercise aims to validate the developed method's decision area and classify its application to what type of decisions can be supported and at what level.

The selection of companies involved in this research was the result of an extensive outreach to the industry. Companies that expressed interest in the research and were familiar with remanufacturing practices were chosen to participate.

Company A refers to a company in the oil and gas sector, Company B refers to a company in the lighting sector, Company C belongs to the energy sector, and Company D is an Information Technology (IT) company. All companies have been anonymized. Companies A and B have additionally supported the development of the proposed method through feedback, case studies, validation, and technical support.

3.10.1 Questionee 1 - Company A

Table 3.4 Contains some general information about the company.

Table 3.4: Company A generic data

Company	**Company A**
Type of remanufacturer	OEM/ OER (Original Equipment Remanufacturer- OER)
Industry	Oil and Gas
Company Size (Annual turnover)	£19,000,000
Size of remanufacturing operations (Annual turnover)	£50,000

3.10.1.1 Environmental Factors

Table 3.5 contains the environmental factors that impact the decision-making for remanufacturing based on the practitioner's response.

The practitioner commented that:

"Customers are now asking us about CO_2 (very early stages). We have identified 2.1 as a 5 at the moment (2021). In 2020, this value would have probably been 2. In the future, maybe as a guess, we believe we may be asked to state CO_2 values for our products, and we may have to charge extra for our products to reduce the CO_2 costs from our supply sources."

Table 3.5: Environmental factors Company A

Environmental factor	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
2.1 Carbon Emissions					X				
2.2 Disposal of finished products* *'Example: We would sort components by waste stream'*							X		
2.3 Customer CO2 requirements*									X

**factors added by the practitioner*

Regarding the factor *2.1 Carbon Emissions*, it becomes evident that the company has just started to consider the environmental impact of its processes and products. Additionally, the added factor '*customer's carbon emissions requirements'* is the most significant decision factor from an environmental perspective. Thus, it becomes evident that focal Company A aims to deliver products with a quantified environmental impact to satisfy their customer's carbon emissions requirements. Those customer requirements could stem from regulations imposed on the customers, suppliers' green credentials or Net Zero goals set by those companies.

Based on factor *2.2 Disposal of finished products*, which is a factor that the practitioner has added, the focal company (Company A) is interested in having some input on how their customers dispose of their products and what their component's waste stream would be. Potentially, those data can be used to tackle any issues with future regulations.

3.10.1.2 Financial factors

Table 3.6 includes the financial factors identified by the company. The cost of remanufacturing and the residual value have an importance of 5/9, which defines them as essential but not critical. On the contrary, the profit and the market demand are rated 9/9. One of the conclusions that may be driven is that as long as there is profit and a market for the remanufactured products, the costs and the residual values of the products are of secondary significance.

Additionally, the company has identified an underlying opportunity in the remanufacturing sector from a financial perspective since Company A added Levys (comment: '*Levys for example government enforced')* and '*Grants and subsidies'* as financial factors with a 7/9 importance rate.

Table 3.6: Financial factors Company A

Financial factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
3.1 Cost of applicable solution					X				
3.2 Residual Value					X				
3.3 Profit									X
3.4 Market demand									X
3.5 Levies (for example government enforced)*							X		
3.6 Grants and subsidies*							X		

**factors added by the practitioner*

Considering that remanufacturing contributes to 0.263% of Company A's total turnover, and given that the predominant financial determinants have thus far been profits and market demand, followed by levies and potential subsidies or grants, it can be inferred that remanufacturing is currently in an exploratory phase for the company. Company A is evaluating its alignment with its existing business model and is ardently working towards establishing a robust foundation for the subsequent expansion of the remanufacturing process. A primary motivation behind this initiative is the company's endeavour to adapt its business operations in compliance with consumers' and governmental regulations' emerging environmental demands.

3.10.1.3 Technical factors

Regarding the technical factors (Table 3.7) that may play a role in the decision-making for remanufacturing a core, the main contributors were the batch quality, the remanufacturability of the core, and the components' availability, all rated at 9/9. The participant commented: "*Our product range would be classed as a mature product, and we have approximately 4500 individual designs, but mainly based on variations on a theme.*"

Such a variation in the products may cause some difficulties in the remanufacturing process from a technical perspective since not all the models will be equally suitable for remanufacturing. Further analysis of the most dominant models in the market, types of variations, value-adding, and main core characteristics may be needed to identify the most central cores for extended remanufacturing.

Table 3.7: Technical factors Company A

Technical factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
4.1 Batch Quality									X
4.2 Design Durability							X		
4.3 Ease of disassembly (eDiM)						X			
4.4 Market obsolescence						X	X		
4.5 Remanufacturing capability									X
4.6 Remanufacturability						X	X		
4.7 Component Upgradability (Technical obsolescence)					X				
4.8 Availability of components									X

**factors added by the practitioner*

From a technical perspective, the main questions that Company A has to answer are: '*What is the quality of the returned cores?*', '*do we have the capability to remanufacture that specific core?*' and '*Are there available components?*'. In combination with the mature product, these questions reveal that the main technical decision factors are related to the suitability of a core for remanufacturing and the level of confidence in the generic remanufacturing processes of the company.

3.10.1.4 Social factors

Table 3.8 includes the social factors *Job creation* and *Harmonisation with the local society needs* rated 2/8, thus not important for Company A and their remanufacturing decision drivers. On the contrary, customer accessibility to high-quality products is rated with 9/9, again revealing the company's customer focus.

Table 3.8: Social factors Company A

Social factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
5.1 Job Creation		X							
5.2 Harmonisation with the local society needs		X							
5.3 Customer accessibility to high-quality products									X

**factors added by the practitioner*

3.10.1.5 Questionnaire Conclusions

Based on the answers to the questionnaire from Company A, it is safe to conclude that:

Remanufacturing is only considered on a testing scale at this point, and there is no intention of changing their business model of linear manufacturing radically

- The main decision factors are financials (profit and market demand), followed by the environmental, but from a customer’s requirements perspective.
- The company tests the idea of remanufacturing in a broader attempt to forestall the imminent carbon regulations and satisfy their customer’s needs while gaining access to governmental funds.
- The company has not yet fully developed the technical aspect of remanufacturing.
- The social aspect of remanufacturing is not one of the main concerns of Company A.

3.10.2 Questionee 2 - Company B

COMPANY B is a lighting company based in Glasgow, UK. Some information follows in Table 3.9:

Table 3.9: Information of Company B

Company	COMPANY B
Type of remanufacturer	OER / Independent Remanufacturer (IR)
Industry	Commercial Lighting
Company Size (Annual turnover)	£1.2 million
Size of remanufacturing operations (Annual turnover)	Less than 5% of turnover

3.10.2.1 Environmental Factors

The main environmental factors are presented in Table 3.10. The practitioners added multiple environmental factors in their decision-making for remanufacturing. Most of them are factors that capture environmental impact, with the most significant being carbon emissions. The supply chain's traceability and environmental impact seem essential for this company since manufacturing is mostly performed in the suppliers' facilities.

Table 3.10: Environmental factors Company B

Environmental factor	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
2.1 Carbon Emissions								X	
2.2 Material Waste*									X
2.3 Water consumption*					X				
2.4 Supply chain traceability*						X			
2.5 Conflict Mineral*					X				
2.6 Hazardous or toxic materials*				X					
2.7 Controlled chemicals*				X					

**factors added by the practitioner*

3.10.2.2 Financial factors

The financial factors are captured in Table 3.11. The practitioner has rated the factors of cost of the applicable scenario and residual value of the product with a significance of 9/9. Profit and Market demand are rated with 8/9, which still classifies them as critical. Finally, the practitioner added the Capital investment required to establish the remanufacturing capability and Cost and time to train operative factors, rated 7/9.

Table 3.11: Financial factors Company B

Financial factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
3.1 Cost of applicable scenario									X
3.2 Residual Value									X
3.3 Profit								X	
3.4 Market demand								X	
3.5 Capital investment required to establish the remanufacturing capability*							X		
3.6 Cost and time to train operative*							X		

**factors added by the practitioner*

Analysis of the factors reveals that the main financial decision factors are initially the costs and profits, but also the added factors by the practitioner confirm the intention of establishing remanufacturing in their business model.

3.10.2.3 Technical Factors

The technical factors are detailed in Table 3.12. Drawing from practitioner insights, the technical decision factors predominantly fall within the important to critical rating spectrum. Consequently, the success of remanufacturing is heavily reliant on the product's design and its appropriateness for remanufacturing rather than the quality of the batch. The respondent exhibited uncertainty regarding one specific factor, namely *4.6 Remanufacturability*, which indicated two differing levels of importance. An average of the two values has been used in this case and any other similar case.

Table 3.12: Technical factors Company B

Technical factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

4.1 Batch Quality					X				
4.2 Design Durability						X			
4.3 Ease of disassembly (eDiM)								X	
4.4 Market obsolescence						X			
4.5 Remanufacturing capability						X			
4.6 Remanufacturability						X	X		
4.7 Component Upgradability (Technical obsolescence)								X	
4.8 Availability of components									X

3.10.2.4 Social factors

Table 3.13 presents the social factors as assessed by the practitioner. While the company recognizes the significance of social considerations, including job creation and ensuring customer access to high-quality products, it does not regard "customer accessibility to high-quality products" as the paramount decision driver for remanufacturing.

Table 3.13: Social factors Company B

Social factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
5.1 Job creation						X			
5.2 Harmonisation with the local society needs					X				
5.3 Customer accessibility to high-quality products						X			

3.10.2.5 Questionnaire Conclusions

The conclusions of this analysis could be briefly described in the following points:

- Remanufacturing is perceived as a promising avenue for future expansion, with Company B actively integrating it into its core business strategy.
- Currently, remanufacturing operations are conducted on a modest scale; hence, strategies for transitioning to an industrial magnitude are under exploration.

- The company is committed to adeptly assimilating remanufacturing into its prevailing business strategy, steering towards a more circular business approach.
- While social factors are indeed factored into decision-making, they do not serve as the primary reason for the adoption of remanufacturing.
- The company's primary objective is to discern and institutionalize efficient remanufacturing processes tailored for products that are most conducive to remanufacturing.

3.10.3 Questionee 3 -Company C

Company C is based in Glasgow, UK, and belongs to the energy sector. Their main products are Company C parts of wind turbines, and some information can be seen in Table 3.14:

Table 3.14: Information Company C

Company	**Company C**
Type of remanufacturer	Independent Remanufacturer (IR)
Industry	Energy sector
Company Size (Annual turnover)	SME (Circa £6M)
Size of remanufacturing operations (Annual turnover)	Circa £1M

3.10.3.1 Environmental Factors

Table 3.15 includes the company's environmental factors. During the discussion, the participant commented, "*We calculate carbon emissions based on the CO_2 equivalent of manufacturing new parts rather than buying refurbished and therefore recirculating used parts.”*

Table 3.15: Environmental factors Company C

Environmental factor	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
2.1 Carbon Emissions									X
2.2 Landfill/scrap avoidance for customers*							X		

*factors added by the practitioner

According to the practitioner, one of the main environmental factors for this company is the carbon emissions that are saved from their customers by supplying them with refurbished parts for their wind turbines.

3.10.3.2 Financial factors

Table 3.16 illustrates the company's financial factors. According to the practitioner, the financial business model of Company C is based on interchangeable parts for wind turbines and a fast supply to the customer. In more detail, the customer provides Company C with their products that need refurbishing. Company C uses its refurbished product inventory to supply the customer's needs quickly. Thus, the customer sells his old equipment to Company C and is supplied with a refurbished one. The delivered equipment is then refurbished and used in the same circular way with another or the same customer in future transactions. Since Company C always buys the returned equipment, its residual value is not critical for them, but they primarily focus on the cost of remanufacturing.

Table 3.16: Financial factors Company C

Financial factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
3.1 Cost of applicable scenario							X		
3.2 Residual Value			X						
3.3 Profit						X			
3.4 Market demand						X			

3.10.3.3 Technical Factors

For this company, the technical decision factors (Table 3.17) of how suitable a product's design is for remanufacturing are more critical than the batch quality. Additionally, the practitioner commented that IP infringement is of concern in their remanufacturing processes and could potentially be a barrier to development for the sector. IP infringement could be a solution constraint regarding the available EoL pathways.

Practitioner’s comment: *“IP infringement is of concern in reverse engineering and is reviewed for the protection of the business. Potentially a significant barrier to development.”*

Table 3.17: Technical factors Company C

Technical factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
4.1 Batch Quality						X			
4.2 Design Durability							X		
4.3 Ease of disassembly (eDiM)							X		
4.4 Market obsolescence							X		
4.5 Remanufacturing capability							X		
4.6 Remanufacturability								X	
4.7 Component Upgradability (Technical obsolescence)							X		
4.8 Availability of components						X			

3.10.3.4 Social factors

Based on the practitioner’s answers, the social factors of remanufacturing and implementing a circular business model have an essential role in the company's decision-making and the answers are included in Table 3.18:

Table 3.18: Social factors Company C

Social factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
5.1 Jobs Creation								X	
5.2 Harmonisation with the local society needs						X			
5.3 Customer accessibility to high-quality products						X			

3.10.3.5 Questionnaire Conclusions

The conclusions of this analysis could be briefly described in the following bullet points:

- Remanufacturing is integrated into the company's business strategy and has been considerably developed.
- In their decision-making process, the primary emphasis is on the design's appropriateness for remanufacturing rather than its direct profitability, underscoring the objective of establishing a consistent supply and demand for remanufactured cores.
- Social factors hold significant importance in shaping the company's business approach.

3.10.4 Questionee 4 - Company D

Company D is an IT company that claims to be "the world's first remanufactured carbon-neutral laptops". Their business model is based on remanufacturing laptops primarily for businesses across the globe. Some information follows in Table 3.19:

Table 3.19: Information on Company D

Company	**Company D**
Type of remanufacturer	Independent Remanufacturer (IR)
Industry	Information Technology
Company Size (Annual turnover)	£50 million
Size of remanufacturing operations (Annual turnover)	100%

3.10.4.1 Environmental Factors

Company D considers carbon emissions to be of critical importance in their remanufacturing decisions. This perfectly aligns with their strategic decision to be the world's first carbon-neutral laptop remanufacturer. The environmental factors are captured in Table 3.20:

Table 3.20: Environmental factors Company D

Environmental factor	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
2.1 Carbon Emissions									◊

3.10.4.2 Financial factors

According to the participant, the financial business model of Company D is based on bulk orders from businesses and a buy-back deal of their older IT items. Financial viability is the most important decision factor for remanufacturing, and every aspect is considered critical. The financial factors are captured in Table 3.21:

Table 3.21: Financial factors Company D

Financial factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
3.1 Cost of applicable scenario									◊
3.2 Residual Value									◊
3.3 Profit									◊
3.4 Market demand									◊

3.10.4.3 Technical Factors

An exciting aspect of the adopted remanufacturing policy emerged when the participant was asked about the technical factors that weigh in the decision process for remanufacturing. Their answers to the questionnaire are captured in Table 3.22:

Table 3.22: Technical factors Company D

Technical factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
4.1 Batch Quality									◊
4.2 Design Durability									◊
4.3 Ease of disassembly (eDiM)									◊
4.4 Market obsolescence									◊

4.5 Remanufacturing capability		◊
4.6 Remanufacturability	◊	
4.7 Component Upgradability (Technical obsolescence)	◊	
4.8 Availability of components		◊

An explanation of those irregularities can be given through a deeper analysis of Company D's business model.

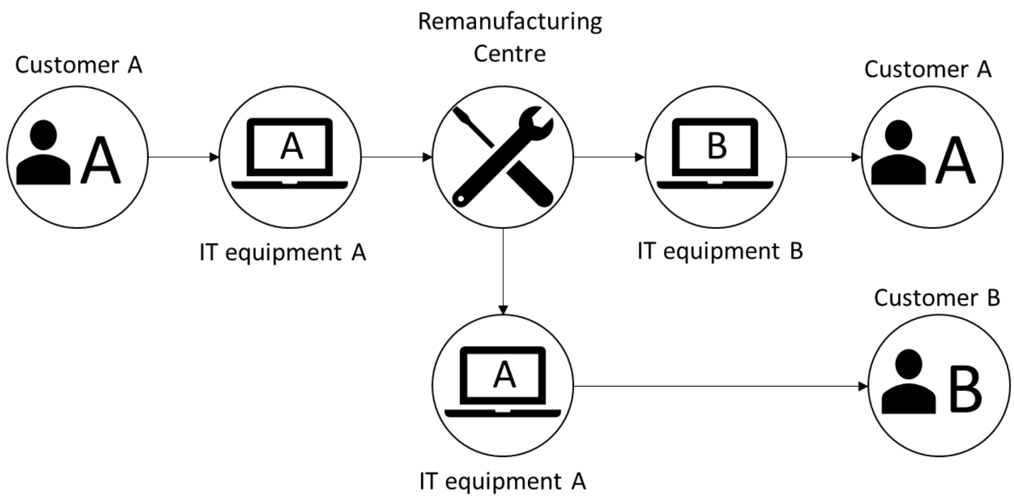


Figure 3.7: Company D's business model

As explained in Figure 3.7, customer A provides Company D with its used IT equipment (IT equipment A) for an agreed price based on the condition of the customer's equipment. Then, the customer is supplied with upgraded IT equipment (IT equipment B). The contract is eligible for changes based on the correctness of the described condition of the returned IT equipment (IT equipment A). Then, this IT equipment (IT equipment A) is remanufactured, upgraded, and sold to the next customer. Thus, factors such as batch quality are crucial for the correct financial success of the business model.

Company D selectively remanufactures specific laptop models that are conducive to upgrades and designs that have remained broadly consistent over an extended period. This implies that factors like design longevity and resistance to market obsolescence are paramount, given that only specific designs prove economically viable for remanufacturing.

In terms of design remanufacturability, Company D deems experience in remanufacturing the particular model as the most crucial determinant. Meanwhile, aspects such as staff training and equipment availability are considered less significant.

Additionally, upgrades and component availability hold marginal significance, as the company focuses solely on remanufacturing designated laptop models. Consequently, these elements do not notably influence their decision-making process.

3.10.4.4 Social factors

Based on the participant's answers, the social factors (Table 3.23) of remanufacturing and implementing a circular business model do not have an essential role in the company's decision-making. Interestingly, despite the growing emphasis on socio-environmental responsibilities in many industries, Company D focused solely on the environmental aspect, as seen in the previous table, drawing a clear distinction between those two aspects. An explanation for such an outcome could be that the company is in the global market; thus, the local needs are not prioritised since its processes are globally distributed.

Table 3.23: Social factors Company D

Social factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
5.1 Job Creation					◊				
5.2 Harmonisation with the local society needs					◊				
5.3 Customer accessibility to high-quality products					◊				

3.10.4.5 Questionnaire Conclusions

The conclusions of this analysis could be briefly described in the following bullet points:

- Company D's exclusive focus lies in the remanufacturing of IT equipment.
- Achieving carbon neutrality is integral to their business strategy, serving as a distinct value proposition.

- By limiting the designs of IT equipment they are remanufacturing, they limit the technical factors to the decision factors, which are mostly the quality of the returned cores.
- Given its global operational scale, the company does not significantly weigh social factors in its decision-making, as it lacks deep-rooted ties to a singular local community.

3.10.5 Decision factors comparison

In this part, a short discussion will follow, comparing the main decision factors for each company and their importance.

3.10.5.1 Environmental Factors

Table 3.24 contains the comparison of environmental factors for the four companies participating in this questionnaire. The safe conclusion is that the more a company has invested in integrating remanufacturing into its business model, the greater the importance of the environmental factors is. Maturity in a circular business model results in a change from a customer-focused environmental impact approach, such as Company A, to a more holistic caption of the impact.

The largest remanufacturing company (Company D) that participated in the questionnaire identified carbon emissions and environmental impact as one of the key value propositions of their business model and the most critical decision factor.

Another conclusion is that the waste stream and disposal of their products are of great importance to the participants, highlighting the need for a method to provide more information on their products' impact in the EoL stage and the possible EoL scenarios.

Table 3.24: Environmental factors comparison - Company A (X), Company B (*), Company C (#), Company D (◊)

Environmental factor	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
2.1 Carbon Emissions					X			*	◊, #
2.2 Disposal of finished products (COMPANY A 'example: We would sort components by waste stream')**							X, #		*
2.3 Customer CO2 requirements									X
2.3 Water consumption					*				
2.4 Supply chain traceability						*			
2.5 Conflict Mineral					*				
2.6 Hazardous or toxic materials				*					
2.7 Controlled chemicals				*					

***factors added by the practitioner*

3.10.5.2 Financial factors

Table 3.25 presents a comparative analysis of the financial factors reported by four survey respondents. Notably, while financial factors are of paramount importance to all the firms in the study, Company A and Company C stand as exceptions.

Company C operates on a stable supply-demand equilibrium for cores, ensuring product interchangeability for its clientele. In contrast, Company A is currently in the preliminary phase of evaluating the feasibility of remanufacturing. Their primary objective is achieving carbon neutrality for their customers. This focus diverges from their conventional profit-centric approach as they realize optimal profits from the linear manufacturing paradigm.

Table 3.25: Financial factors comparison - Company A (X), Company B (*), Company C (#), Company D (◊)

Financial factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
3.1 Cost of applicable solution					X		#		◊, *
3.2 Residual Value			#		X				◊, *
3.3 Profit					#			*	◊, X
3.4 Market demand					#			*	◊, X
3.5 Levys (for example government enforced)*							X		
3.6 Grants and subsidies**							X		
3.5 Capital investment required to establish the remanufacturing capability**							*		
3.6 Cost and time to train operative**							*		

***factors added by the practitioner*

3.10.5.3 Technical Factors

Regarding the technical factors (Table 3.26), the results seem to be less consistent than in the categories above, revealing aspects of their business model and maturity in remanufacturing for each company.

The batch quality is divided into two groups: Group A, where the batch quality is of most importance and where Company D and Company A belong, and Group B, where the quality is important but not critical. Members of the last group are Company B and Company C.

Overall, we could conclude that Company D has built a business model that depends heavily on the quality of the returned cores and not on their remanufacturing capabilities or technical aspects. They succeed by limiting the amount of IT equipment designs they are willing to remanufacture. Factors such as design durability, market obsolescence, and ease of disassembly are critical to those selected designs.

Regarding market obsolescence, it emerges as a non-pivotal concern for most practitioners. However, an exception is seen in Company D. This deviation can be attributed to the more rapid obsolescence inherent in IT equipment compared to products like industrial accumulators or luminaires.

Remanufacturing capability holds pronounced significance for Company B within the lighting industry. In stark contrast, its importance is perceived as moderate by other entities. Regarding the remanufacturability of design, there appears to be a collective agreement among the respondents, recognizing its importance, though not deeming it paramount.

Component upgradability emerges as a critical factor for both Company B and Company C. Conversely, it is deemed non-essential by Company A and Company D. The rationale behind this disparity can be traced to Company A's product maturity, which inherently circumscribes potential technological advancements. Similarly, Company D, with a limited number of product designs earmarked for remanufacturing, finds the availability of components less consequential.

Table 3.26: Technical factors comparison - Company A (X), Company B (*), Company C (#), Company D (◊)

Technical factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
4.1 Batch Quality					*	#			◊, X
4.2 Design Durability						*	X, #		◊
4.3 Ease of disassembly (eDiM)						X	#	*	◊
4.4 Market obsolescence						X, *	X, #		◊
4.5 Remanufacturing capability						*, ◊	#		X
4.6 Remanufacturability						X, *, ◊	X, *	#	
4.7 Component Upgradability (Technical obsolescence)					X, ◊		#	*	
4.8 Availability of components						◊, #			X, *

3.10.5.4 Social factors

A comparison of the social factors among the participants reveals that they are important for some companies but have a secondary value for others, as suggested in Table 3.27. Customer accessibility to high-end products has been interpreted to be related more to market demand than to consumers' access to better products from

Company A. It is noteworthy that all participating firms operate within a "*business-to-business*" framework. Furthermore, an overarching observation indicates that environmental factors carry more weight than social ones across the entities assessed.

Table 3.27: Social factors comparison - Company A (X), Company B (*), Company C (#), Company D (◊)

Social factors	**Importance**								
	Not important			**Important but not critical**			**Critical**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
5.1 Jobs Creation		X			◊	*		#	
5.2 Harmonisation with the local society needs		X			*, ◊	#			
5.3 Customer accessibility to high-quality products					◊	*, #			X

3.10.6 Factors' classification comparison

The last type of analysis is illustrated in Table 3.28 and contains the classification of the factors as operational, tactical and tactical/ strategic.

The aim of Table 3.28 is to classify the decision factors identified as operational, tactical and tactical/ strategic decisions. Strategic decisions set the direction with a time horizon of years and a broad and far-reaching impact. Tactical decisions determine how to pursue that direction, and their time horizon expands from months to years. Operational decisions deal with daily activities that support tactical and strategic decisions, varying from daily to monthly activities.

From Table 3.28, it becomes evident there is a consensus that social factors in decision-making for remanufacturing tend to have a tactical/ strategic character. The only exemption is the *customer accessibility to high-end products*, where each participant allocated the decision factor on a different decision level.

Additionally, from the same table, a much clearer picture regarding the environmental factors is drawn. Through the expression of carbon footprint in environmental impact in kilograms of CO_2, all questionees agreed that this is a tactical/strategic goal. Such an outcome highlights the need for clear and quantifiable environmental impact of any applied EoL pathway since such information can support those long-term goals.

There is much more variety in the results of financial and technical factors. The factors have been allocated differently among the organisation's decision levels. Factors that may have played a role in this diversity of results lie within the participants' interpretation of what each factor represents, the level of applied manufacturing within the organisation and its maturity. Interestingly, batch quality is clearly a unanimous operational decision factor, while the market demand is a much more strategy focused factor.

The allocation of the decision factors among the different organisational decision levels supports the correct identification of what type of decisions the proposed method can support and how the proposed method can be utilised in an industrial environment.

Finally, Company D did not complete this part of the questionnaire due to time limitations; thus, there are no insights from them.

Table 3.28: Factors' classification comparison - Company A (X), Company B (*), Company C (#)

	Decision making Categorisation	Operational	Tactical	Tactical/ Strategic
	Factors\ Factor's focus	**Batch focused**	**Product design focused**	**Strategy focused**
Social				
	Jobs creation			X, #, *
	Harmonisation with the local society needs		X, #	*
	Customer accessibility to high-quality products	X	#	*
Added factor (s)	(None)			
Environmental				
	Environmental Impact in kgCO2 eq			*,X, #
Added factor (s)	Material Waste		*	
	Water consumption		*	
	Supply chain traceability		*	
	Conflict Mineral		*	
	Hazardous or toxic materials		*	
	Controlled chemicals		*	
Financial (Market)				
	Cost	#, *	X	
	Residual value	*	#, X	
	Profit	#, *		X
	Market demand	*		X, #
Added factor (s)	Capital investment required to establish the remanufacturing capability		*	
	Cost and time to train operative		*	
Technical				
	Batch Quality	X, #, *		
	Ease of disassembly (eDiM)	#, *	X, *	
	Availability of components	*	X, #, *	
	Component Upgradability (Technical obsolescence)	*	*	X, #
	Market obsolescence			#
	Remanufacturing capability		#	
	Remanufacturability		#	
	Design Durability	*	X, *	#

3.11 Decision Model

The questionnaires' outcomes, including the industry feedback and the literature results, have been compiled in Figure 3.8. The figure contains the decision clusters, sub-factors and solutions constraints that constitute the default version of the decision model. Additionally, Figure 3.8 includes the classification of those variables as '*tactical*' and '*operational*' decision factors. Factors that are non-dynamic and not related to the batch's condition but related to the product's design itself are classified as '*tactical*' decisions since they support decisions associated with EoL recovery options and production planning (Rizova et al., 2020) and are all interconnected with how well a product's design support circular EoL pathways.

On the contrary, decisions linked with the returned batch's quality are '*operational*' decisions since they focus on serving strategic and tactical levels by efficiently executing everyday activities (Anthony, 1965). Thus, the developed method is a hybrid method that manages to support both *tactical and operational decisions* depending on how the decision-maker uses it.

Finally, as depicted in Figure 3.8, the main difference in the classification of the decision-making support the method provides is based on the use of the application or not of the pre-screening process, a strictly operational process linked to a returned batch's quality characteristics. The operational decision support emerging from the pre-screening process is cascaded to all the related factors, such as cost, profit, residual value and all the environmental data that occurred from the LCA. Those factors are illustrated with a white box in Figure 3.8 to highlight their relation with the quality condition of the batch and the pre-screening process that is applied based on them. Those factors would need to be updated in recurring batches of the same product, which only vary due to their quality, thus supporting operational decisions.

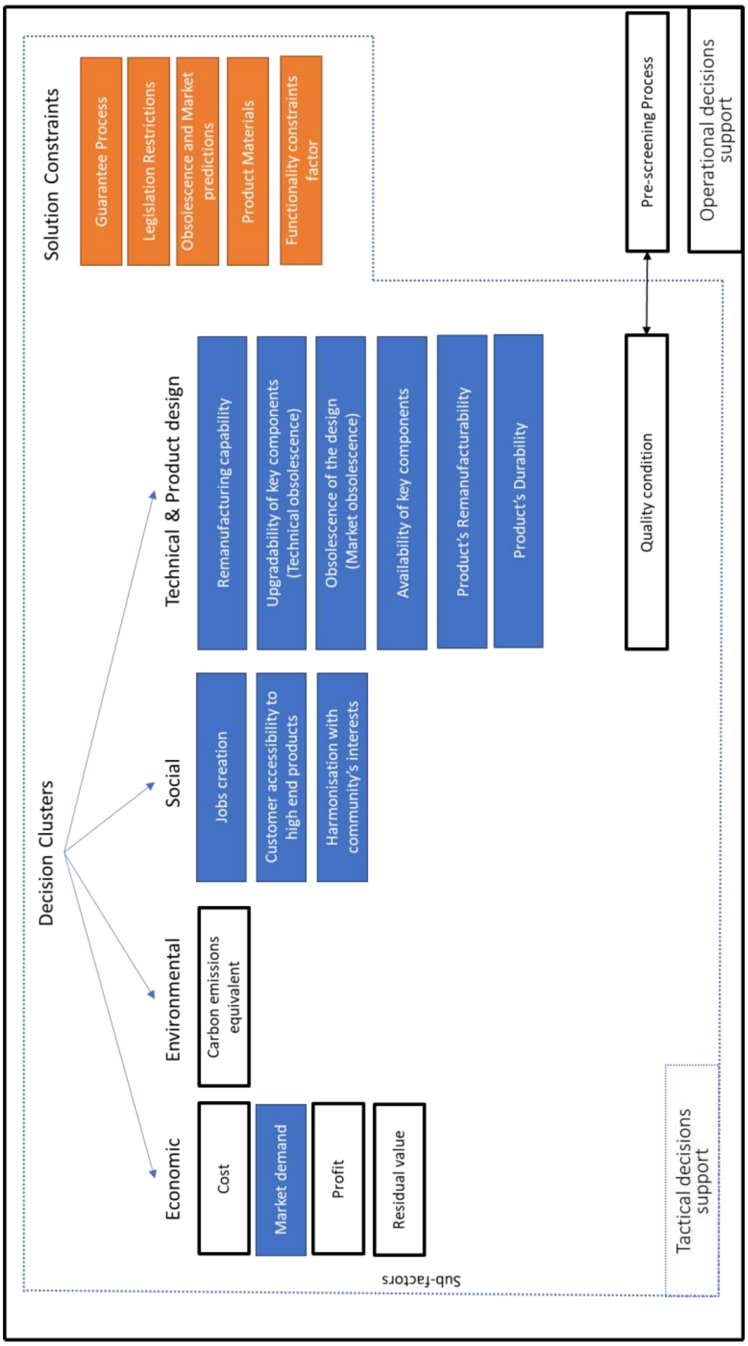


Figure 3.8: Decision clusters, sub-factors, solution constraints and tactical and operational classification

An additional application of the decision model is evident when a decision-maker seeks insights into the comparative suitability of a CEBM application across two distinct products. One can ascertain the suitability of each product's design by employing the proposed method and preliminary estimations on cost and environmental repercussions. This, in turn, facilitates informed decisions pertaining to return disposition policies or product procurement, thereby strengthening future strategic decisions.

3.11.1 Decision factors and sub-factors analysis

Figure 3.8 contains the decision clusters and the factors related to each of those. Table 3.29 contains the decision clusters and sub-factors used in the developed decision model.

Table 3.29 differs from Table 3.28 since it incorporates the final sections for decision clusters, factors, and sub-factors. The main differences arise in the environmental impact section. Unlike Table 3.28, which considers multiple metrics for environmental impact as suggested by one of the participants, Table 3.29 solely utilizes the carbon emissions equivalent. This approach is chosen due to the complexity of measuring environmental impact through various methods. Additionally, some suggested factors are not easily quantifiable, challenging quantitative analysis. For the purposes of this research, quantifying all environmental impacts in kilograms of CO2 equivalent is deemed the best choice. This method illustrates that the final environmental calculations integrate various environmental factors, ensuring that this integration is woven into the simplified LCA methodology. Meanwhile, batch quantity and eDiM have been differently integrated into the decision model. The additional economic factors of *capital investment* and *cost and time to train operatives* were deemed beyond the scope of this work after discussions with other participants.

Table 3.29 also contains an example of default weights for each factor and sub-factor. Decision weights are a concept used in behavioural economics and decision theory to describe how individuals perceive and assign importance to different outcomes when making decisions under uncertainty. Further analysis of the weights and their role in the decision model will be presented in 3.11.4. The subfactors were added after the questionnaire, based on feedback from the industry, for a clearer interpretation of elements of the focal factors. The practitioner is not required to rank or use the sub-factors, but they can directly allocate a decision weight to the umbrella factor. The default weights are there for illustration purposes since the practitioner of the decision model is responsible for entering the weights that correspond to their preferences. The sub-factors also have weights allocated to them by default. In the decision model, developed based on the PROMETHEE method, those weights can be manually entered or automatically calculated based on the total weight of the factor.

Table 3.29: Hierarchy of Decision Factors

Decision clusters and sub-factors				
Decision Weights	**Clusters**	**code**	**Sub-factors**	**3rd level factors**
0.05	**Social**			
0.33		S1	Creation of job positions	
0.33		S2	Harmonisation of solution with local society concerns	
0.33		S3	Customer accessibility to high end products	
0.3	**Environmental**			
1		E1	Environmental Impact	
1		TE1		Carbon Emissions equivalent (kgCO2 eq)
0.5	**Economic**			
0.25		F1	Cost of applied pathway	
0.25		F2	Market Demand	
0.25		F3	Profit of the applied pathway	
0.25		F4	Residual Value	
0.15	**Technical**			
0.166		T1	Remanufacturing capability	
0.333		TR1		Adequate Training
0.333		TR2		Available Equipment
0.333		TR3		Experience in this product/process and confidence
0.166		T2	Upgradability of key components (Technical Obsolescence)	
0.166		T3	Obsolescence of the design (Market obsolescence)	
0.333		TO1		Use of classic or minimal aesthetic
0.333		TO2		Broadness of the applicable market
0.333		TO3		Susceptibility to changes in market demand
0.166		T4	Availability of key components	
0.166		T5	Product's Remanufacturability	
0.166		TP1		Easiness of inspection/ Testing
0.166		TP2		Standardization of components
0.166		TP3		Easiness in repair/ maintenance
0.166		TP4		Fastener’s standardisation index

0.166	TP5		Materials index
0.166	TP6		Electrical connections index
0.166	T6	Design Durability	

The following paragraphs briefly describe the economic and technical factors that constitute the final version of factors and sub-factors that haven't been analyzed before.

3.11.1.1 Economic decision cluster

This paragraph includes the economic factors that have been selected to express the backbone of the developed decision model. The practitioner can always add or delete some of those economic factors based on their preferences. The first factor is the '*Cost of applied pathway',* which is the average cost per product for the investigated EoL pathway. In recycling and disposal, it would be the cost of recycling per unit based on the product's weight, while in remanufacturing, it is the average of the cost for remanufacturing based on the pre-screening process and the application of the developed method. The *'Market Demand'* factor aims to capture the market demand for a specific product and time. The *'Profit of the applied pathway'* captures the profitability of an applied EoL pathway and differs from the cost since it gives the practitioner a chance to prioritise more profitable batches of products against less profitable ones. The '*Residual value*', also known as salvage value, is the estimated value of a product at the end of its useful life. After every life cycle, it should be updated to capture the value of the upgraded components and the degradation of the non-upgraded ones.

3.11.1.2 Technical decision cluster

This section is dedicated to the technical decision cluster and its factors and sub-factors.

The first factor is the *'Remanufacturing capability'*, which aims to capture the ability to produce the specific remanufactured product using existing resources and the current capacity of the plant (Bag et al., 2019) and is based on averaging the values of the sub-factors of *training*, *equipment*, and *experience in this product/process and confidence*.

Upgradability of key components (Technical Obsolescence): The upgradability of a key product's components is crucial for tackling technical obsolescence. The key components are the ones that are directly connected to the efficient functionality of the product, either from a performance point or from an aesthetic performance. Failure to update the product with the latest technologies may result in technical obsolescence, thus, less motivation for applying a circular EoL pathway.

Design Durability: It focuses on the overall durability of the design and the materials used in a specific product design. For instance, products with low-quality plastic parts will have a much higher probability of material failure than those that use metals or better-quality materials. Additionally, if there are known issues with the durability of a specific component of a product's design, this is the factor that is responsible for capturing that information.

Obsolescence of the design (Market obsolescence): One of the key metrics of how many times a product can be used is how fast its design will be considered obsolete either due to technological factors or aesthetics and fashion, and the decision-maker is responsible for grading this feature in a qualitative scale. This factor is based on a qualitative scale emerging from averaging the following three sub-factors: *i) Use of classic or minimal aesthetic, ii) Broadness of the applicable market* and *iii) Susceptibility to changes in market demand.*

Availability of components: This factor aims to measure the ease of finding compatible components for a product and their availability. It is a qualitative scale based on the practitioner's experience.

Remanufacturability: The remanufacturability factor consists of sub-factors belonging to the 3rd hierarchical level and aims to capture the ease of remanufacturing for a product's design. It examines multiple aspects of the product's design expressed through the following sub-factors: i) standardisation of its components and fasteners, ii) easiness in testing and inspection, iii) easiness in repair and maintenance, iv) materials used and v) electrical connections index. Those sub-factors are combined, and the final remanufacturability score is identified qualitatively.

3.11.1.3 Scales of the decision factors

In this section, the scales of the decision factors are described. The main categories of scales are quantitative and qualitative. Quantitative factors belong to the economic decision cluster and the environmental cluster, while the social and technical decision factors are qualitative.

The social cluster includes decision factors that are expressed through a five-point qualitative scale, as seen in Table 3.30:

Table 3.30: Social factors

Social factors	5-point scale	Description
Jobs creation	very poor	This EoL scenario is overall very negative on employment, either through net job creation, up-skilling, pay or working condition
	poor	This EoL scenario is overall negative on employment, either through net job creation, up-skilling, pay or working condition
	average	This EoL scenario is neutral on employment, either through net job creation, up-skilling, pay or working condition
	good	This EoL scenario is overall positive on employment, either through net job creation, up-skilling, pay or working condition
	very good	This EoL scenario is overall very positive on employment, either through net job creation, up-skilling, pay or working condition
Harmonisation with the local society needs	very poor	This EoL scenario conflicts with the local societal needs
	poor	This EoL scenario does not align with the local societal needs
	average	This EoL scenario is neutral to the local societal needs
	good	This EoL scenario aligns with the local societal needs
	very good	This EoL scenario aligns to a great extent with the local societal needs
Customer accessibility to high quality products	very poor	This EoL scenario limits the customer's accessibility significantly to high quality products
	poor	This EoL scenario limits the customer’s accessibility to high quality products
	average	This EoL scenario is neutral to the customer's accessibility to high quality products
	good	This EoL scenario aids the customer's accessibility slightly to high quality products
	very good	This EoL scenario promotes to a great extent the customer's accessibility to high-quality products

The technical decision cluster also consists of decision factors and sub-factors that have a similar five-point qualitative scale designed to capture each EoL pathway performance, which is presented in Table 3.31:

Table 3.31: Technical factors and sub-factors

Technical	Scale	Description
Batch Quality	Quantitative	Input from the pre-screening process
Design Durability	very poor	The core's design durability is generally very poor, with multiple significant flaws
	poor	The core's design durability is generally poor, some critical flaws
	average	The core's design durability is acceptable, with some non-critical flaws
	good	The core's design is generally durable, with limited non-critical flaws
	very good	The core's design durability is generally excellent, with no critical flaws
Obsolescence of the design (Market obsolescence)	Average value of sub-factors	
average from qualitative scale of sub-factors	very poor	The product's design is aesthetically very obsolete
	poor	The product's design is aesthetically obsolete
	average	The product's design is aesthetically fairly modern
	good	The product's design is aesthetically modern
	very good	The product's design is aesthetically very modern
sub-factors	**Use of classic or minimal aesthetic**	
	poor	The product's design is not classic and is aesthetic is niche
	average	The product's design is neutral
	good	The product's design is very classic
	Broadness of the applicable market	
	poor	The product's design can only be used in a specific application
	average	The product's design can only be used in a small array of applications
	good	The product's design can only be used in a wide array of applications
	Susceptibility to changes in market demand	
	poor	The product's design is very susceptible to changes in market demand
	average	The product's design is neutral to changes in market demand

	good	The product's design is not susceptible to changes in market demand
Component Upgradability (Technical obsolescence)		
	very poor	Component's upgradability efficiency is low and easiness low-average
	poor	Component's upgradability efficiency is low-average and easiness low-average
	average	Component's upgradability efficiency is average and easiness average
	good	Component's upgradability efficiency is average-high and easiness average -high
	very good	Component's upgradability efficiency is high and easiness high
Remanufacturing capability	Average value of sub-factors	
average from qualitative scale of sub-factors	very poor	The remanufacturing capability is very limited (solution constraint of remanufacturing)
	poor	The remanufacturing capability is limited
	average	The remanufacturing capability is average
	good	The remanufacturing capability is good
	very good	The remanufacturing capability is very good
sub-factors	**Adequate Training**	
	poor	Personnel training is inadequate for handling this product
	average	Personnel training is adequate for handling this product
	good	Personnel training is entirely sufficient for handling this product
	Available Equipment	
	poor	The available equipment is inadequate for handling this product
	average	The available equipment is adequate for handling this product
	good	The available equipment is entirely sufficient for handling this product
	Experience in this product/process and confidence	
	poor	Personnel's experience and confidence is inadequate for handling this product
	average	Personnel's experience and confidence is adequate for handling this product
	good	Personnel's experience and confidence is entirely sufficient for handling this product

Availability of components	very poor	Components for this product are extremely difficult to find or to produce (Solution constrain-no remanufacture)
	poor	Components for this product are difficult to find or to produce
	average	Components for this product are common or easy to produce
	good	Components for this product are very common and easy to produce
	very good	Components for this product are extremely common or standardised or extremely easy to produce

Remanufacturability	Average value of sub-factors	
average from qualitative scale of sub-factors	very poor	The product's design is unsuitable for remanufacturing (solution constraint of remanufacturing)
	poor	The product's design is poor for remanufacturing
	average	The product's design is average for remanufacturing
	good	The product's design is suitable for remanufacturing
	very good	The product's design is excellent for remanufacturing
sub-factors	**Easiness of inspection/ Testing**	
	poor	The product's design makes inspection/ testing difficult
	average	The product's design has no significant impact on the inspection/ testing difficulty
	good	The product's design makes inspection/ testing easy
	Standardization of components	
	poor	The product does not use standardised components
	average	The product uses some standardised components
	good	The product uses only standardised components
	Easiness in repair/ maintenance	
	poor	The product's design makes repair/ maintenance difficult
	average	The product's design has no significant impact on the repair/ maintenance difficulty
	good	The product's design makes repair/ maintenance easy
	Fastener's standardisation index	
	poor	The product does not use standardised fasteners

	average	The product uses some standardised fasteners
	good	The product uses only standardised fasteners
	Materials index	
	poor	Materials are mixed, non-durable
	average	Materials are averagely durable and mixed
	good	Materials are not mixed and durable
	Electrical connections index	
	poor	Electrical replacement, rewiretability and replaceability is very poor
	average	Electrical replacement, rewiretability and replaceability is average
	good	Electrical replacement, rewiretability and replaceability is good

The sub-factors are used to aid in scoring the main decision factors for the practitioner, who has to address them first to have the result of the main decision factor.

One of the key attributes of the proposed factor's scales is that they are built in a 'hard' and 'soft' criteria approach. For instance, in the remanufacturability decision factor, all the sub-factors can be graded as 'average', which impacts the decision model since it identifies that the specific product design is not very suitable for remanufacturing, but remanufacturing is still a viable EoL pathway. In this case, the remanufacturability decision factor acted as a 'soft' criterion that has a weight that favours 'recycling' and 'disposal' in comparison with 'remanufacturing' as EoL pathways. In the case that the results of the sub-factors were averagely graded as 'poor', remanufacturing would be omitted from the available EoL pathways, thus acting as a 'hard' constraint. In this example, the 'hard' would mean that the remanufacturability decision factor acts as a solution constraint. Remanufacturing is omitted from the available EoL pathways, thus remaining only direct reuse, recycling, and disposal.

3.11.2 Solution constraints

As explained in the previous section, a decision factor that acts as a 'hard' constraint is responsible for opting out of one or more of the available EoL pathways due to standards not being adequately satisfied. On the contrary, a 'soft' decision factor does not opt out of any EoL pathway but provides different scores on the available EoL pathways based on their performance, thus ranking the EoL pathways. Finally, a 'soft' constraint can be escalated to a 'hard' constraint when threshold values or specific conditions are met, as explained before with the remanufacturability decision factor. The decision factors following a 'hard' approach will be defined as 'solution constraints'. In addition to the constraints of the solution emitting from the transition of 'soft' decision factors to 'hard' ones, in the proposed method, three more key constraints have been added that may adversely impact the application of specific EoL pathways. All the solution constraints that have been selected to be the default version of the method's solution constraints are presented in Table 3.32:

Table 3.32: Possible EoL restriction per constraint

Constraints	Restricted EoL Pathways	Reasoning
Guarantee Process	Reuse	Product's reliability compromises direct reuse
Legislation Restrictions	Reuse	Legislation prohibits/discourages direct reuse
	Remanufacture	Legislation prohibits/discourages remanufacturing
	Recycle	Legislation prohibits recycling
	Disposal	Legislation prohibits disposal
Combined Obsolescence (Market & Technical)	Reuse	Product's obsolescence compromises direct reuse
	Remanufacture	Product's obsolescence compromises remanufacturing
Pre-screening Process (Batch quality)	Reuse	Product's quality compromises direct reuse
	Remanufacture	Product's quality compromises remanufacturing
Product Materials	Recycle	Product's materials cannot be recycled
	Disposal	Product cannot be disposed
Remanufacturability	Reuse	Product's remanufacturability rating prohibits direct reuse
	Remanufacture	Product's remanufacturability rating prohibits remanufacturing
Availability of components	Remanufacture	Components for this product are extremely difficult to find or to produce
Remanufacturing capability	Reuse	The limited capability prohibits direct reuse
	Remanufacture	The limited capability prohibits remanufacturing

Table 3.32 includes three additional categories that act as solution constraints besides the 'hard' decision factors transforming into solution constraints.

The *guarantee process* is a process that adopts two principal checks but can be developed for each product specifically to capture any compromise related to insufficient efficiency in the functionality of the product. According to the remanufacturing definition (W. L. Ijomah et al., 2007), a 'product must be returned to a condition at least equal to as new'. Therefore, the guarantee process becomes a critical consideration in evaluating the feasibility of direct reuse and remanufacturing, particularly when this essential criterion cannot be met. The process hinges on the product's key components' lifespan and usage duration. The first of the principal checks is a 'Baseline life expectancy check', defined below:

$$L - U_p \geq 0$$

Equation 12: Baseline life expectancy check

The value L represents the life expectancy of a component, and Up is the past usage of the component. This check ensures that the remaining lifespan of the component is reliable.

The second check addresses the component's future usage (U_f) in its new application and the potential guarantee period (G) the remanufacturer is willing to offer. The inequality expresses this:

$$U_p - U_f < G$$

Equation 13: Life expectancy check when a guarantee is given

The objective of this check is to determine confidently whether the component has a sufficient lifespan for its future usage and whether this exceeds the guarantee period offered by the company.

An example of a tailored developed guarantee process can be found in the case study described in Chapter 5, and an in-depth analysis of the guarantee model developed for this application can be found in section 5.6.1.1.

The solution constraint '*Legislation Restrictions'* aims to capture any restrictions related to any of the available EoL pathways that may occur due to product-specific legislation. Input to that restriction is expected from the practitioner of the proposed method.

The *pre-screening process* is developed to capture the returned batch's average expected cost and environmental impact when remanufactured. Quantifying those two major decision factors offers an opportunity to create threshold values that work as 'hard' constraints, thus, solution constraints for reuse require pristine condition cores and remanufacturing when the cost or environmental impact is too severe compared to purchasing a new product.

The '*product materials'* solution constraint refers to the materials composing the product and the potential issues with recycling or disposal. For instance, an electrical device cannot be landfilled (disposed) due to legislation. In contrast, a product composed of non-recyclable material such as Styrofoam, ceramics, mirrors, etc., can only be landfilled (disposed).

The *'Combined Obsolescence (Market & Technical)'* is a solution constraint that combines both the Component Upgradability (Technical obsolescence) and the Obsolescence of the design (Market obsolescence). The practitioner must define the threshold value of which combination of those two decision factors can act as a hard constraint. For instance, a product whose obsolescence of design is very poor but upgraded technically might still offer remanufacturing as a viable EoL pathway since its functionality and efficiency are directly compared with current products.

The '*Remanufacturability'* solution constraint is based on an average result from combining multiple sub-factors. The aim is to capture the ease with which a product can be remanufactured based on its design. Products with very low remanufacturability cannot be remanufactured due to their design's complexity. In combination with the '*Remanufacturing capability'* solution constraint, which captures the available resources to perform remanufacturing and the confidence to achieve the tasks related to it, remanufacturing can be omitted for the available EoL pathways as well as direct reuse due to the lack of resources for cleaning the returned cores.

Finally, if the 'Availability of components' is very poorly graded, the product under analysis cannot be remanufactured since the supply chain needed to support those tasks does not exist, and the acquisition of those components is troublesome or lacks mass scale.

These solution constraints are the backbone, and the default version of the solution contains that this method applies. Following the same approach as any other model of this method, the solution constraints are also highly customizable. They can be altered based on the practitioner's preferences, creating a highly versatile method that can describe multiple problems across different industries and disciplines. The applicability of this method and the solution constraints are highlighted sequentially through the two case studies found in Chapters 5 and 6.

3.11.3 Solutions ranking

After defining the solution constraints, the final stage of this method is to define the EoL pathways that act as solutions and are being ranked from the MCDA method. The solutions and their definition within the boundaries of this research are the following:

Reuse: It contains products that, during their testing, they had sufficient scores for direct reuse. The only process those products need is cleaning. No disassembly or replacement of any component is needed.

Remanufacture: It contains products that need disassembly and component replacement. The components that will be replaced will be either recycled or disposed. Thus, remanufacturing as a solution contains partial recycling and disposal. The new components could be reused or brand new. In the event of remanufacturing, there is no need for a whole new product to be purchased.

Recycle: The recycling option focuses on recycling the whole product because remanufacturing is an unprofitable solution. In the event of recycling, a new product must be purchased, and its environmental and economic impact is added to the recycling solution.

Disposal: Similar to recycling, disposal contains whole products, and repairing them is considered too costly. Disposal is a distinct solution to our framework since not all product components are recyclable. Additionally, the developed framework aims to support decisions without ruling out possible solutions; the practitioner can determine validity at a later stage.

In the next section, the multicriteria decision aid method is presented.

3.11.4 Multi-criteria decision aid (MCDA) method

The proposed method aims to provide decision support to the practitioner to identify the most suitable EoL pathway for a returned batch of products. Delivering such decision support requires multiple decision factors and sub-factors to be weighted, and their differences in performance can alter the ranking of the available EoL pathways. Thus, this work utilizes a MCDA method, named PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations), to provide an integrated approach to the optimum EoL pathway by considering quantitative and qualitative criteria and solution constraints that are customizable by the practitioner. The following section thoroughly describes the PROMETHEE II full-ranking method and the decision model developed for the proposed method.

3.11.4.1 PROMETHEE II

As discussed in the previous chapter, the PROMETHEE II full ranking method is used in this study, which was originally developed by *J.P. Brans* (1982) and updated by *Vincke and Brans* (1985). It is an MCDA method that is based on ranking a finite set of alternative actions against a selected number of criteria, which may be conflicting (Dhouib & Elloumi, 2011).

MCDA methods are generally developed with the aim of supporting decision-making when there are many compromising alternatives (Dhouib & Elloumi, 2011). The PROMETHEE family includes a variety of outranking methods such as the PROMETHEE I, which does a partial ranking of the solutions, the PROMETHEE II, which does full ranking of the alternatives and is applied in this study, the PROMETHEE III for ranking based on the interval, the PROMETHEE IV that includes a partial and complete ranking of alternatives, the PROMETHEE V for problems with segmentation constraints (Brans & Mareschal, 1992). Other versions may focus on the human brain representation, such as PROMETHEE VI (Brans & Mareschal, 1995) or on group decision-making, such as PROMETHEE GDSS (Macharis et al., 1998). Finally, an addition to the PROMETHEE methods came through graphical representation based on the visual interactive module GAIA (Geometrical Analysis for Interactive Aid) (Brans & Mareschal, 1994; Mareschal &

Brans, 1988), which enabled the method to be used in much more complex decision-making problems.

According to an extensive literature review conducted by Behzadian *et al.* (2010), the PROMETHEE methods have been applied to a plethora of areas. Specifically, in a sample of 195 applications of the method across the literature, areas such as *'Environment Management'*, '*Business and Financial Management'* and '*Manufacturing and Assembly'* aggregated a total of 47% of the whole, as depicted in Figure 3.9.

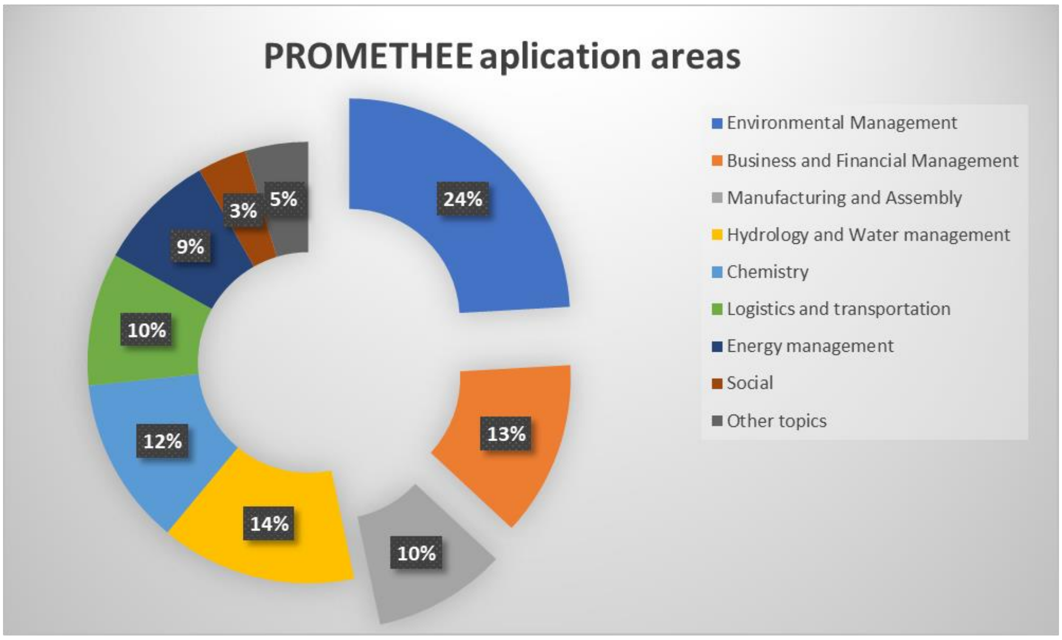


Figure 3.9: Promethee Application areas, adopted from (Behzadian et al., 2010)

The three aforementioned areas are the melting point of application for this research's proposed method, highlighting the PROMETHEE method's suitability for developing and solving the complex decision problem of this study.

3.11.4.2 PROMETHEE Operation

The basic principle of PROMETHEE II is based on comparing a pair of alternatives, a and b, in each single criterion k to determine partial binary relations designating the strength of preference between the alternatives (Mergias et al., 2007). The final ranking of the alternatives against the criteria is based on the calculation of the net outranking flow, which allows the complete ranking available in PROMETHEE II. As with most of the MCDA methods, an additional input to the PROMETHEE II is the weights of the criteria, which are direct input from the practitioner.

The first step of the method is the determination of the deviations based on pair-wise comparisons of criteria *a* and *b*. The next step is the definition of a preference function for each criterion. The functions that can be used are (1) usual criterion, (2) U-shape criterion, (3) V-shape criterion, (4) level criterion, (5) linear and (6) Gaussian criterion (Behzadian et al., 2010). These functions aim to successfully translate the evaluation difference between two alternatives into a single number belonging to [0,1]. Their application is based on the definition of three threshold values defined by the practitioner and has clear significance. Step 3 aims to calculate an overall or global preference index where the weighted sum is calculated for each criterion and the weights associated with it. In step 4, the calculation of the outranking flows takes place, where for each alternative, both the positive flow $\varphi^{+}(\alpha)$ (also known as Phi+), and the negative outranking flow $\varphi^{-}(\alpha)$ (also known as Phi-). In the final step of the method, the calculation of the net outranking flow talks place, and the alternatives are ranked based on the net flow $\varphi\,(\alpha)$ (also known as Phi). For greater detail of the method's mathematical model and the implementation steps, the reader is advised to refer to more specific literature (Behzadian et al., 2010; J.-P. Brans & Mareschal, 1995; J. Brans, 1982; J. Pierre Brans & Mareschal, 1992; J.P. Brans & Mareschal, 1994).

3.11.4.3 Selection of visual PROMETHEE

The Visual Promethee, MCDA aid software selected for this study, will be presented in this section. According to the Visual PROMETHEE manual (Mareschal, 2013), the method is designed to provide support with:

1. Evaluation of multiple decisions or items according to a plethora of possibly conflicting criteria
2. Identification of the best decision and ranking of the alternatives
3. Sorting of items into classes
4. Visualization of the decision problem and its result for supporting the decision-maker

5. Justification of decisions based on in-depth knowledge of the decision problem and its results

The proposed method evaluates the available EoL pathways based on multiple criteria/ decision factors that may be directly linked, such as the cost of applied EoL pathway and profit, or indirectly conflicting with each other, such as obsolescence and market demand. Those factors may be positive, negative or neutral correlated to each EoL pathway. For instance, *'obsolescence of the design'* correlates negatively to EoL pathways such as *Reuse'* or *'Remanufacturing'* because the product's design might be perceived as outdated to an extent by the consumer. On the contrary, the same factor may positively correlate to the EoL pathways of *'Recycle'* or *'Disposal'* since a new product must be bought to satisfy the customer's need.

Additionally, the developed method sorts the items into classes by grouping decision factors into clusters and then ranking the available EoL pathways based on those criteria. Finally, the developed decision model that is part of the proposed method provides visualisation of the results through the GAIA (Geometrical Analysis for Interactive Aid) Visual Analysis, which is a method that illustrates in a two-dimensional view the ranking of the solutions and the criteria that are compared against and acts as an extension of the Promethee results through the visualisation and interactive procedure (J.P. Brans & Mareschal, 1994; Mareschal & Brans, 1988). All these visual aids, methods, and tools provide adequate support to the decision-maker or practitioner of the proposed method to make a well-informed decision. Thus, applying the Promethee II full ranking method in the developed study aligns perfectly with the aforementioned areas of crucial support the method can offer, thus highlighting the correctness of choice to use the method.

3.11.4.4 PROMETHEE model description

For building the Promethee decision model, the first step was to align the proposed method's decision model to the terminology of the Visual Promethee 1.4 software. Table 3.33 contains the decision model elements and their description linked to the Visual Promethee terminology.

Table 3.33: Terminology and elements of the developed PROMETHEE model

Promethee terminology (according to (Mareschal, 2013)	**Proposed Model application**
Action: the term is used for the designation of a possible decision or a possible item that requires evaluation.	*'Actions'* are the four Eol pathways named reuse, remanufacture, recycle and disposal, while depending on the solutions constraints, all four or fewer may be active.
A 'Cluster' is composed of a subset of criteria within one or several criteria groups and can be grouped for simplification of the analysis.	In the developed study, the cluster created was named '*Decision Factors'* and includes all four of the criterion groups.
A 'Criterion group' defines a subset of criteria that share the same identification colour and symbols within the same cluster and is used for simplification of the visualisation of the analysis.	Four criterion groups were created in the developed study: *financial, environmental, technical, and social*. Each of those is a subset of criteria related to the group's theme.
A '*criterion'* is an attribute that is associated with each of the available actions and allows the comparison of the actions for the identification of the best ones.	*'Criteria'* are the isolated decision factors and sub-factors used in the decision model. Those criteria make it possible for the actions (EoL pathways) to be compared.
A '*scenario*' expresses a set of evaluations emerging from the criteria and the actions described in the decision model and can represent different views of different decision-makers.	There is only one decision-maker in our study, the practitioner of the proposed model. Thus, only one 'scenario' captures the criterion groups' scores and the ranking of the actions. If the decision-maker decides to test another hypothesis, they can create another scenario and alter the weights and values of the criteria.

Correct identification of the terminology of the Promethee MCDA software leads to an adequate definition of the decision model since the crucial set of actions (EoL Pathways) have been set, the criteria for which those actions will be ranked and compared against and finally, who the responsible person is for this analysis, the decision-maker. The criteria hierarchy of the decision model is illustrated in Figure 3.10:

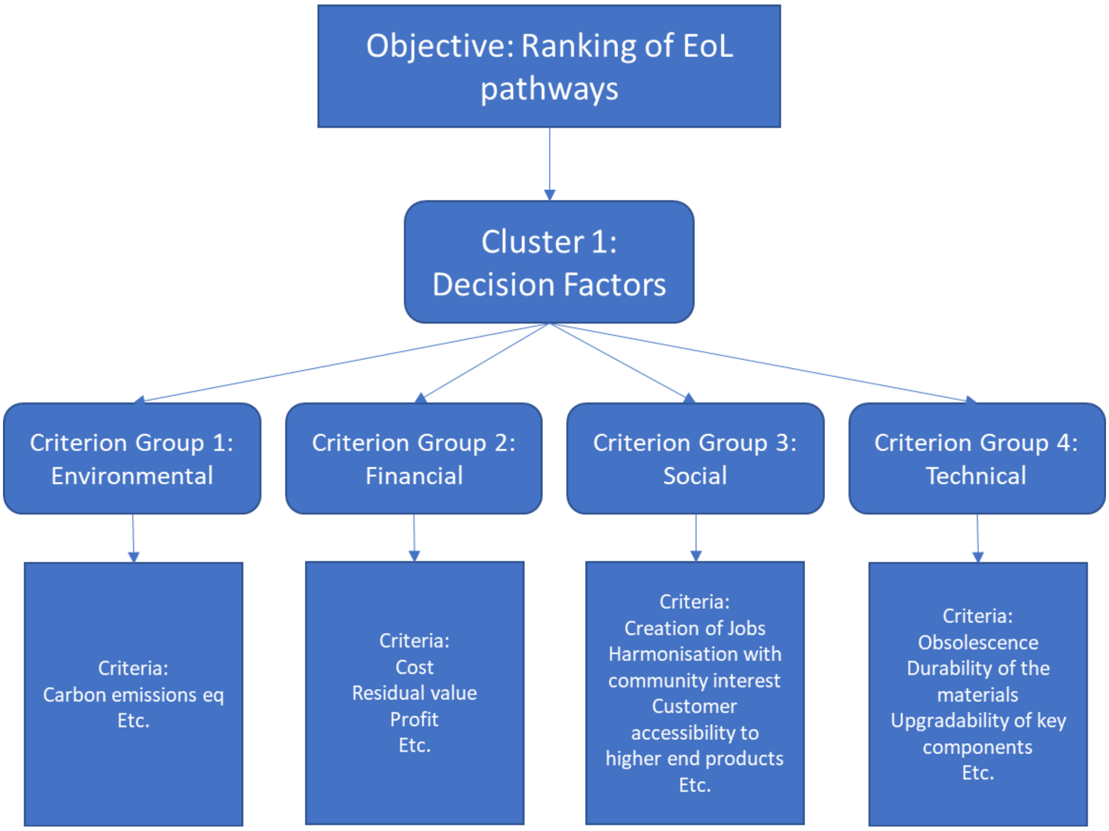


Figure 3.10: Criteria’s hierarchy of the decision model

The next step is weighing the decision factors that act as criteria. Their weights are positive numbers that represent the importance of that criterion. In the developed decision model during the case studies, the balance of power tool provided by Visual Promethee 1.4 was used to allocate the weights to each criterion group based on the practitioner’s input.

3.11.4.5 Promethee tools of Analysis

The Promethee II full ranking method is based on the reference flow of the available solutions for ranking them. The findings of the decision method must also be appropriately presented to the decision-maker and practitioner of the developed method for optimization of the information communication. The use of Visual Promethee 1.4 software allowed the researchers to use the Promethee- GAIA tool, the walking weights sensitivity analysis, and a clear depiction of the ranking of the solutions based on the flow table. Below are some of the tools available in the decision aid software, along with a short description.

The first group of tools is the one for tools focused on illustrating the ranking of the available solutions. Such tools are the Promethee II Rankings and the Promethee Diamond, which both illustrate the solution rankings across a [-1, +1] vertical axis that represents the reference flow and, on that axis, the flows for each solution are marked, thus providing the decision maker with the ability to understand the differences in magnitude between the solutions fully. The Promethee II Rankings tool is illustrated in Figure 3.11.

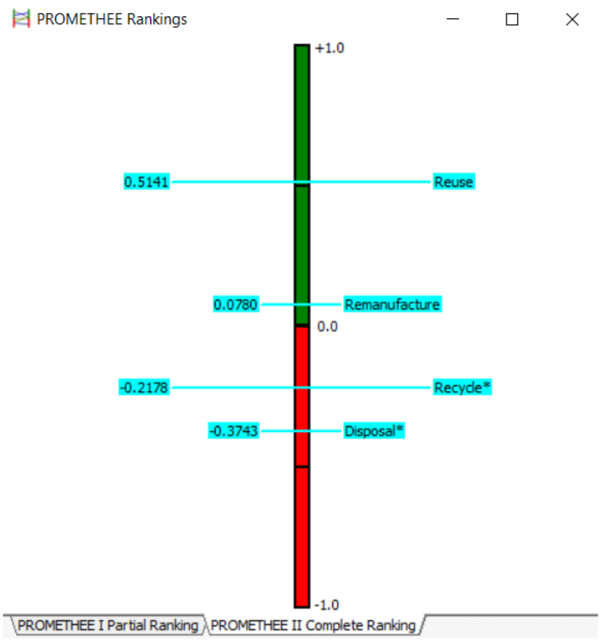


Figure 3.11: PROMETHEE II Rankings

The main advantage of the PROMETHEE Diamond is that it can visualise the alternatives as rectangles or parallelograms, with their shapes determined by scores on the positive flow $\varphi^{+}(\alpha)$, axis and its counterpart, often the outranking flow $\varphi^{-}(\alpha)$. The higher an alternative's rectangle reaches on the positive axis, the better it is deemed in performance, as depicted in Figure 3.12.

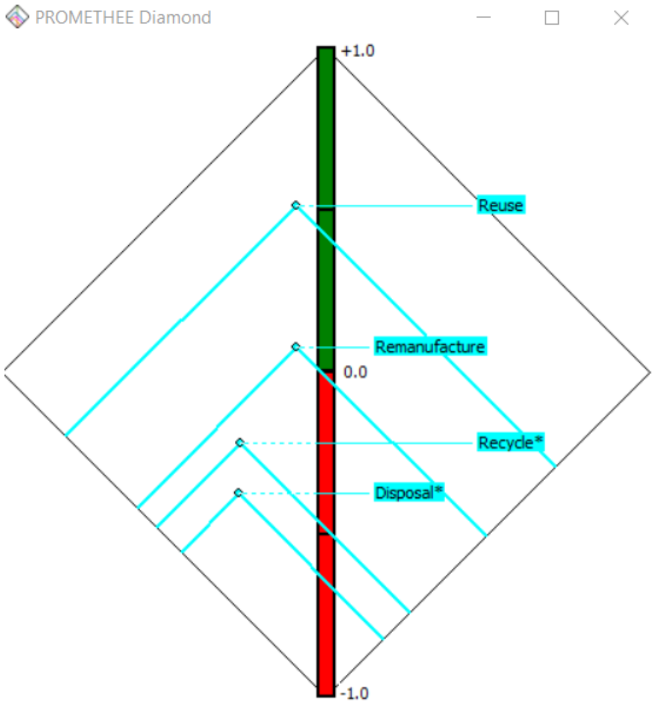


Figure 3.12: Promethee II Diamond

Additionally, the results from the solution of the decision model are captured in the Promethee Flow table (Figure 3.13), which includes the input, output and total reference flow of the available solutions (actions). The next tool of representation is the PROMETHEE Rainbow, which displays from left to right the ranking of the available solutions of the decision model alongside the criterion groups that each of the represented solutions is strong or weak with respect to the other actions.

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	Reuse	0.5141	0.7105	0.1964
2	Remanufacture	0.0780	0.4942	0.4162
3	Recycle*	-0.2178	0.2593	0.4771
4	Disposal*	-0.3743	0.1793	0.5536

Figure 3.13: PROMETHEE II flow table

Figure 3.14 includes the PROMETHEE Rainbow graph in an application of the proposed decision model for exhibition purposes.

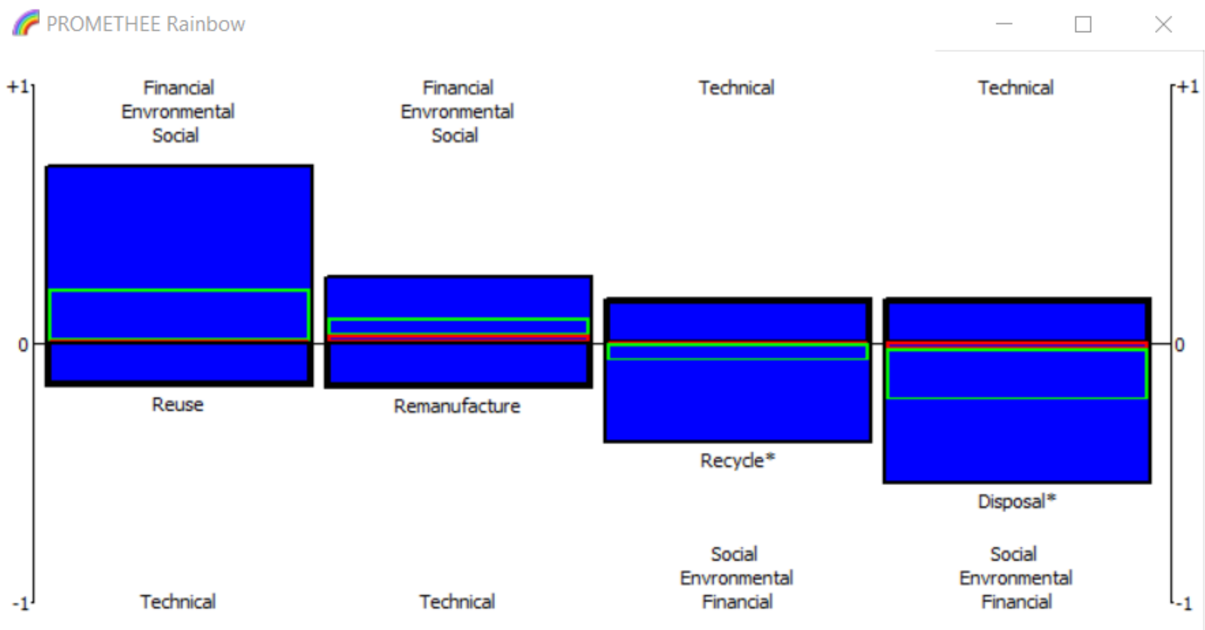


Figure 3.14: PROMETHEE II Rainbow

In the example of Figure 3.14, all the EoL pathways are available, and their ranking reveals that direct reuse is the action with the best net flow since it has a positive flow in the Financial, Environmental and Social criterion group while only having a negative flow on the Technical criterion group. The green line represents the net flow value, while the red line expresses the importance of the criterion used.

The next tool of great importance that has been used for communicating the results of the developed decision model is the GAIA plane, which is a descriptive complement to the Promethee Rankings (Figure 3.11) and is a multidimensional representation of the problem and its solutions. The dimensions of the problem are equal to the criterion number, and the mathematical method named Principal Components Analysis is used to reduce the number of dimensions with limited loss of information. In Visual Promethee, three dimensions are computed: U, V and W. The U-V plane is used in our 2D illustration of the results since it has the highest level of information confidence with 97.3% quality. According to the Visual PROMETHEE manual (Mareschal, 2013), for the 2D GAIA analysis to be reliable, the quality level must be 70% and above. Figure 3.15 depicts the 2D GAIA graph for an example case study of the proposed decision model. The four criterion groups and the four EoL pathways are visible in the graph. The actions in our model, the EoL pathways, are represented by a point in the GAIA U-V plane. Their position expresses the similarities between actions that performed likewise to the evaluations against the group of criteria.

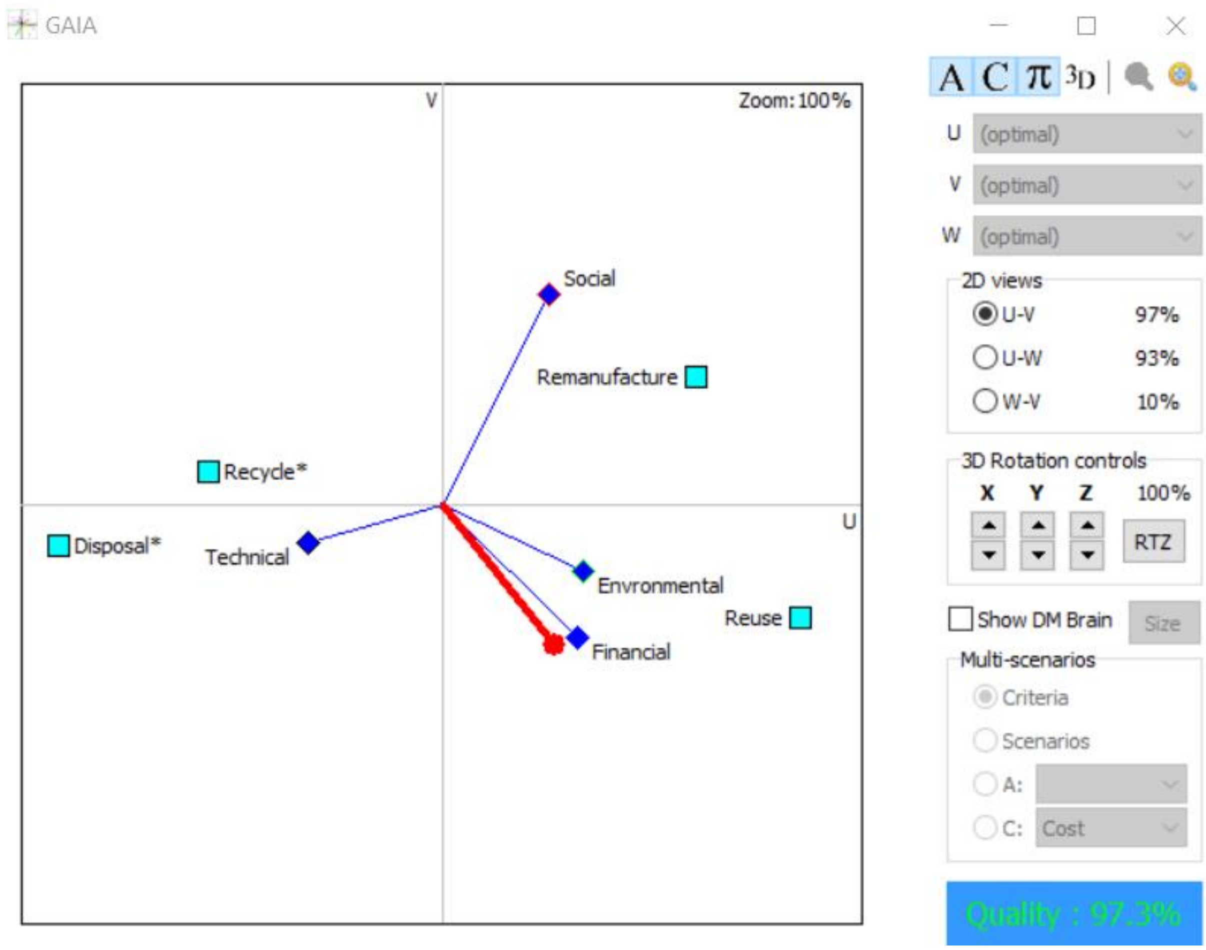


Figure 3.15: PROMETHEE 2D GAIA

Figure 3.15 shows that the criterion groups are represented through an axis from the centre towards the action that is evaluated best against that specific group. The distance between the criterion axis and their position also reveals similar preferences or conflicting criteria. Thus, in our example, recycling and disposal had similar evaluations in their performance to the criterion groups. At the same time, remanufacture and reuse had significant differences due to the social criterion group evaluations. Finally, the social criterion group is conflicted with the technical criterion group. The decision axis is the thick red axis and is a projection of the Decision Stick onto the GAIA plane (Mareschal, 2013).

The next tool in the arsenal of the Visual Promethee 1.4 is the Walking Weights. The Walking weights allow the decision-maker to alter the weights of the criterion groups while the rankings of the available actions change in real-time. The Walking weights tool is illustrated in Figure 3.16.

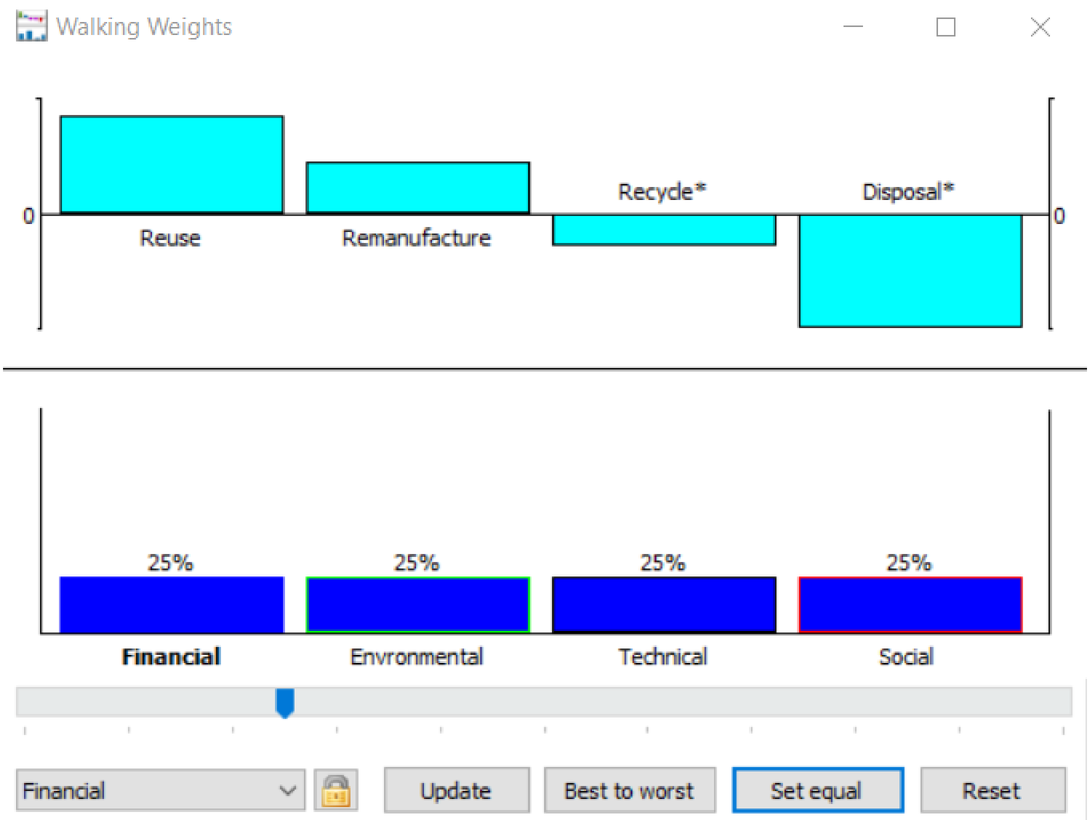


Figure 3.16: Walking Weights

Finally, the decision-maker can make use of the Visual Stability Intervals to examine the stability of the solution based on each criterion independently. Through that tool, the practitioner can identify the tipping point where the weight of a criterion group is able to alter the ranking of the available actions as illustrated in Figure 3.17, where the tipping point for the social criterion group is the 42.67% weight where remanufacturing becomes a higher-ranking action than reusing due to a better evaluation against the Social criterion group.

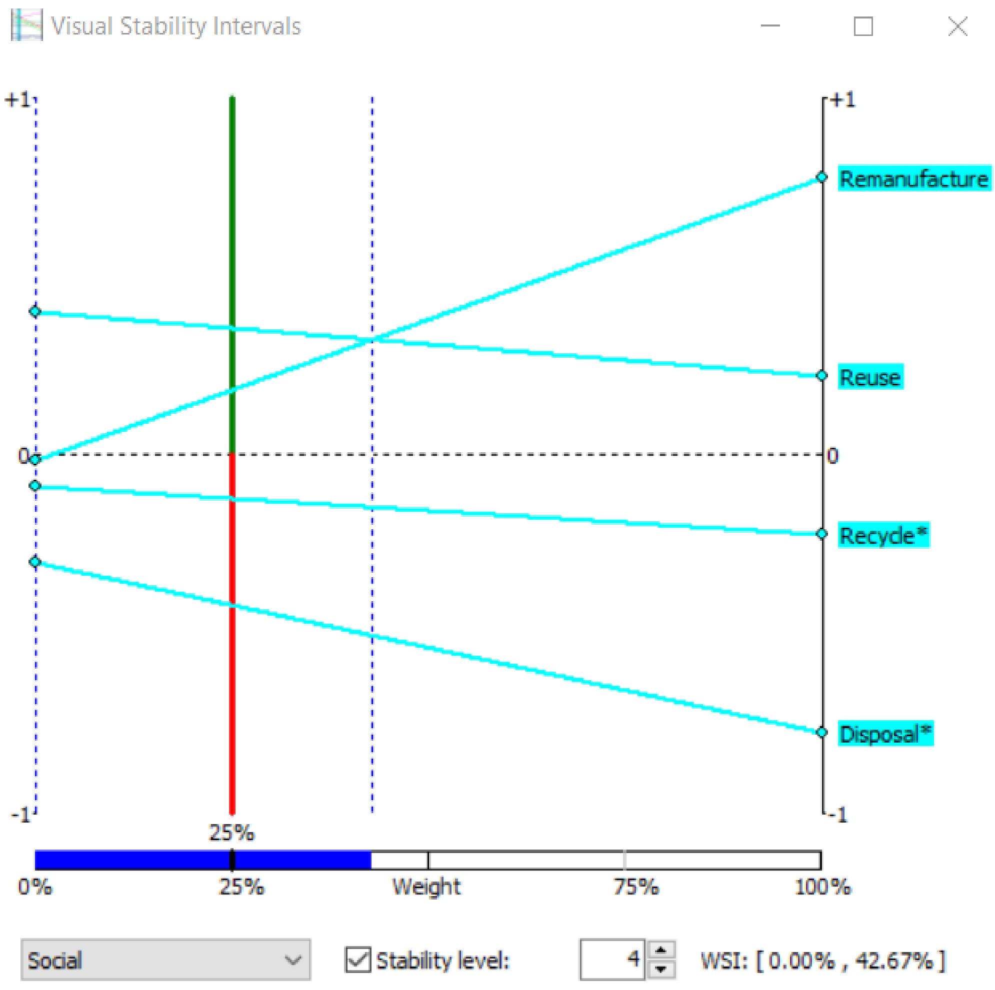


Figure 3.17: Visual Stability Intervals

These are the main tools that the developed method uses to analyse the decision model and its results and represent those results to the practitioner who acts as the decision-maker.

3.11.4.6 Method limitations and assumptions

This section discusses the limitations of the proposed method and the assumptions related to this work.

The level of complexity of the models used for each of the elements of the proposed method has been kept relatively low due to the wide range of sectors for application. Thus, complex applications of the method may need further development to be fully applicable and efficient. The presented generic model is a high-level description of the model that can be used as the base model for tailoring the proposed method to a specific sector if needed. This is presented in Chapters 5 and 6 through the case studies, which enrich the proposed method with case-specific elements developed to tailor it to their needs further. At the same time, the generic model introduced in this chapter allows flexibility for those other additions.

Another limitation of this work emerges from selecting key components to apply the proposed method. Due to complexity, only some components are considered for the financial and environmental analysis. Thus, the outputs from these models are linked to the successful selection of the key components and their characteristics. As a result, the final ranking of the EoL pathways of the method and the CEDA graph are highly correlated to the inputs from those key components. Their correct identification is key to the implementation of this method.

The application of the eDiM method offered standardisation of the dis- and re-assembly time needed to complete the tasks. Any limitations linked to the method of eDiM are inherited from the proposed method. The main limitations linked to the eDiM method are emerging from the databases used for the method, the non-extensive taxonomy of types of fasteners and the accuracy/ complexity ratio of the method (Vanegas et al., 2018). More specifically, the eDiM database does not include specific product designs that may adversely impact the time needed to undo and redo a fastener but is based on some generic and more common tasks. Additionally, the non-extensive taxonomy of fasteners synergy with difficulty determining the correct measurable parameters for all the disassembly categories may lead to results that are linked with higher uncertainty. Although this limitation has been identified in the past (Vanegas et al., 2018), it is a necessary trade-off between the accuracy and the level of detailed information needed to implement the method.

This work focuses on providing decision support for selecting a returned batch's most suitable EoL pathway when specific decision factors and sub-factors are weighted in. One of the limitations is that even though there is a structural analysis of the product through the HALG representation, and it uses hierarchical levels to identify costs for re- and dis-assembly, the proposed method does not provide any input on the sequence of those tasks and does not take into consideration salvaging the cores for spare parts.

Both recycling and disposal as EoL pathways do not include spare parts salvaging from the cores and any labour cost related to that in their financial analysis.

The environmental analysis for this work is based on a simplified LCA of the product based on the ISO 14040 guidelines. Albeit the principles of PAS 2050 create a strong base on how to quantify the emissions of a process, such as the remanufacturing process used here, in this study, the data shared from the case studies did not make possible the implementation of the PAS 2050 standard. The environmental impact of the remanufacturing process was based solely on the energy consumption and the tools used. Once a company has established a remanufacturing process, those data can be fed into the proposed method, thus building a much more precise environmental capturing model. Finally, the method's scope may be limited by focusing solely on carbon emissions as a measure of environmental impact. This approach might overlook other critical ecological concerns that are not directly correlated with carbon emissions or climate change, such as marine ecotoxicity, carcinogenic risks to humans, and the depletion of mineral resources. The impact of this limitation is mitigated through standardised lifecycle methods, such as the ReCipe 2016, that confidently translate all the environmental impacts to carbon emissions equivalent.

The proposed method aims to support operational and tactical decision-making. The economic investigation of this work is based on a simplified model that captures the main cost centres for each of the EoL pathways and is not intended to be an extensive financial study. This is because the method uses data input from the case studies and from the literature, and limited access to specified data such as infrastructure costs, equipment costs, and more sophisticated financial costs was not possible and out of scope for this work. Thus, strategic costs related to the company's infrastructure or facilities that apply the method have not been considered. Finally, the costs and prices associated with future market demand emerge from the practitioner’s input, not from market prediction models.

Another limitation of this study emerges from the fact that the practitioner of the proposed method is responsible for inputting much data that will form the results of the method. Thus, the method is not error-proof of input errors, and any outputs are linked to the input’s quality of information. Such errors could be mitigated by constraining the freedom of the practitioner's input and selecting practitioners who are well-informed and educated in the proposed method while simultaneously having the method tailored to their needs.

The decision model used in this work has been developed based on the existing literature, feedback from the industry, and case studies. While it encompasses the fundamental aspects of decision-making processes, not all the decision factors and sub-factors may be equally applicable across all sectors. Hence, a limitation in the caption of the decision variables emerges from generalising the model enough to be applicable across multiple sectors. Overcoming this hurdle involves a more customized approach, adapting the model to meet individual industry requirements. This customization can be achieved by identifying key decision variables unique to each sector, creating specialized mini-models (such as a quality testing model, a warranty application model etc.) that consider solution constraints and specific decision factors, and delineating the scope of the method's applicability to ensure it addresses the particularities of each industry's circumstances. This approach has been followed in Chapter 5, which includes the case study A- luminaire, where specific models have been developed for higher applicability of the method.

3.12 Chapter Summary

This chapter presents a novel method to support decision-making in the sustainable implementation and advancement of the Circular Economy, specifically by evaluating and ranking End-of-Life (EoL) options for returned products. The method is meticulously deconstructed into its fundamental components, with a detailed depiction of the tools employed at each phase. The decision model was also introduced alongside all the decision clusters, factors, sub-factors, and the solutions' constraints. Visual Promethee, a software tool for applying the MCDA Promethee method, was demonstrated, and its main advantage for utilization in this work was demonstrated. Finally, tools such as the GAIA and walking weights were introduced to visualize the method's results. The next chapter discusses the method's verification, validation, and qualification.

4 Method Evaluation

4.1 Introduction to chapter

This chapter presents this work's approach to evaluate the proposed method. The steps of the evaluation process, its qualification, verification, and validation will be thoroughly described, and the supported work will be presented in this chapter.

4.2 Introduction to the method evaluation approach

One of the critical tasks for providing relevant information to the decision-maker and assisting them in making an informed decision is assessing the proposed method to ensure its derived results and quality. According to the literature, this task is captured through the evaluation, which aims to assess "*the effectiveness and the validity of the research results*" (Duffy & O'Donnell, 1999). Evaluation requires a set of criteria which will be used to evaluate the proposed method. In this research, those are *utility*, *accuracy* and *applicability*. Those criteria are related to three key areas of great interest in academia: *qualification*, *verification* and *validation*. Focused on those three terms, Schlesinger (1979) and Thacker (2004) identified them as key phases in assessing the accuracy of a proposed method.

The work developed in this thesis adopts a hybrid approach, integrating methodologies from multiple sources. It incorporates the key stages of qualification, verification, and validation as outlined by Schlesinger (1979) while also adopting the assessment criteria for each stage described by Oberkampf and Roy (2010). This approach combines the strengths of both frameworks, ensuring a comprehensive and rigorous evaluation of the method developed. Schematically, the adopted method evaluation approach is described in Figure 4.1:

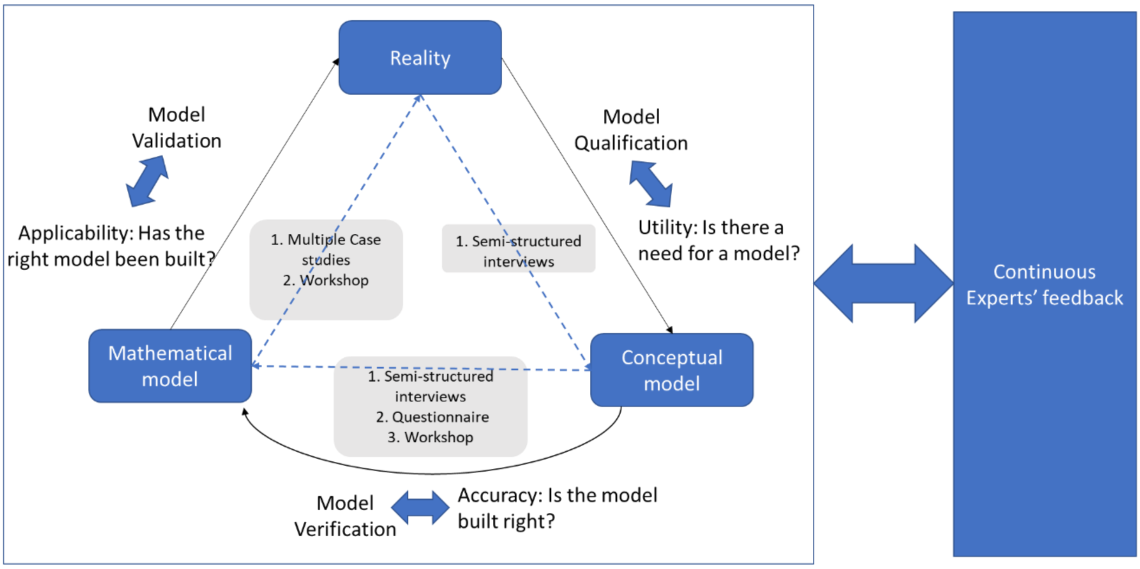


Figure 4.1: Method evaluation framework (based on Oberkampf and Roy, 2010)

The aim is to evaluate the proposed method to support decisions during the EoL of products. The initial key element is *reality,* which leads to the *conceptual model* element. Through the *model qualification,* the criterion of *utility* must be met during this transition between those elements. In other words, the answer to whether there is a need for the proposed model must be covered during the qualification stage. Model qualification is defined as '*the 'determination of the adequacy of the conceptual model to provide an acceptable level of agreement for the domain of intended application'* (Schlesinger et al., 1979). This has been expressed more simply by Hay (2015) as the '*usefulness and fitness for purpose*' of a model and represents the criterion of utility. In this thesis, qualification is evaluated through feedback semi-structured interviews with industry experts and continuous feedback from experts from the companies that provided products for the case studies. The expert's feedback is constant and continuous across all three key stages of the method evaluation process.

The next transition is from the *conceptual model* to the *mathematical model* element. During this, the stage of *model verification* is defined. Verification should answer whether the proposed model is built right (Karkasinas & Rentizelas, 2019), thus satisfying the *accuracy* criterion. A more thorough definition for verification is expressed as: '*Verification: confirmation, through the provision of objective evidence, that specified requirements have been fulfilled'* (ISO, 2005). Similarly, accuracy is defined as '*the quality or state of being correct or precise'* (Moore, 2023). In this thesis, verification is obtained through expert feedback both from a workshop and during the model development, a questionnaire and semi-structured interviews.

Finally, the last transition is between the *mathematical model* and *reality,* completing the closed loop in Figure 4.1. The validation stage is applied during this transition, and the proposed model's applicability is assessed. In the validation of a model, the question that must be answered is *if, indeed, the right model has been built* (Karkasinas & Rentizelas, 2019). Validation is defined as: '*Validation: confirmation, through the provision of objective evidence, that the requirements for specific intended use or application have been fulfilled'* (ISO, 2005). In this stage, the criterion of *applicability* must be satisfied, which is also defined as the relevance and appropriateness of the intended use (Usepa, 2009). This thesis fulfils the applicability criterion by implementing multiple case studies and a focused workshop with industry experts. The whole method was presented during this workshop, and the experts provided their feedback and essential input regarding the method's applicability and the right selection of elements.

4.3 Method Qualification, Verification and Validation

This section builds upon the previously discussed qualification, verification, and validation definitions. It presents in-depth the assessment activities of qualification, verification and validation, the criterion for each activity and the adopted actions for each stage. During the development of the proposed method, the researcher had continuous communication and feedback from the companies providing products for the case studies; thus, their feedback has been part of each of the stages of the method's evaluation. Table 4.1 summarises this information, and each assessment action is discussed in the following paragraphs.

Table 4.1: Qualification, verification and validation of the proposed method

Assessment	Criterion	Action
Qualification	Utility of the model	Semi-structured interviews Experts' feedback
Verification	Accuracy of the model	Semi-structured interviews Questionnaire Experts' feedback Workshop with industry experts
Validation	Applicability of the model	Multiple Case studies Workshop with industry experts Experts' feedback

4.3.1 Method Qualification

Method qualification covers the transition from reality to the conceptual stage. Through this transition, the criterion of utility for the proposed method must be assessed. Initially, the conceptual development of the proposed method was based on the review of the relevant academic literature. Since the academic perspective had been captured, the next step was to gain insights from the industry to acquire the much-needed industrial approach as well. One of the proposed method's key aspirations is to use sector-agnostic across multiple industries and be tailored for supporting decision-making in the EoL of many products to shed light on more complicated EoL pathways, such as resource-intensive remanufacturing.

Industry experts had to be advised to gain an industrial perspective on how useful the proposed method is for supporting decision-makers in the EoL of various products. Thus, semi-structured interviews were held with industry experts to gain their insights on the proposed method and its various expansions. In addition to the semi-structured interviews, expert feedback was also obtained for the qualification of the proposed method. Semi-structured interviews are more flexible than structured interviews (similar to oral surveys) and have a more general guide to be followed. At the same time, the interviewer allows the conversation to flow more naturally, adjusting the sequence of the questions and interacting with the participant's responses (Wildemuth, 2016). Complementary to the interviews with experts, qualification of the proposed method was additionally obtained through continuous feedback from the collaborating companies that provided the case studies presented in Chapters 5 and 6. Although their feedback was constant through all three evaluation stages for the proposed method, different information was captured in each step, ensuring that the relevant evaluation criterion was met. Specifically, during the method’s qualification stage, the experts consulted and provided feedback on the proposed method's scope, characteristics, and intended function, aiming to maximise its utility. Through iterations, constant communication through progress meetings and reviews, their feedback was integrated into the proposed method. The characteristics of each participant are presented in Table 4.2, while participants who were members of the companies that became the case studies are marked with an asterisk (*).

Table 4.2: Characteristics of the Interview Participants

Interview	**Participant**	**Position**	**Years of experience in the sector**	**Years of experience in the company**	**Company**
Interview 1 (I1)	Participant 1 (P1)	General Manager – Refurbishment Engineering	28 years	5 years	C1
Interview 2 (I2)	Participant 2 (P2)	Head of Global ITAD, Circular Economy & Sustainability	7 years	7 years	C2

***Interview 3 (I3)**	*Participant 3 (P3)	Lead Remanufacture Engineer	3 years	3 years	C3
***Interview 3 (I3)**	*Participant 4 (P4)	Remanufacture Engineer	3 years	3 years	C3
***Interview 4 (I4)**	*Participant 5 (P5)	Graduate Quality Engineer	3 years	3 years	C4
***Interview 4 (I4)**	*Participant 6 (P6)	Quality Manager	7 years	7 years	C4

The first participant's job title is '*General Manager – Refurbishment Engineering',* and they have spent 28 years in the wider remanufacturing industry, primarily expressed through maintenance and reconditioning. In the last five years of their career, participant 1 (P1), as they will be referred to, has focused on developing a circular economy business model around the offshore wind industry. The company (referred to as C1 from now on) that employs P1 is solely based on remanufacturing activities; thus, EoL management is crucial for the company, making P1 a perfect candidate for assessing the utility of the proposed method. The role of P1 involves working with large utilities and service companies in the wind industries to develop solutions that cut waste by finding routes back to the market for used components. According to P1, each product development requires creating a business case, R&D, the development of a refurbishment process, testing, packaging, and marketing to create a sustainable and scalable solution to service the sector. In addition, their main role in C1, P1, had worked as an ambassador for promoting a circular economy across Scotland through a key organisation based in Glasgow.

The second participant, now referred to as (P2), is the Group Sustainability Director for a computing hardware remanufacturer firm, referred to as C2, from now on. C2, which they have been employed for the past seven years, is one of the first laptop remanufacturers certified by the British Standards Institution (BSI). Thus, the participant has gained great experience in remanufacturing and EoL product management as well as implementing standards in a newly developed market. C2 has managed to establish their position in the remanufactured laptops market. Although this journey has been successful, it provided P2 with first-hand experience of the challenges of each related aspect of remanufacturing, such as EoL product management, core acquisition, current regulations, trends and future opportunities in the field. Additionally, P2, through their previous role in a standards committee for almost six years, is an expert on process standardisation and conveying sustainable design methodologies and practices to industry standards.

The third interview, referred to as (I3) in Table 4.2, had two participants, P3 and P4, respectively. The third participant, now referred to as P3, is the Lead Remanufacture Engineer for one of the companies that provided a product to build a case study for the proposed method. P3 was tasked with developing the company's (C3) remanufacture process, including procurement of used products, design engineering, and compliance with relevant standards and legislation. Their experience with a wide variety of tasks related to the EoL field of electrical equipment and the fast application of newly developed methods into practice in a real industrial environment provided this research with key feedback on each step. Additionally, P3 had the chance to consult the company's director, who, with more than 20 years of experience, also provided key input to the proposed method. P4 has a supportive role as a remanufacture engineer to the lead. Their task was similar to P3 but from a more operational aspect.

The fourth interview, referred to as (I4) in Table 4.2, had two participants, P5 and P6, respectively. P5 has been employed as a Graduate Quality Engineer and has been with the company (C4) for the past three years, while P6 is the quality manager of the same company and has been in that position for the past seven years. C4 provided the product for the second case study for the proposed method, as described in Chapter 6. Similarly to C3, which supported the development of the first case study, C4 supported the development of the proposed method during its methodological development and application stages.

The interviews in this study aimed to capture the industry's perspective on supporting decision-making for EoL, with remanufacturing being a viable pathway. The feedback provided through the interviews was used for the qualification of the proposed method, thus addressing its utility from an industrial point of view.

The first objective of the interview was to capture how the participant's company implements a CEBM that applies remanufacturing as a viable solution. During this semi-structured discussion, the participants provided information about current company practices and how their company's CEBM is applied. The discussion led to the interview's next two objectives, which focused on capturing the key points of application of their CEBM and the key decision factors that impact the current practices. Finally, the last objective was to identify any future trends in the industry. After those questions had been adequately answered, a short description of the proposed method was provided, and the participants were able to give feedback regarding its usefulness. All the feedback provided by the participants was considered during the development of the proposed method.

The companies that provided the products for the two case studies provided feedback across collaboration through continuous communication in multiple forms, emails, meetings, on-site visits, etc. Their feedback is partly captured in the form of a semi-structured interview as well, although the continuous nature of the collaboration is also defined as *expert feedback,* as illustrated in Figure 4.1 through a rectangular that represents the constant support across all stages of the method's evaluation.

The conceptual method's qualification is discussed in greater detail in the following paragraphs, with the main interview objectives analysed in depth. Moreover, the findings from the interviews, the expert's feedback, and their implications on the proposed method are also discussed.

4.3.1.1 Current company practice description

The company's current practices and the basic implementation principles of CEBM were discussed. For the participants from I3 and I4, who belonged to the companies C3 and C4, which provided products for the case studies of the proposed method, their CEBM has been thoroughly described in sections 5.1.2 and 6.1.2, respectively. P1 from C1, an independent remanufacturer, claimed that the low and unpredictable volume of returned cores is what defines their production rates. P2 from C2, another independent remanufacturer that sometimes acts as a contracted remanufacturer, said that their core procurement model is based on bulk buys and a small variety of model acceptance. Additionally, they have semi-circular clients, providing C2 with a more predictable demand for their B2B services. Thus, establishing circular suppliers and clients is only one way to stabilise the supply of returned cores, while the other one focuses on the product's suitability. This conclusion has also been drawn through the P3 and P4 experts' feedback, where they highlighted the importance of the product's design being suitable for applying a CEBM model. Thus, industrial feedback has also identified and validated the need for a method that would provide the decision maker information on how suitable a product is for the application of a CEBM. In addition to the points raised before, another interesting aspect was raised by all participants as well. They all stated that their main competition is the new products and that the remanufactured ones have to be able to present a much more attractive case to the customer to have a market advantage. The need for a method that provides comparisons in more than one dimension, such as financial and environmental, of the remanufactured product with the identical new one has also been identified.

Based on the findings from the interviews and the expert's feedback above, it becomes evident that there is a lack of a method that holistically supports EoL decision-making for companies where remanufacturing is a viable EoL pathway. Additionally, it was highlighted that for the proposed method to be as useful as possible, it should be able to provide a direct comparison between an identical new product and a remanufactured one to showcase the remanufactured product's benefits in more than one dimension. As a result, the proposed method fully adopts those suggestions. Through the CEDA graph, a *clear indication of the product's design suitability is provided to the practitioner. Moreover, by incorporating other key decision factors in the decision model that will be discussed later, the proposed method offers holistic support to the EoL decision-maker.*

4.3.1.2 Key points of application of a CEBM and obstacles identification

The next objective of the semi-structured interviews was to identify the key points for applying a CEBM. This objective, acting as a follow-up to the previous one, sheds more light on the crucial elements of a proposed method for wider industry adoption and utilisation. As identified in the literature, one of the key issues P1 mentioned is the uncertainty related to the reverse logistics of used cores, which would provide a stable supply. As is, their company C1 is based upon unscheduled failures, which have a high degree of unpredictability for supplying returned products. P1 then summed up the main benefits of C1's CEBM, including the short lead times for the replacement components and its competitive prices compared to new components. Thus, the importance of a proposed method that estimates those two elements, the price (profitability) and the lead time, has been identified. P2 agreed that profitability is the main driver from both a remanufacturer's and a client's perspective. P2 identified that the reliability of the seller and the trust in remanufactured goods play a vital role. P3 and P4 have also highlighted the need for wide market acceptance of remanufactured goods and the role of quality in achieving this. Conversely, Participants P5 and P6, whose companies operate in a highly regulated industry, perceive their products' quality as stable. This perception is attributed to the necessity of meeting stringent industry regulations and ensuring consistent product standards.

As a result, from the interviews and the expert's feedback, it became clear that the financial criteria are of key importance but not the only ones. Other key points, such as a steady supply of cores, short lead time, quality of the final *products and market acceptance, have also been highlighted. Thus, the industry also validated the multidimensional nature of EoL decision-making. The proposed work considers all of those key areas of interest since the analysis provides an estimation of the costs and the profits as well as the calculated lead time per batch and per product based on the eDiM methodology and the scenarios identification. Additionally, the quality of the cores is captured through the pre-screening process, and the quality of the delivered product is established through the fully flexible guarantee and lifespan process. The lead time was calculated using the well-established eDiM method to calculate the time needed to remanufacture the average product of a specific returned batch.*

Furthermore, those key areas are not considered separately; instead, they are part of a method that provides EoL decision support in a holistic, multidimensional manner, capturing economic, environmental, social and technical data. However, the proposed method does not include an analysis of the reverse logistics or optimisation of the stabilisation of it. It captures market demand through the practitioner's predictions and complies with the input of the rest of the decision factors. Identifying and adopting those key points of application of CEBM through the industrial semi-structured interviews and the expert's feedback have improved the proposed method's utility since it responds to the industry's needs.

4.3.1.3 Key decision factors impacting decision-making in EoL

The next objective of the semi-structured interviews concentrated on identifying the key factors that impact decision-making in EoL. P1, based on the remanufacturing practices of C1, mentioned that three of the main aspects are considered the most: traceability, in-house experience, and standards to ensure the quality of the final product. Similarly to P1, P2 also referred to the importance of traceability through documentation. Moreover, P2 mentioned that C2 had developed an in-house remanufacturing index that aims to identify the remanufacturability of a product. The main elements of C2's index are the documentation, the disassembly easiness, the availability of spare parts, their price and some other product-specific aspects which were not revealed. Finally, P1 claimed that some of the core's components are of greater significance than others due to their functionality or value; thus, they play a much more critical role in remanufacturing the product.

Feedback from the experts also highlighted the need to identify the key components of the product. Furthermore, their feedback on the same objective revealed great alignment with the findings of the interviews. More specifically, they also underpinned the importance of considering multiple aspects in a multidimensional decision-support tool. The usage of an index to express the product's suitability has also been emphasized. The aspects discussed by the experts cover the ones mentioned in the interviews, including market acceptance, environmental impact, and obsolescence of the product or the technology.

As a result, based on the findings of the interviews and the continuous expert feedback, it became evident that EoL decision support is not a single-dimensional problem. On the contrary, many aspects should be covered for a proposed method to be useful in the industry. The proposed method addressed all the areas mentioned in the interview participants' and experts' feedback.
Transparency of the remanufacturing decision-making process is crucial for achieving good process traceability. The proposed method provides plenty of information related to the product and its key components. From a structural point of view, the HALG and eDiM provide a traceable and well-documented caption of the disassembly process. Additionally, through the caption of the practitioner's input in the decision method, supplementary information is obtained in key areas, such as guarantee, legislation, obsolescence, product materials, remanufacturability and profitability for the returned product. The caption of the information provides a fully transparent and traceable decision process that can provide the decision maker's impactful support.

Moreover, in the proposed method, two of the parameters captured through the practitioner's input are the functionality constraints factor and the difficulty factor. Those two encapsulate the feedback from the P1 and are translated into a feature of the proposed method.

The quality of the cores is captured through the pre-screening process. Additionally, the quality of the company's service towards the customer is captured through the guarantee process. Thus, the proposed method addresses quality in both cases, as driven by the findings from the interviews and the expert's feedback.

Finally, the proposed method was built based on the feedback that some components are of much greater importance for EoL decision-making. The proposed method addresses this issue by initially identifying the key components of each product. Then, remanufacturing scenarios are rooted in alternations of the key component numbers that will need replacement to provide in-depth analysis to support the EoL decision maker.

4.3.1.4 Identification of future trends in EoL decision-making

The final objective of the semi-structured interviews was to identify future trends in EoL decision-making. P2, when the proposed method was described to them, showed great interest in the multicriteria decision-making method that can compile multiple decision aspects together and provide support to the practitioner. Additionally, the fact that their company of employment, C2, has already developed a remanufacturing index highlighted the industry acceptance of such an index. When P2 was shown the CEDA graph, a visual index of the product's suitability for remanufacturing that the researcher developed, they directly highlighted the index's value for identifying the correlation of the environmental impact and remanufacturing scenarios. Then, P2 claimed that the constantly added environmental restrictions and new regulations would provide a much more fertile ground for remanufacturing. In that case, the need to quantify the environmental impact of remanufactured goods will only get more outstanding. P1 similarly noticed that they are aware of a *'gradual transition towards CE'*.

Feedback from the experts highlighted the need for environmental quantification of the remanufacturing processes but from a customer's perspective since their B2B clients want to limit their carbon footprint drastically. Although they have also noticed the wider application of CEBM across their industries, they marked that volatile regulations, lack of government incentives for further development of those models, tight competition, and unpredictable market acceptance result in remanufacturing being considered 'too risky'. This risk associated with remanufacturing may limit its growth and application.

Based on the findings from the interviews and the discussions with the experts, it became clear that in order for the proposed method to be utilised in the future, it should be able to de-risk remanufacturing for the practitioners. The proposed method builds its own product's 'suitability for remanufacturability' index through the CEDA graph. Moreover, integrating the multiple decision factors into one method holistically supports the decision maker, providing a fully ranking solution of the available EoL pathways, thus providing insights on the impact of the application of each available EoL pathway.

Additionally, companies' growing interest in exploring CEBM once again highlights the need for tools to support the smooth transition from linear to circular BM and aid in the initial engagement with remanufacturing processes. Such a finding only strengthens the case for the proposed method to satisfy the utility criterion since industry experts have also highlighted the need.

The semi-structured interviews and the continuous expert feedback through continuous communication have led to the key findings of the qualification process described above. The experts provided feedback and insights on how well the proposed method represents reality and how its key elements are aligned with the industry's needs. This feedback was used to assess the method's utility in real-life industrial applications.

4.3.2 *Method Verification*

As illustrated in Figure 4.1, verification bridges the gap during the transition from the conceptual model to the mathematical model development. Verification aims to assess the accuracy of the proposed method by evaluating the model's parameters; thus, it seeks to answer the question of whether the proposed model is built right (Karkasinas & Rentizselas, 2019).

The proposed method consists of multiple elements verified through the same semi-structured interviews discussed during the qualification stage, through a questionnaire sent to the participants regarding the decision factors impacting EoL decision making and through the continuous feedback of the experts that provided the products for the case studies. Additionally, during the workshop with people from the industry, feedback was collected based on the question of how correct the selection of the elements of the proposed method was.

The tools selected to be elements of the final proposed method, such as the HALG, LCA, eDiM, and the Visual Promethee, are all well-established across academia and the industry and have many applications. Those tools' refinement to adequately describe the reality when applied to the proposed method has been assessed by the collaborating companies that provided their products for the case studies described in Chapters 5 and 6.

In each of them, errors occurred during the verification process of the proposed method that required solving. During the HALG representation, it was imperative to accurately identify the product's hierarchical levels and correctly group the components. Repeating the process and incorporating expert feedback proved to be effective in avoiding errors in this area. The eDiM is a well-established metric for estimating the ease of disassembly and standardising the time needed to perform specific tasks. Through actual disassembly and reassembly of the product, the estimations of eDiM were verified, and for tasks that slightly differed in the time needed, the sources of the difference were identified, and then the times were adjusted accordingly.

In the LCA, potential errors often arose from limited product manufacturing and supply chain information data access. To mitigate this, average data from established databases like Ecoinvent 3.6 were used, complemented by expert feedback on manufacturing processes and materials. Additionally, the financial equations were refined through continuous expert feedback and step-by-step validation of the results. Consequently, all intermediate outputs of these elements were meticulously checked to ensure their reasonableness.

During the verification process of the proposed method, it was critical to identify and rectify any errors in the initial estimations regarding decision factors, their significance, and other necessary elements of the assessment. The method relied on expert feedback based on the original conceptual model’s assumptions about the selected decision fact to address these issues.

Additionally, various approaches were adopted to ensure accuracy and avoid errors. For instance, parts of the model were applied with numerical examples to verify whether the intermediate outputs were reasonable. This approach helped in identifying any discrepancies early on. In cases where an error was detected, the mathematical model and its components were presented to supervisors and external experts for review and correction. This collaborative approach provided additional scrutiny and expertise, ensuring the method's robustness.

The initial construction of the conceptual model involved selecting key decision factors from existing literature, relevant research, and a tool developed by the Scottish Institute for Remanufacturing at the University of Strathclyde’s Department of Design, Manufacturing & Engineering Management (DMEM). This tool, known as The Remanufacturing Competency Checklist, was designed to evaluate a company's readiness for remanufacturing (D. Stewart & Balfour, 2021).

For the correct mathematical model to be built, insights directly from the industry were needed to verify this selection. For this objective, a questionnaire was sent to all the participants listed in Table 4.2. Their responses to the questionnaire were used to verify the key decision factors that are the core of the proposed method’s decision-making model and to select the exact decision factors from a wider set of factors that were originally included in the conceptual model. The questionnaire can be found in Appendix A.

Additionally, the selected elements of the proposed method were critically assessed by industrial participants during the workshop. After a detailed presentation of the proposed method, participants had to answer whether the right elements had been selected for the proposed method. The average rating was 8.33 out of 10, as seen in Figure 4.2, with one participant commenting '*too many variety'* (Figure 4.3). Another participant commented, '*I would not remove or add any, as all elements in decision making, I feel are included*', as seen in Figure 4.3.

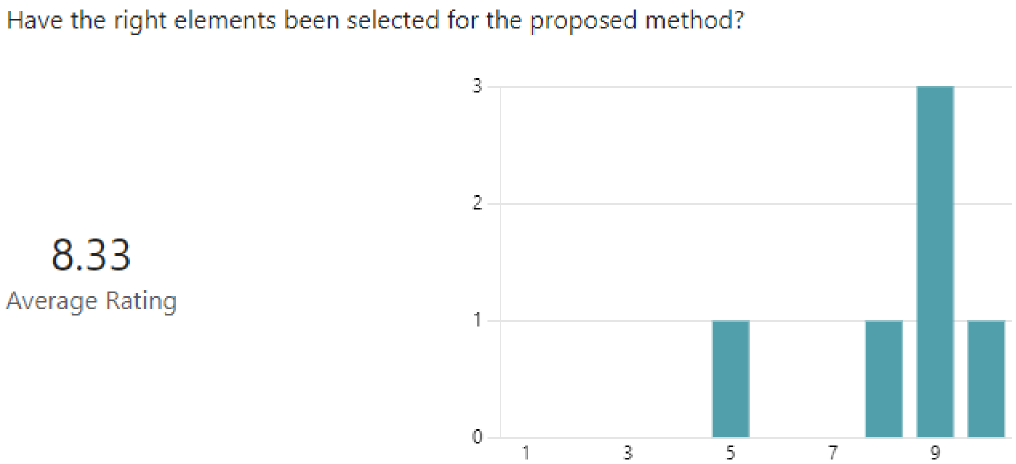


Figure 4.2: Scoring the selection of elements for the proposed method

14. If you think the right elements have not been selected for the proposed method, which would you add or remove?

2 Responses

ID ↑	Name	Responses
1	anonymous	i would not remove or add any, as all elements in decision making I feel are included
2	anonymous	too many variety

Figure 4.3: Comment on the selection of elements of the proposed method

One of the key findings from the semi-structured interviews and the continuous expert feedback is that there cannot possibly be a '*one solution fits them all*' approach in EoL decision-making. The variations in the types of remanufacturers, such as Original Equipment Remanufacturers (OERs), Contracted Remanufacturers (CRs), and

Independent Remanufacturers (IRs), and the difference between the products they remanufacture, require solutions that can be tailored to their specific needs. Thus, the proposed method has to be as flexible as possible while keeping all the key aspects of remanufacturing at the core of the method. The proposed method balances those two opposites by providing the decision maker or the practitioner of the method the ability to capture their input regarding the product's structure, the economic aspects of the EoL pathways, their environmental impact and multiple other decision factors that may or may not act as solutions constraints, depending on the selection of the threshold values from the practitioner.

4.3.3 Method Validation

Method validation is the last step for evaluating a method and closes the loop by linking the mathematical models developed back with reality, as illustrated in Figure 4.1. In simple terms, method validation answers the question of whether the right model has been built by addressing the applicability and effectiveness of the method as a whole. The proposed work has been validated through multiple case studies as well as through a workshop where the whole method was presented, and people from the industry provided their feedback.

4.3.3.1 Validation workshop

During the workshop, six industry participants provided feedback when presented with the proposed method. Four of the six participants stated that they are not remanufacturing yet, but they plan to do so in the future. The other two participants were contracted remanufacturers and independent manufacturers, with 50% and 5% of their total annual turnover stemming from remanufacturing. Initially, the participants were asked to score the key decision factors based on their importance per decision cluster. This exercise aimed to identify any missing decision factors and create a core of decision factors for the method. The next stage was for the participants to rate the effectiveness and applicability of the method.

As seen in Figure 4.4, the social factors were weighted from *not important* to *critical* based on the participants' inputs. The decision factor with the lowest score was the *harmonisation with the local society needs,* while the one that consistently scored high in importance was *customer accessibility to high-quality products*. This aligns with the obstacle identified previously, which is that customers of remanufactured goods don't perceive the value of the products.

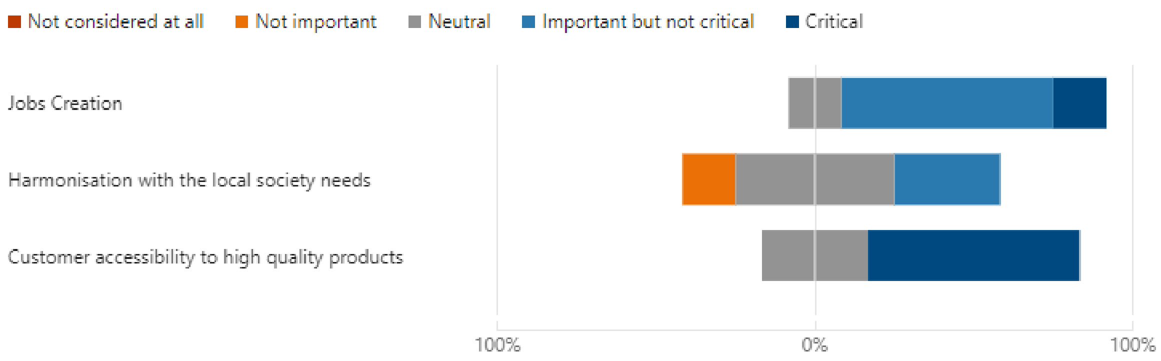


Figure 4.4: Social decision factors scoring

In Figure 4.5, the importance of the environmental factors is illustrated. In this case, there seems to be consensus on the criticality of those factors, with carbon emissions having the highest score. Such a result fully supports the proposed method's environmental impact quantification through an LCA hybrid approach that expresses its results in carbon dioxide equivalent (CO_2 eq).

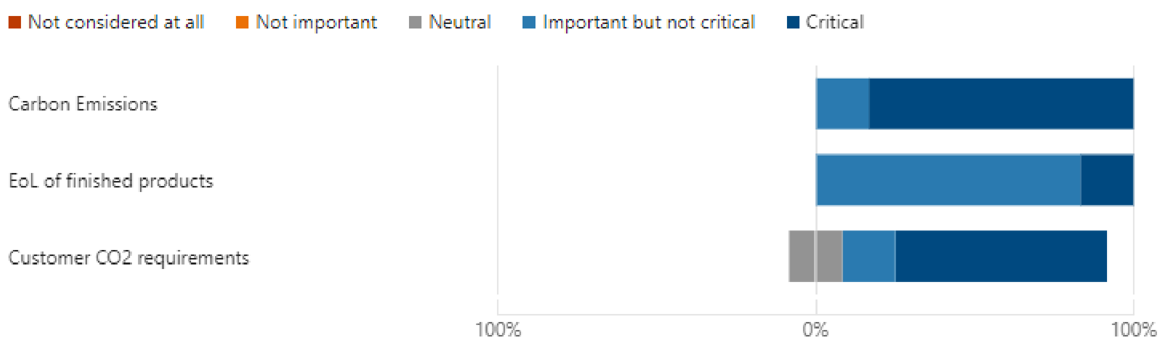


Figure 4.5: Environmental decision factors scoring

The financial decision factors have all been highly important, as seen in Figure 4.6. This may be the reason why previous research in the literature was mainly focused on the financial aspects of EoL decision-making.

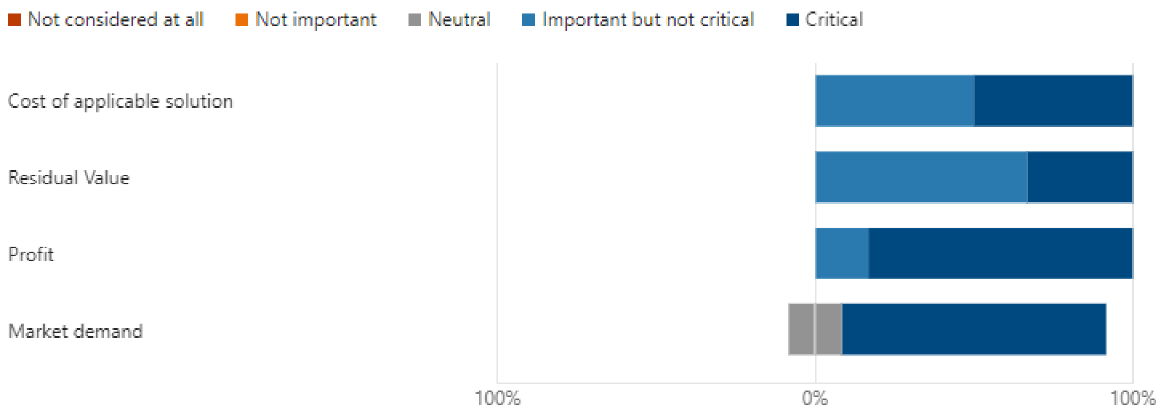


Figure 4.6: Financial decision factors scoring

Finally, in Figure 4.7, the technical decision factors are presented. The factors are rated all of great importance, except for *market obsolescence*, which has a more neutral score. Since the number of participants was relatively small, there are no deterministic conclusions to be drawn. Nevertheless, after further discussion with the participants, it was concluded that the nature of the remanufactured good, a high-value tooling component, and its resistance to any type of consumer trend were the reasons for this difference in importance rating.

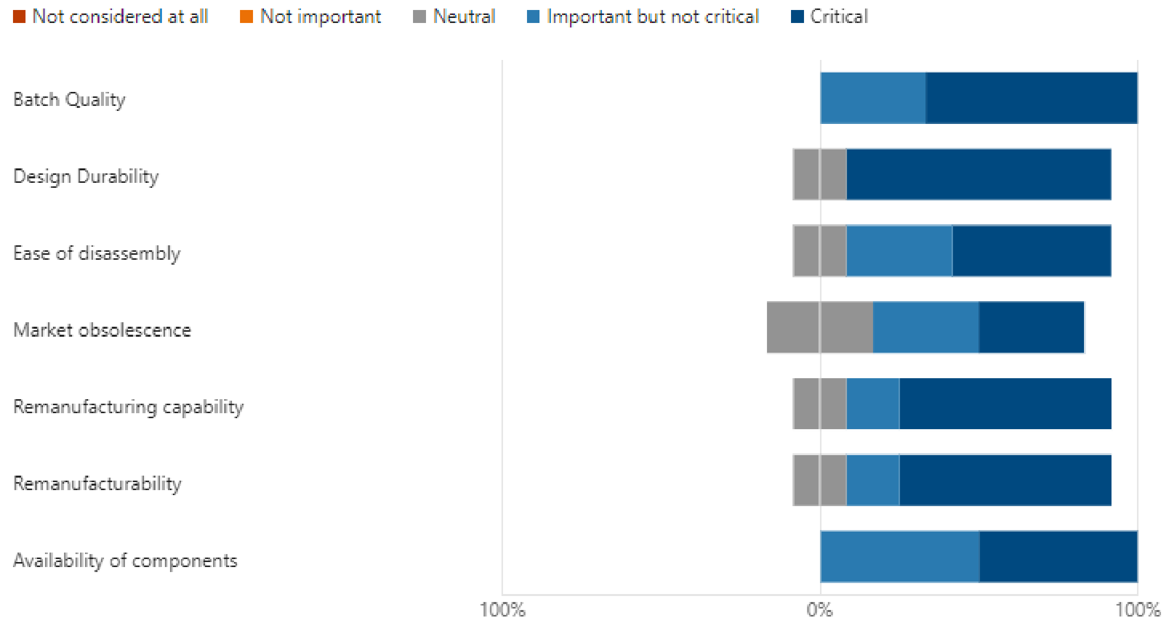


Figure 4.7: Technical decision factors scoring

As previously mentioned, the process of scoring the selected decision factors was designed to identify any overlooked factors and stimulate discussions that would provide feedback for the proposed method. This approach was instrumental in ensuring a comprehensive consideration of all relevant factors. The validation of the core decision factors was then achieved based on the inputs provided by the participants.

The next stage of the workshop focused on rating the applicability of the proposed model. Initially, as illustrated in Figure 4.8, the effectiveness of the proposed method to deliver EoL decision support was, on average, rated as 8.67/10. All the participants rated it very highly, with only one rating of 7 out of 10, adding that the method was ‘hard to follow’ as feedback on its effectiveness.

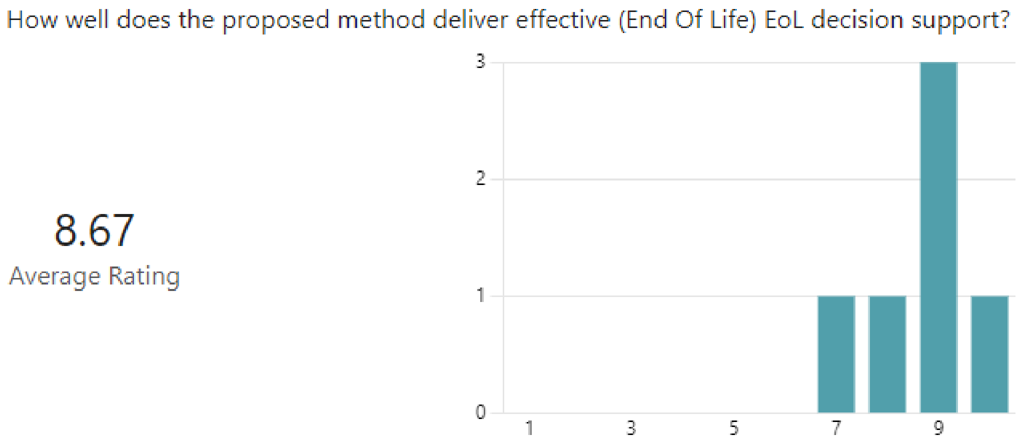


Figure 4.8: Effectiveness rate of the proposed method

The feedback expressing difficulty following the method’s presentation and application steps was further discussed with the participant. According to them, the multiple steps of the method and the different models used that were input to others created some confusion. The confusion was mostly related to how each of the models interacted with each other rather than the final results when implementing the method. However, it's important to note that this confusion was not a critical concern, as evidenced by the high effectiveness rating given by the participant. Despite these complexities, the participant rated the method's effectiveness as seven out of ten (7/10). This high rating underlines the method's overall effectiveness and validates its utility, as evidenced during the workshop, and suggests that the confusion did not significantly impede the understanding or application of the method.

The participants were also asked to rate the applicability of the proposed method. The average rating was equal to 8.17 out of 10, as seen in Figure 4.9. The lowest rating came from the same participant who found the method ‘*hard to follow’* and commented that the method would need ‘*expert support to implement*’.

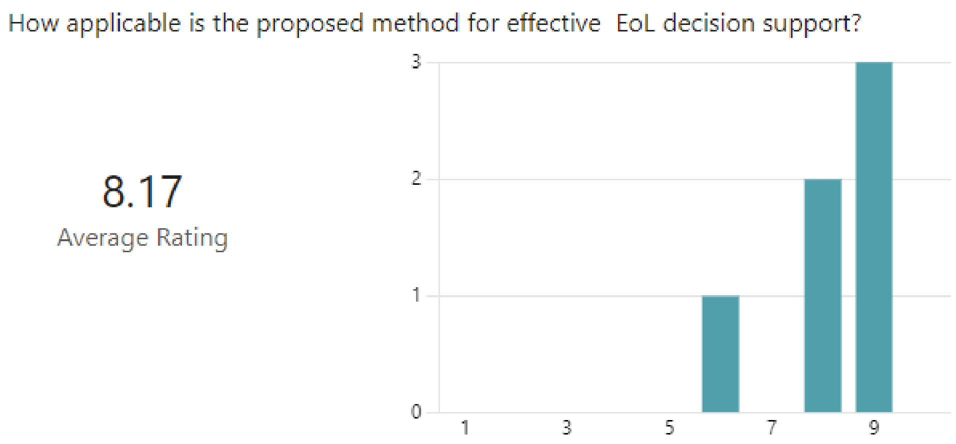


Figure 4.9: Applicability rate of the proposed method

Again, during further discussion of the method's results, **Error! Reference source not found.** was used to illustrate which method's steps would have to be repeated after the first application of the method and which not. This explanation provided some more confidence from the participants in the method's applicability. Nevertheless, their comment reveals a potential limitation of the proposed method. The method, in order to be applied correctly the first time, might require some external consultation if the practitioner is not very familiar with applying decision support tools and the various models of the method. Through the method's validation in the workshop, this limitation of the proposed method was identified, further providing insights into how the method can be applied to the industry and what the requirements would be in that case. Finally, the high scores in applicability and effectiveness for the proposed method provided the validation that it adequately describes reality and can be applied in an industrial environment.

4.3.3.2 Case studies

The proposed method was also validated through case studies of real industrial products, adopting academia's argument that one of the objectives of the case study is to explore and illustrate the applicability of a model or method in a specific real situation (Yin, 2009). Additionally, applying the proposed method to two different industries proved the sector-agnostic aspect of the method and provided generalised results that could fulfil the purpose of validation more effectively.

The selection of the two companies for the case studies was intentionally diverse, varying not only in their business sectors but also in their sizes. This diversity was crucial in designing the method to ensure its applicability across different industrial sectors and among companies with varying resource profiles. The first case study (CS1) involved a company from the consumer electronics manufacturing sector. According to the EU SME definition (*Commission Recommendation of 6 May 2003 Concerning the Definition of Micro, Small and Medium-Sized Enterprises*, 2003), this company is categorized as 'small'. The second case study (CS2) featured a company from the 'Machining' sector, which is also active in the Oil and Gas industry. Based on the same EU definitions, this company is classified as 'Medium' in size.

Through both of the case studies, experts from the companies continued to provide their feedback until the full development of the proposed method and the case study application. When both of the case studies were fully developed, a report was compiled to communicate the proposed method and its application to the company's relevant personnel. According to the CS1 expert, the method was highly applicable since it could be tailored to the multiple products their company considered implementing a 'product as service' business model. Through the proposed method, they could gain insights into which product's design is better designed for applying such a model. Additionally, by captioning the environmental impact per remanufactured product and limiting their supply chain emission, they could support their environmental goal of becoming a carbon-neutral company. Finally, the results of the method were compared to business practices, and the experts agreed on their validity.

A similar approach was followed for CS2, and a follow-up meeting was arranged. In this occasion, the push for the application of the proposed method came from a 'B2B' customer of the company. The customer also participated in the meeting. After being presented with the proposed method's CS2 data and results, both companies provided feedback on the method. The CS2 company was interested in using the method to develop a circular business model. Their customer also wanted to obtain a 'product as a service' contract. Based on their feedback, this method had a high degree of applicability in their industry and could potentially bridge the gap between decision-making that is based upon experience and decision-making that is based on well-informed practitioners with lots of support from data analysis decision-making tools.

4.4 Chapter Summary

This chapter presented the evaluation process for the proposed method. Three distinct evaluation phases have been identified: qualification, verification and validation of the method. In 4.3.1, the method’s qualification was described, and the semi-structured interviews were used to transition from reality based on the literature to a conceptual model that links those together. The model's utility has been achieved through this stage since the key parameters needed from the EoL decision support sector industry were identified. In sector 4.3.2, the verification process of the proposed method was described. The actions that supported the verification process were semi-structured interviews, a workshop with participants from the industry, and a questionnaire to capture key information regarding the decision factors, which would be part of the proposed method. All of these actions contributed to verifying the proposed method's different modules and correctly transitioning from a conceptual model to a mathematical representation. In section 4.3.3, the applicability of the proposed method was secured through the validation process. Through the workshop described before and two case studies, the method was fully applied, feedback from multiple participants was captured, the transition from a mathematical representation of the conceptual model back to reality was achieved and based on the results of the validation process, the proposed method managed to illustrate a high degree of industrial applicability and versatility successfully. Finally, throughout the whole method’s development process, there was continuous feedback from the CS experts from both companies that further supported the evaluation of the method.

5 Case Study A: Luminaire

In Chapter 5, the first case study of the proposed method is presented to illustrate the applicability of the proposed framework and identify the optimal configurations. The product of choice is a luminaire from the Electrical and Electronics Equipment (EEE) industry, specifically the lighting sector. In comparison with Chapter 3, where the proposed method was first introduced, this chapter will use real-life data, analyse them in a detailed step-by-step approach, and focus on the quantitative nature of the framework. After an overview of the case study in section 5.1, chapters 5.2 and 5.3 retrospectively contain the product characteristics and its structural analysis. In greater detail, chapter 5.4 includes the product's environmental assessment and 5.5 the CEDA analysis. Chapter 5.6 describes the decision-making process, the practitioner’s input regarding the constraints of the solution, the weights of the decision factors and the solution ranking, which is the final output of the developed method. Chapter 5.7 discusses the application of the method in this case study, and section 5.8 summarises the chapter's content.

5.1 Case study overview

5.1.1 Company Introduction

EGG Lighting is a Scottish SME lighting company under the umbrella of TreeGreen Ltd, which provides developing, designing and consulting services in the lighting sector, a sub-section of the Electronic and Electrical Equipment (EEE) industry. The company's annual turnover is estimated at £1.2 million, and remanufacturing is responsible for less than 5% of the year 2020.

The company's mission is to provide lighting technology that is ‘*socially and environmentally responsible’*. Participating in this study aimed to gain knowledge from the academic perspective on how to implement the circular economy principles and which of their products are the most suitable for a circular model. The collaboration with the company was on close terms, providing a constant feedback loop to the researcher and validation for each of the method’s steps.

5.1.2 How the company operates

Figure 5.1 illustrates the 'as-is' operational business model of EGG lighting. Lighting products are manufactured from the suppliers, and EGG provides those products to the customer. After the product's end of life, the company is responsible for collecting the luminaires from the customer and transporting them to a recycling facility.

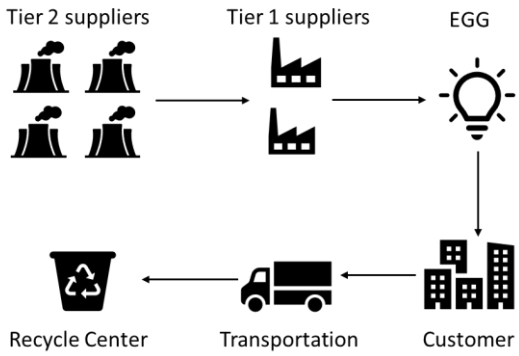


Figure 5.1: Linear business model

EGG, acknowledging the evolving landscape of the lighting industry, recognizes the need for more sustainable solutions beyond just recycling. Remanufacturing is considered the most sophisticated pathway in the circular economy (Ijomah, 2019), and it has seen widespread adoption in the automotive, technology, and aerospace industries. However, according to the company's experience, its application in the lighting sector remains limited. Given the significance of implementing a circular business model in the lighting industry, EGG has begun integrating it alongside its existing linear business model, as depicted in Figure 5.2.

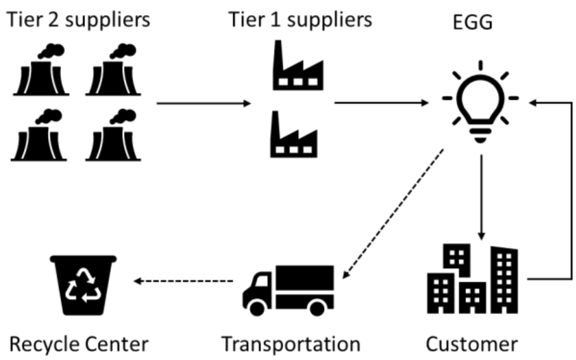


Figure 5.2: Circular Economy Business Model (CEBM)

The main difference with the linear business model is that the product is not directly transported to a recycling centre at the end of the product life. It is transported back to EGG's facilities, where the returned cores' conditions are evaluated, resulting in a percentage of them being reused or remanufactured. The rest of them are being sent to the recycling centre.

5.1.3 Case study assumptions

Figure 5.3 illustrates the remanufacturing process EGG is willing to implement. The flowchart demonstrates how the proposed method potentially provides decision support regarding whether the returned batch should proceed to the buyback scheme or be directly recycled.

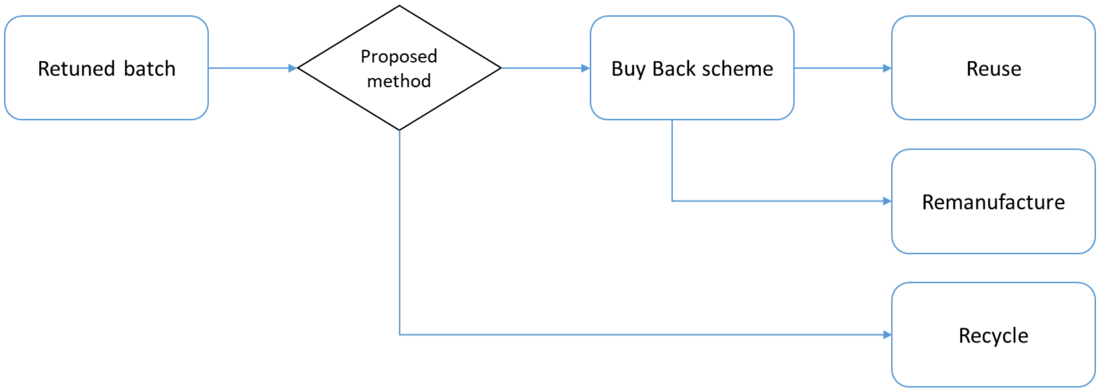


Figure 5.3: EGG remanufacturing process

In this case study, we consider a scenario where a customer of EGG possesses a total of 500 Strathclyde luminaires, which they are looking to replace. These luminaires have been in operation for the past five years. These assumptions were based on real-life data provided by the company. The following additional assumptions have been made:

- All the final products will be tested (100% testing).
- The products have all been used for the same amount of time.
- Section 3.5.1 describes all the assumptions regarding how the LCA was conducted when defining the scope, system boundaries, and functional unit.
- Only the selected key components are subject to replacement, as described in section 3.4.

- When no other data is available, the EoL value for each component is considered to be one-third of its value when new.
- Due to the international nature of the supply chain, all the prices are expressed in US dollars.
- The scrapping prices per material originate from experts (*Scrap Metal Prices*, n.d.) and the average values based on the year 2020 were selected after being converted to US dollars to kg (with a conversion rate of £1= $1.41).
- A used component is always replaced with a new, identical or similar one of equal financial value when new.
- A simplified approach has been adopted for materials that cannot be recycled due to the complexity and limited data on various waste streams and rates. In this case, the disposal cost is $0.10 per kilo for each kilogram of material disposed. This simplification helps manage the intricacies of accounting for multiple possible waste streams and their respective rates.
- The lighting product was manufactured and assembled in China, as well as its components and raw materials, as described in the assumptions of the case study; thus, no additional transportation has been calculated for each component. The environmental impact of transporting one component is considered very low due to its very low weight; thus, this assumption is considered reasonable and has no real impact on the LCA.
- Direct reuse includes only the costs of cleaning the diffuser, the bookplate and the inspection cost per unit, a fixed cost of $2.5 per unit (due to an average labour time of 7.5 minutes of inspection per unit).
- We consider an average transportation of 50km per trip to the customer. The vehicle we considered was a small lorry transport, Euro 0, 1, 2, 3, 4 mix, 7,5 t total weight, 3,3 t max payload.
- In the scenario of direct reuse, we consider two trips: the product recovery from the customer to the company's facilities and the trip to the new customer's facilities, and the distances are typical.
- The environmental impacts of recycling and landfilling the product have been calculated for the whole product and then distributed to its components based on their weights proportionally to the products.

- Each level of disassembly must be completed before moving on to the next level. This is a prerequisite for replacing any component at a subsequent level.
- The ‘Strathclyde’ luminaire components were also produced in the same country where the assembly takes place; thus, no additional transportation has been calculated for each component or the raw materials.
- For the LCA results analysis, only components that have a contribution of one per cent or more (≤1%) to the manufacturing environmental impact will be considered for the EoL study, as stated in ISO 14040, which defines that the key environmental issues arise when their contribution is greater than 1% (K.-M. Lee & Inaba, 2004).
- The energy consumption of the electric tools used in the dis- and re- assembly processes have been integrated into the final environmental impact of remanufacturing, while the cleaning and testing of the product are considered to have zero impact based on input from the company’s engineers.

5.2 Product Characteristics

The product selected for this case study is the ‘Strathclyde’ luminaire from the lighting catalogue for offices, schools and retail. Due to its low cost and high-efficiency characteristics, this is a widely used luminaire that is an ideal replacement for linear fluorescent luminaires in educational environments. Figure 5.4 introduces the product and some of its fundamental characteristics.

Figure 5.4: ‘Strathclyde’ luminaire description from the company’s catalogue

5.3 Structural analysis of the product

Since the practitioner has decided on which product they will apply the proposed method, the first step of application is to submit the data related to the structure of the product. These data are used for structural analysis of the product and result in the creation of the BOM, HALG and the calculation of the eDiM. Each tool is presented in the following sub-chapters for this specific case study.

5.3.1 Multi-level BOM

Section 3.2.1.1 describes the practitioner developing a multi-level BOM based on the product's components. Table 5.1 contains all the components of the Strathclyde luminaire and their weights, as seen below:

Table 5.1: Components of the luminaire

Component	weight (gr)	Key component?	Reason
Diffuser	710	YES	Long-life, high value
Bookplate	1497	YES	Long-life, high value
Driver*	208.5	YES	Efficiency, high value
Grommet	2	NO	No need to be replaced
End cap (2)	=38.25*2	YES	Long-life, high value
LED strip*(4)	=43.1*4	YES	Efficiency, high value
Packaging	350	NO	Limited value and longevity
Packaging Bag	2	NO	Limited value and longevity
Rail	422	NO	No need to be replaced

Standoff	3.5	NO	No need to be replaced
Terminal Block (housing)	3	NO	No need to be replaced
Terminal Block (metal)	6	NO	No need to be replaced
Wires	28	NO	Consumable
Bolts & nuts	17	NO	Consumable
Total weight (gr)	**3497.9**		

The driver and the LED strips are presented in the table with an asterisk (*)because they are assemblies and, thus, are not composed of a single material. Using the list of the components, the practitioner builds the multi-level BOM of the product, as illustrated in Figure 5.5. The creation of the multi-levelled BOM identified the assemblies and the components of the product and provided a foundation for the HALG.

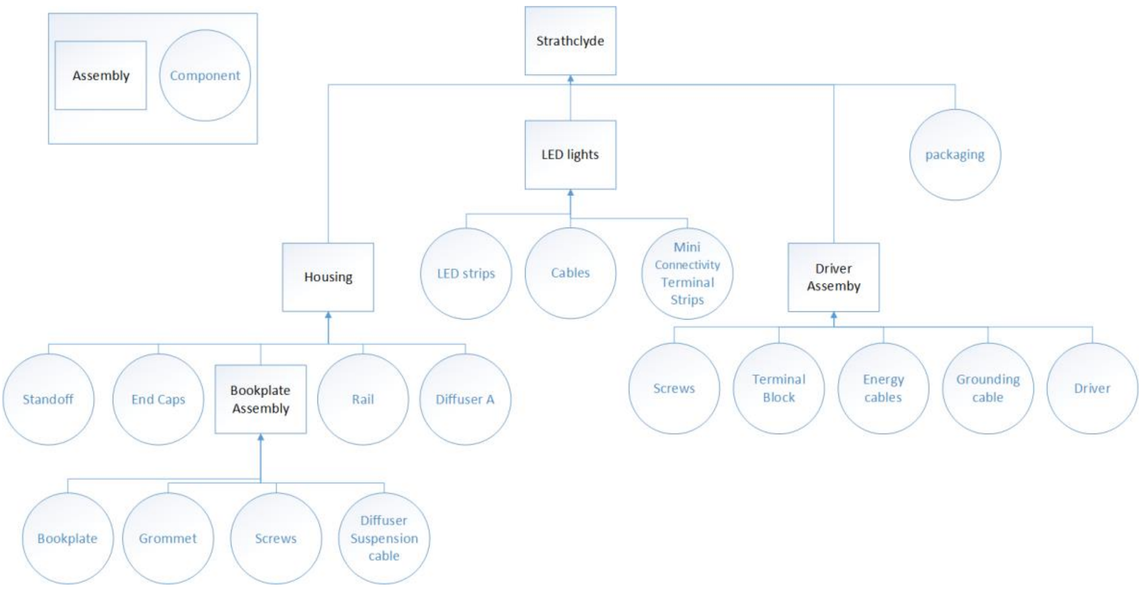


Figure 5.5: BOM of Strathclyde luminaire

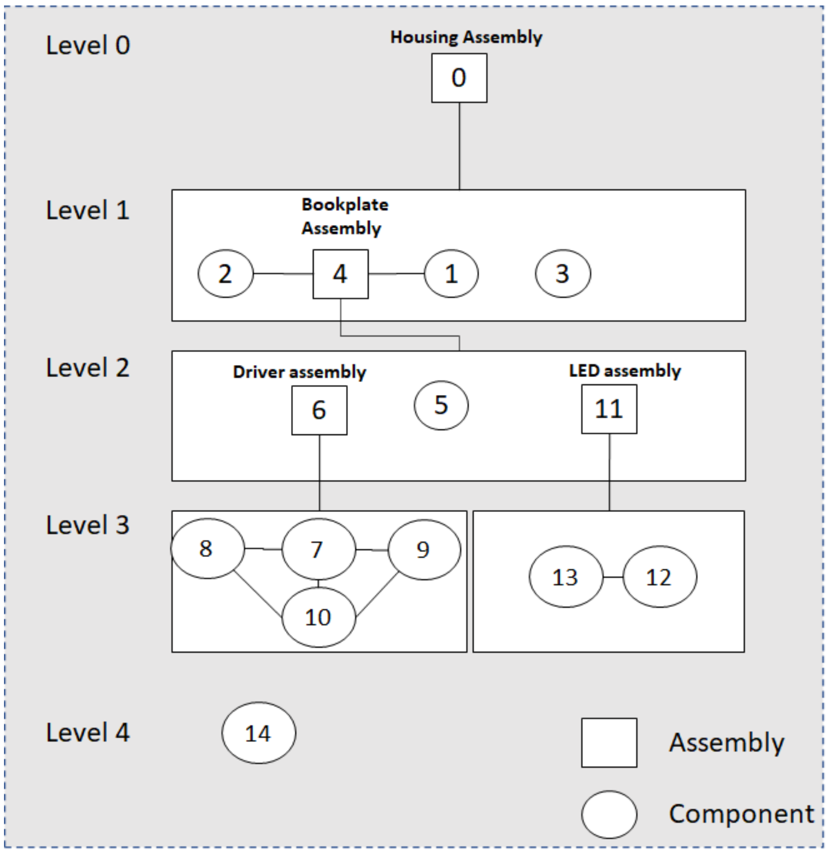
‘Strathclyde’ consists of four sub-assemblies and seventeen main components. After creating the BOM chart for the product, the practitioner is asked to identify the key components.

The next step is simplifying the product's structure by focusing on the key components and grouping the cables and bolts, which are part of every sub-assembly. Table 5.1 also contains the key components for the case study's assembly and the reason for selection.

The selected key components will be the base of analysis for the method since they are the ones considered for replacement during the remanufacturing process.

5.3.2 Hierarchical Attributed Liaison Graph (HALG)

Figure 5.6 demonstrates the HALG for the luminaire of choice, with a focus on the key components. As shown, HALG is a simplified way of illustrating the connections of the main product's components and grouping the components to disassembly levels for easier identification of the effort needed for each component. In the HALG, each line represents a connection between the connected components.



0	**Housing Assembly**
1	Diffuser A
2	End caps
3	Standoff
4	**Bookplate Assembly**
5	Channel / stiffener
6	**Driver assembly**
7	Driver unit
8	Terminal block
9	Grommet
10	Energy cables
11	**LED assembly**
12	Led strips
13	Cables
14	Bookplate

Figure 5.6: Strathclyde luminaire HALG and table of components

Level 0, as depicted in Figure 5.6, contains the housing assembly which is equal to the luminaire as a whole, and no disassembly processes have occurred to this point. Level one is the first step of disassembling the luminaire, which contains the bookplate assembly and three components: the end caps, the standoff, and the diffuser. The end caps are connected to the bookplate assembly through snap-fit connections, and the diffuser is connected to the same assembly through a rail that holds the plastic diffuser tensed and in place. Finally, the standoff holds its position due to the tension between the diffuser and the rest of the bookplate assembly, which is responsible for keeping the centre of the diffuser adequately distanced from the driver.

Level 2 includes the driver assembly, LED assembly, and channel/stiffener. Level 3 contains the components of the driver's and LED's assemblies. The driver assembly contains the energy cables, the driver unit, and the terminal block. The LED assembly contains the LED strips and the cables connecting the strips with the driver.

Finally, the bookplate is available in Level 4 when all the components have been disconnected.

At this point, the practitioner has gained knowledge of the structure of the product and the connections between its components and identified the key components which will be the focus of the remanufacturing process and its economic and environmental analysis.

5.3.3 Ease of disassembly (eDiM)

As introduced in section 3.3, this research uses the eDiM to estimate the disassembly and reassembly time for each of the cores being processed. eDiM is based on the Maynard Operation Sequence Technique (MOST) and provides a clear and comparable index which describes the effort required to replace key components in a returned core.

Table 5.2 contains the eDiM analysis for the disassembly, and Table 5.3 contains the reassembly analysis and the total eDiM index for the complete dis- and re-assembly of the Strathclyde luminaire. In both tables, all the values are used as a measurement unit, the second (s).

Table 5.2: eDiM disassembly table of Strathclyde in seconds

						Disassembly						
Disassembly sequence of components	Disassembly sequence of connectors of components	Number of connectors	Number of product manipulations	Identifiability	Tool type	**Tool change**	**Identification of connectors**	**Manipulation**	**Positioning**	**Disconnection**	**Removing**	**eDiM(dis)**
End cap A	Snapfit Type 1	2	1		flat head screwdriver	1.4	28.8	1.8	2.8	10	1.4	46.2
End cap B	Snapfit Type 1	2	1		flat head screwdriver	1.4	28.8	1.8	2.8	10	1.4	46.2
Diffuser	Snapfit Type 2	2	1			1.4		1.8	2.8	14	1.4	21.4
Styrofoam								0	0	0	1.4	1.4
Rail	Snapfit Type 2	2	1					1.8	2.8	14	1.4	20
Rail	Screw type 1	2	1		PH2	1.4		1.8	2.8	2.8	1.4	10.2
Rail	Spanner	1	0		Spanner	1.4		0	1.4	1.4	1.4	5.6
Driver	Screw type 1	2	1		PH2	1.4	14.4	1.8	2.8	2.8	2.4	25.6
Driver	cable plug type1	3			PH2	1.4		0	4.2	3.3	1.4	10.3
Grommet			1					1.8	0	0	1.4	3.2
Terminal Block	Screw type 1	1	1		PH2	1.4	14.4	1.8	1.4	1.4	1.4	21.8
Terminal Block	Screw type 2	1	1		flat head screwdriver	1.4		1.8	1.4	1.4	3.4	9.4

Terminal Block	cable plug type4	4		PH2	1.4		0	5.6	20	1.4	28.4
LED strip A	Plastic Clips (extract)	8	8	Scrapper	1.4	14.4	14.4	11.2	3.2	1.4	46
LED strip A	Cables	4	1	Pliers	1.4		1.8	5.6	8.8	1.4	19
LED strip B	Plastic Clips (extract)	8	8	Scrapper	1.4	14.4	14.4	11.2	3.2	1.4	46
LED strip B	Cables	4	1	Pliers	1.4		1.8	5.6	8.8	1.4	19
LED strip C	Plastic Clips (extract)	8	8	Scrapper	1.4	14.4	14.4	11.2	3.2	1.4	46
LED strip C	Cables	4	1	Pliers	1.4		1.8	5.6	8.8	1.4	19
LED strip D	Plastic Clips (extract)	8	8	Scrapper	1.4	14.4	14.4	11.2	3.2	1.4	46
LED strip D	Cables	4	1	Pliers	1.4		1.8	5.6	8.8	1.4	19
Bookplate					1.4		0	0	0	1.4	2.8
Total					26.6	144	81	98	129.1	33.8	**512.5**

Based on data from Table 5.2, a pie graph was composed of the main disassembly tasks and their percentage of time for the Strathclyde luminaire, as depicted in Figure 5.7. Such categorisation allows the identification of most time-demanding tasks, which can later be aimed for improvement.

The graph shows that identifying connectors is the most time-consuming activity (28%), followed by disconnection (25%). This is because the method is applied to this specific design for the first time, and no prior experience exists regarding the disassembly process. With greater experience, the impact of the identification of connectors' time will be mitigated; thus, the cost of remanufacturing will be lessened.

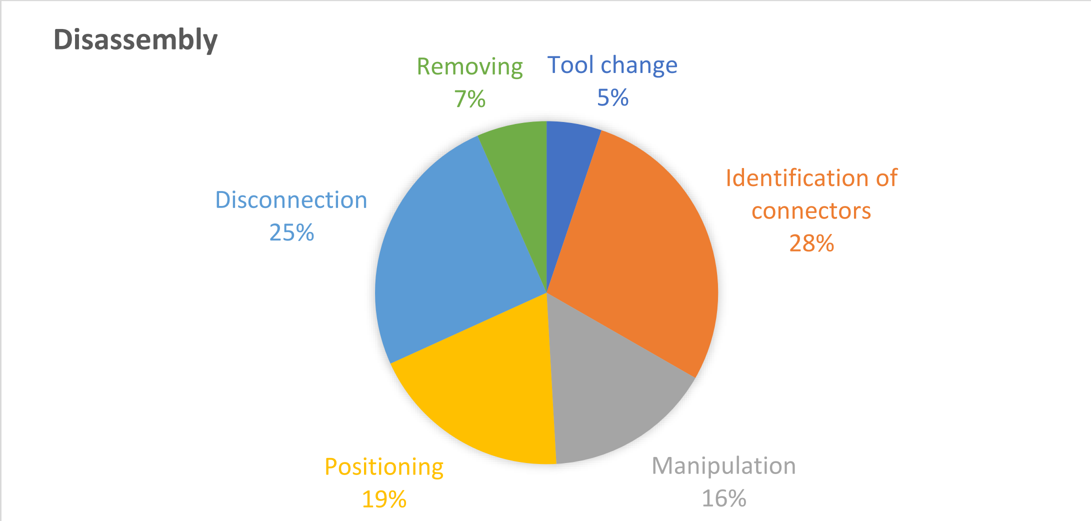


Figure 5.7: Percentage of the duration of disassembly tasks

Table 5.3 contains the time needed and the analysis for the reassembly process of the very same product. Additionally, it calculates the total eDiM needed for both dis- and re-assembly for each of the product's main components. Some components do not have unique eDiM values, so their numbers have been incorporated into other connecting components or assemblies.

Table 5.3: eDiM reassembly and total table of Strathclyde

						Reassembly							dis+re
Reassembly sequence of components	Reassembly sequence of connectors of components	Number of connectors	Number of product manipulations	Identifiability	Tool type	**Tool change**	**Identification of connectors**	**Manipulation**	**Positioning**	**Connection**	**Adding**	**eDiM(re)**	**eDiM (total)**
Bookplate								0	0	0	1.4	1.4	4.2
LED strip A	Plastic Clips (insert)	8	16		Scrapper	1.4		28.8	11.2	20	1.4	62.8	143.6

LED strip A	Cables	4	1	Pliers	1.4	1.8	5.6	5.6	1.4	15.8	
LED strip B	Plastic Clips (insert)	8	16	Scrapper	1.4	28.8	11.2	20	1.4	62.8	143.6
LED strip B	Cables	4	1	Pliers	1.4	1.8	5.6	5.6	1.4	15.8	
LED strip C	Plastic Clips (insert)	8	16	Scrapper		28.8	11.2	20	1.4	61.4	142.2
LED strip C	Cables	4	1	Pliers	1.4	1.8	5.6	5.6	1.4	15.8	
LED strip D	Plastic Clips (insert)	8	16	Scrapper	1.4	28.8	11.2	20	1.4	62.8	144.6
LED strip D	Cables	4	1	Pliers	1.4	1.8	5.6	5.6	2.4	16.8	
Terminal Block	Screw type 1	1	1	PH2	1.4	1.8	1.4	1.4	1.4	7.4	147.4
Terminal Block	Screw type 2	1	1	flat head screwdriver		1.8	1.4	1.4	1.4	6	
Terminal Block	Cable plug type 1	4		PH2	1.4	0	5.6	20	1.4	28.4	
Grommet			1			1.8	0	0	3.4	5.2	8.4
Driver	Screw type 1	2	1	PH2	1.4	1.8	2.8	2.8	1.4	10.2	68.1
Driver	Cable plug type 1	3		PH2	1.4	0	4.2	15	1.4	22	
Rail	Snapfit Type 2	2	1			1.8	2.8	10	1.4	16	67.6
Rail	Screw type 1	2	1	PH2	1.4	1.8	2.8	2.8	1.4	10.2	
Rail	Spanner	1	0	Spanner	1.4	0	1.4	1.4	1.4	5.6	
Styrofoam						0	0	0	1.4	1.4	2.8
Diffuser A	Snapfit Type 2	2	1			1.8	2.8	10	1.4	16	37.4

End cap A	Snapfit Type 1	2	1	flat head screwdriver	1.4	1.8	2.8	10	1.4	17.4	63.6
End cap B	Snapfit Type 1	2	1	flat head screwdriver	1.4	1.8	2.8	10	1.4	17.4	63.6
Total					25.2	138.6	98	187.2	32.4	**481.4**	**1042.7**

Figure 5.8 displays a pie chart illustrating the percentage of time allocated to each main task during the reassembly process. A distinct difference between the disassembly and reassembly charts is the omission of time for identifying connectors in reassembly, a result of familiarity with the design's connectors from the previous disassembly. Interestingly, while the identification time decreases, there's an increase in the time taken for connections. For example, connectors such as mini plastic clips were easier to disconnect but more difficult to reconnect. Implementing connector solutions that allow for faster, less alignment-dependent connections, like snap fits, could substantially reduce reassembly time.

For the method to hold practical value, the eDiM should be estimated during a stable disassembly process, post the learning curve phase. A company would not base decisions on data from the initial disassembly by a worker unfamiliar with the process, as this is likely to change significantly and quickly, thus not representing the long-term process accurately. Such an approach would result in an overestimate of time and cost. The proposed method applied the eDim methodology to resolve this issue. The eDiM standardises the time needed for each task after the learning curve. Thus, the values estimated in this table have been produced following this approach and validated by the company providing the case study.

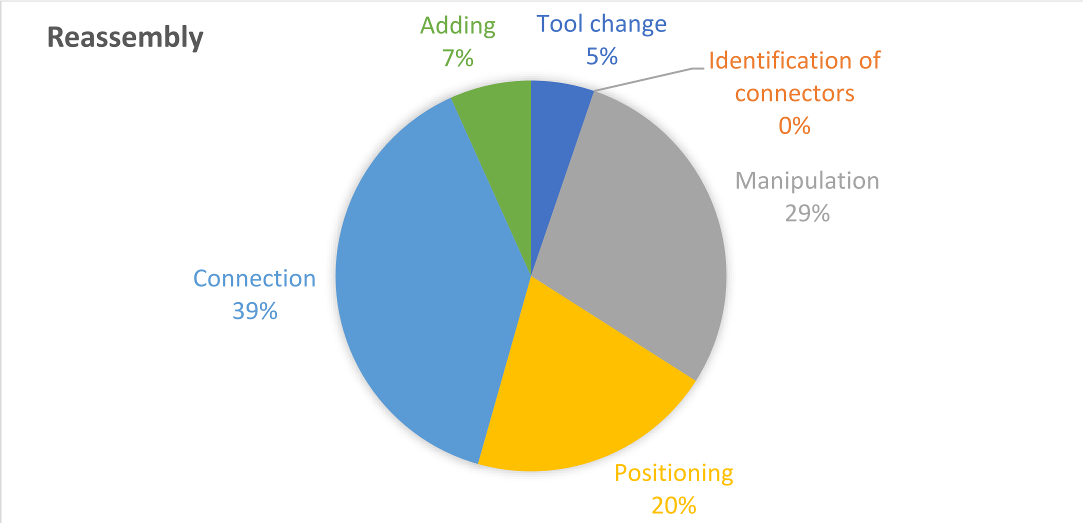


Figure 5.8: Percentage of the duration of reassembly tasks

5.3.4 The components replacement scenarios

As described in Chapter 3, the remanufacturing scenarios in this study are defined based on the potential replacement of one or more of the key components. Thus, in the case study of the luminaire with the five key components illustrated in Table 5.1, the total number of scenarios is 32 and presented in Table 5.4, where the value "0" equals the component not being replaced and "1" to being replaced.

Table 5.4: Scenarios of components replacement for the luminaire

Scenarios	Diffuser A	Bookplate	End caps	LED strips	Driver
1	0	0	0	0	0
2	0	0	0	0	1
3	0	0	0	1	0
4	0	0	0	1	1
5	0	0	1	0	0
6	0	0	1	0	1
7	0	0	1	1	0
8	0	0	1	1	1
9	0	1	0	0	0

10	0	1	0	0	1
11	0	1	0	1	0
12	0	1	0	1	1
13	0	1	1	0	0
14	0	1	1	0	1
15	0	1	1	1	0
16	0	1	1	1	1
17	1	0	0	0	0
18	1	0	0	0	1
19	1	0	0	1	0
20	1	0	0	1	1
21	1	0	1	0	0
22	1	0	1	0	1
23	1	0	1	1	0
24	1	0	1	1	1
25	1	1	0	0	0
26	1	1	0	0	1
27	1	1	0	1	0
28	1	1	0	1	1
29	1	1	1	0	0
30	1	1	1	0	1
31	1	1	1	1	0
32	1	1	1	1	1

In Table 5.4, scenario 1 refers to no component replacement and equals direct reuse, while the rest of the scenarios are equal to remanufacturing since some of the components need to be replaced.

5.4 Environmental Assessment of the product

One of the key parts of the proposed method is the product's environmental analysis during both the manufacturing and the EoL stages. The method selected was the simplified LCA as described by Christiansen (1997), and it was selected against a traditional thorough LCA due to the balance between the complexity of the data needed to perform an LCA and the impactful and efficient assessment of the product's entire lifecycle with accuracy. Additionally, the simplification of the LCA was decided since the environmental impact will be expressed solely in carbon emissions equivalents for more straightforward quantification and incorporation into the proposed method.

5.4.1 Lifecycle Assessment

In this section, all the stages of the lifecycle assessment will be described as those identified in Chapter 3.5. Although this study conducts a simplified LCA, the main guidelines for applying an LCA have been applied as those are expressed through standards of practice from the series ISO 14040.

Goal and scope definition

The selected product is a 30-watt Strathclyde Luminaire. The simplified LCA of the Strathclyde luminaire was undertaken to secure data for capturing the existing design's environmental impact and through additional analysis to identify its suitability for application of circular solutions after its EoL stage. Additionally, the LCA will provide insights on the impact of the existing design following the 'cradle to grave' approach. The audience for this study is the practitioner of the suggested method, and the results are kept internal and are not comparative to any similar product; thus, no third-party verification is needed. Finally, the results will further support the developed decision-making method proposed by the researchers.

Functional Unit

The selected functional unit arises from the fact that the goal of this LCA is not to compare it to other design decisions but to analyse the environmental impact of the existing product. Thus, the functional unit is one unit of the product defined as 'Strathclyde luminaire'.

System boundaries

The boundaries of this simplified LCA are dictated from the 'cradle to grave' approach, as depicted in Figure 3.4. The stages considered were the raw material extraction, production of basic materials and components, transportation, usage, and EoL stages of the luminaire. The lighting product was manufactured and assembled in China, as well as its components and raw materials, as described in the assumptions of the case study; thus, no additional transportation has been calculated for each of the components. The datasets used for material processing include raw material extraction and processing, as defined by the Ecoinvent 3.6 and Industry 2.0 databases. Realistic assumptions have been made regarding the manufacturing processes and the materials where no data were available, and only components with equal to or more than one per cent (1%) contribution to the manufacturing environmental impact will be taken into consideration for the EoL study. The components that are not part of the study are less than 5% of the total product's weight.

Life cycle Inventory (LCI) data

Data regarding the materials and their weights have been collected through interviews with the company engineers and managers and the disassembly of an existing product. For the estimation of the usage stage, it was considered a lifespan of 7 years, 255 days per year, 10 hours per day (17850 hours in total), and a consumption of 31.7 watts LED. Detailed inventory data can be found in Table 5.5, Table 5.6, and Table 5.7 for the luminaire, the driver, and the LED strip sequentially. It should be noted that the seven-year lifespan is applied to the definition of an average usage stage of the luminaire and is not the same as the case study's previous usage stage, which was defined at five years.

Table 5.5: Luminaire Composition

Component	**material**	**weight (gr)**
Diffuser	Polycarbonate granulate (PC), production mix	710
Bookplate	Steel engineering steel/ASIA	1497
Driver*	Assembly	208.5
Grommet	Polypropylene (PP) (replace)	2
End cap (2)	Polypropylene, PP, granulate, at plant/RER	=38.25*2
LED strip*(4)	Assembly	=43.1*4
Packaging	Folding boxboard/chipboard	350
Packaging Bag	Polyethylene, LLDPE, granulate, at plant/RER	2
Rail	Steel engineering steel/ASIA	422
Standoff	Polyurethane flexible foam (PU) - TDI-based, no flame retardant, high-density	3.5
Terminal Block (housing)	Polyvinylidene chloride (PVDC) E	3
Terminal Block (metal)	Copper sheet, technology mix, market mix, at plant	6
Wires	Cable, unspecified	28
Bolts & nuts	Steel hot-dip galvanised coil/Asia	17
Total weight		**3497.9**

A process tree has also been developed for illustrating the LCI data and the product's manufacturing process, as depicted in Figure 5.9.

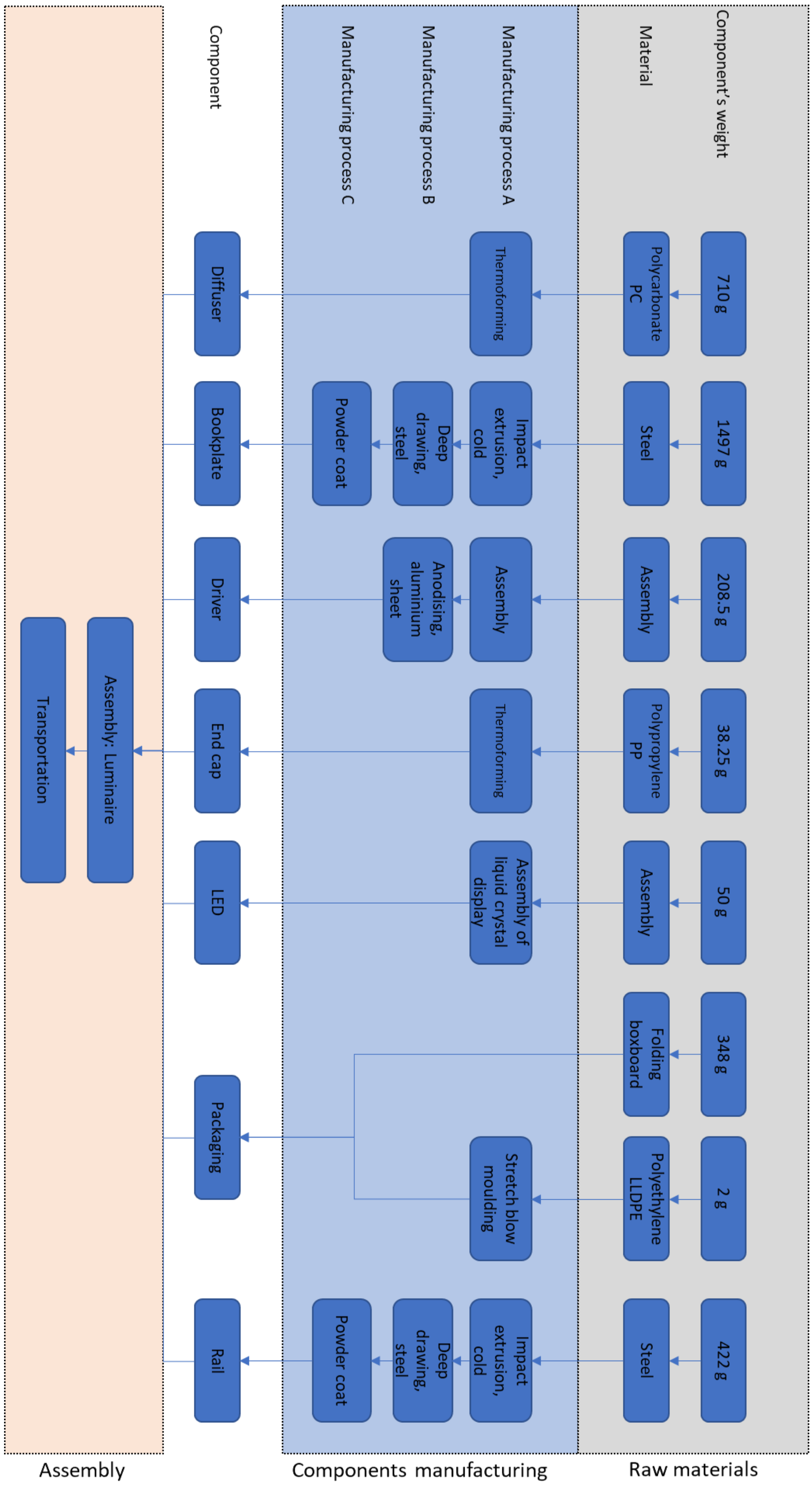


Figure 5.9: Luminaire Manufacturing Process tree

Regarding the driver assembly, components that already pre-exist and are modelled in the Ecoinvent database, such as inductors, printed wiring boards, capacitors, and other electrical components, were used. The 'Market datasets' option was used from the Ecoinvent database when selecting the electric components to account for prior processes such as raw material extraction, transportation and other manufacturing processes.

Table 5.6: Driver Composition

Driver*	
Component	**weight (gr)**
Printed wiring board for power supply unit, desktop computer, Pb containing	13.5
Inductor, ring core choke type	4
Capacitor, film type, for through-hole mounting	8
Capacitor, electrolyte type, < 2cm height	9
Transformer, high voltage use	50
Capacitor, for surface-mounting	2
Resistor, metal film type, through-hole mounting	2
Electric connector, peripheral component interconnect buss	9
Integrated circuit, logic type	7
PET film (production only) E	3
Solder, bar, Sn63Pb37, for electronics industry	3
Steel plate/Asia	84.5
Aluminium alloy, AlLi	13.5
Total weight	**208.5**

The driver's process tree that contains the assumptions and LCI data used is depicted in Figure 5.10.

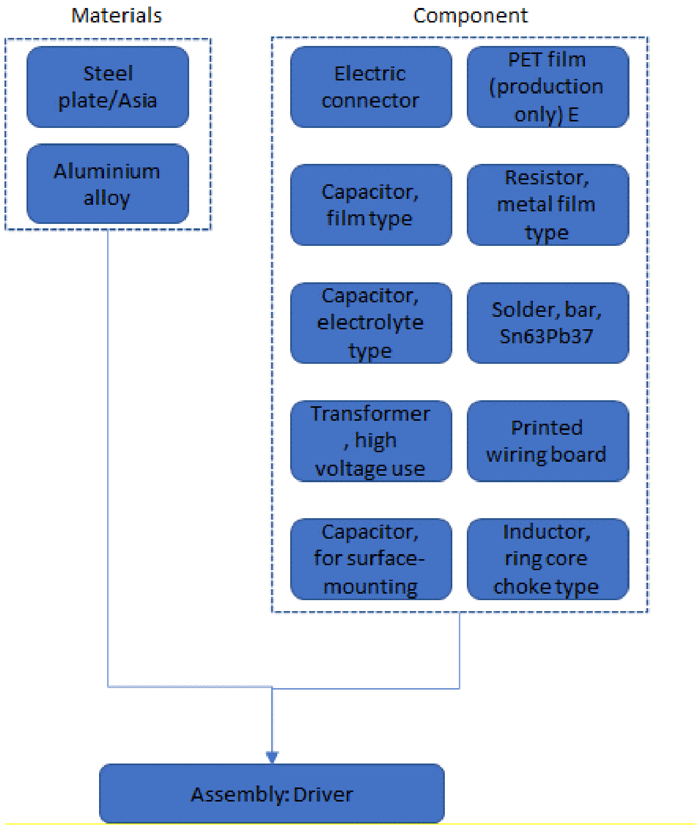


Figure 5.10: Driver Process tree

The LED strip assembly was also based on pre-existing components such as the Light-emitting diode. The selected datasets contain all data from the previous manufacturing steps as those were described before. One of the assumptions made for the calculation of the LED environmental impact stems from the fact that the Ecoinvent database does not include a manufacturing process allocated for lighting fixtures and lamps. Thus, a similar process of manufacturing an LCD screen was adopted to capture the environmental impact. This assumption is based on the similarity of the process and has been used in LCA reports of lighting products from companies that dominate the industry (Navigant Consulting Europe, 2009).

Table 5.7: LED strip composition

LED strip*	
Component	**weight (gr)**
Light emitting diode	8.5

Cable, unspecified	4.625
Aluminium alloy, AlLi	30
Total weight	**43.125**

The process tree that describes the LED assembly is depicted in Figure 5.11.

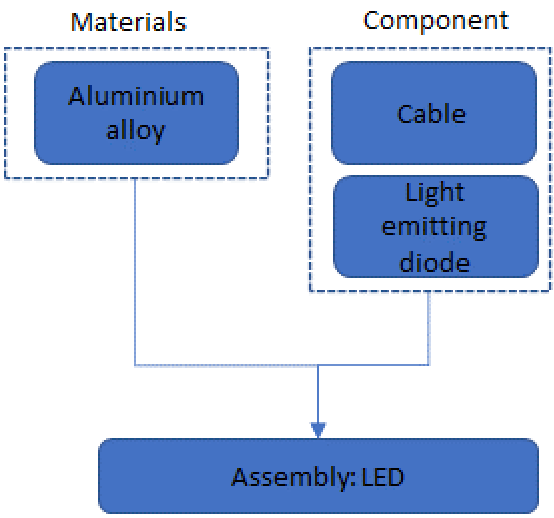


Figure 5.11: LED Process tree

LCIA method of choice

The LCIA method of choice was the ReCiPe Midpoint 2016 (H) V1.04 / World (2010) (H) because it provides 18 midpoint impact categories with Climate Change as the focus. Climate change is expressed in kilograms of Carbon emissions equivalent (kgCO_2 eq) as described in section 3.5.1.5.

5.4.2 LCA Results Analysis

In this part, the results of the LCA will be analysed with a focus on delivering the goals and the scope described before.

'Cradle to Grave' approach

As mentioned before, the approach of this simplified LCA is cradle to grave; thus, all the stages from raw material extraction to EoL recycling scenario are analysed. Figure 5.12 depicts the selected product's LCA network, the usage stage, and the recycling scenario. The width of each line in the network corresponds to the environmental impact of that source in the total impact calculated by the LCA, with thicker lines being responsible for greater impact and vice versa. The usage stage is responsible for 317 kgCO_2 eq emissions, which is matched to 89.6% of the total emissions during the product lifecycle. The assumption that the product will be using energy from the UK grid has been made and that the product will be operative for 17850 hours in total (7 years) with a consumption of 31.7 watts. Although the nominal power value of the product is 30 watts, measurements from the technicians revealed that the actual power is 31.7 watts; hence, that was selected as a more realistic value.

Additionally, as illustrated in Figure 5.12, recycling of the luminaire results in a total savings of 5.31 kgCO_2 eq or 12.96% of the total emissions during the production phase of the product. This outcome aligns with previous studies that support recycling a product cannot be a viable, sustainable EoL solution and that recycling is the least value-adding environmentally friendly EoL solution among reuse, remanufacturing or upcycling (Jehanno et al., 2022). The recycling EoL scenario includes all the waste types of materials.

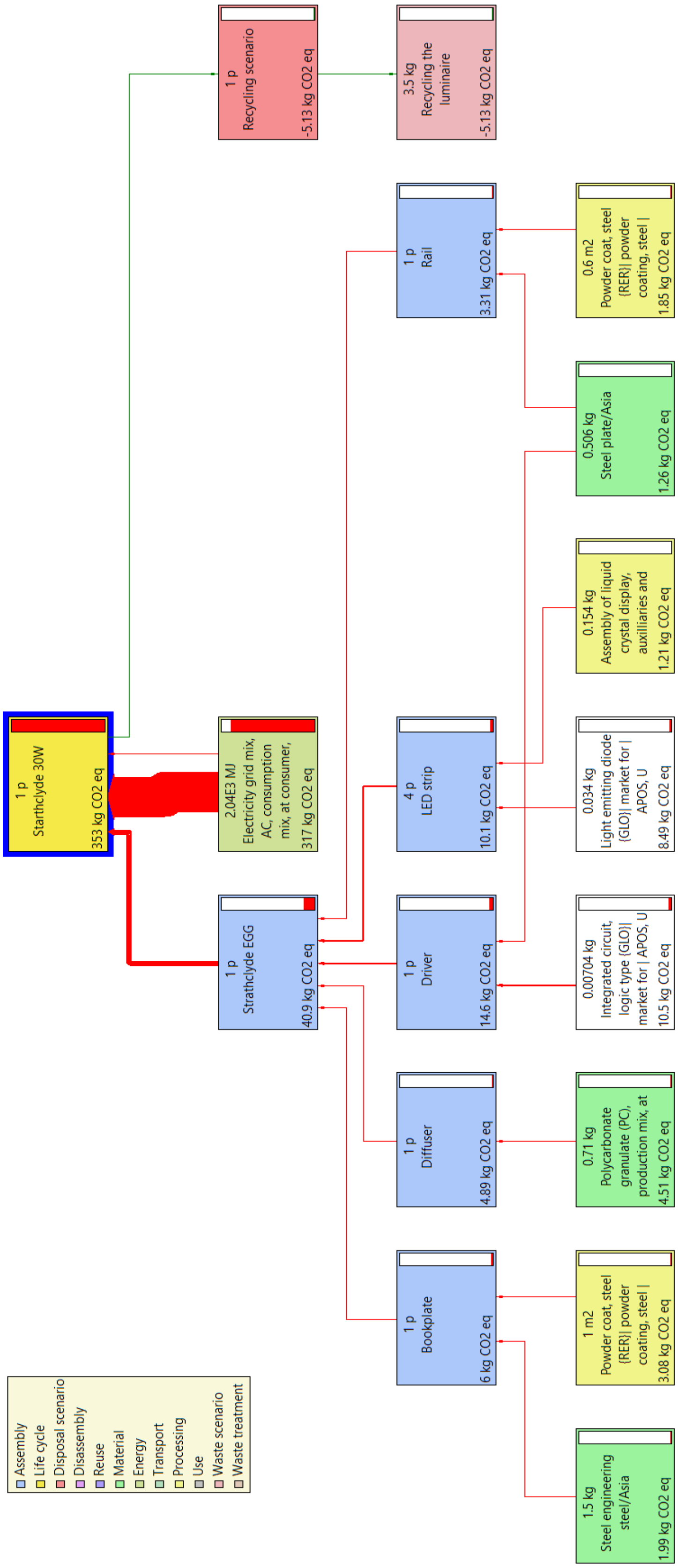


Figure 5.12: LCA network of 30W luminaire

In this case study, landfill is not a viable option for EoL since waste treatment is required due to the laws applied in the UK for electrical equipment. However, an analysis has also been conducted for the landfill to gain some insight in comparison with the recycling scenario to quantify those scenarios. The impact from recycling the whole luminaire is -5.13 kgCO_2 eq, with the negative sign referring to a positive impact. On the contrary, the landfill scenario generates 0.72 kgCO_2 eq. Although a detailed analysis of those scenarios has been conducted, it is out of scope to describe it in detail in this thesis.

5.4.2.1 *Luminaire Assembly*

In this part, a further analysis of the environmental impact of the assembly will be presented. More specifically, this part will focus on capturing the environmental impact per component, the impact assessment of the whole assembly, and identifying the environmental contribution of each of the manufacturing processes and their input to the total assembly.

The LCA results of the environmental impact per component can be found in Table 5.8, as well as their percentage compared with the total impact. The driver is responsible for the higher contribution, and second in impact are the LED strips, which account for 60% of the total emissions. According to the company engineers, this is an interesting outcome for the analysis since those two components are the most prone to failure. Their high failure rate and significance for lighting efficiency dictate that their correct operation after the product's usage stage is crucial for the product to be used again.

Table 5.8: Luminaire's components carbon emissions

Component	**Global warming impact (kg CO2 eq)**	**% of total**
Bookplate	6.00	14.7%
Diffuser	4.89	12.0%
Driver	14.56	35.6%
End cap	0.13	0.3%

Grommet	0.00	0.0%
LED strip	10.13	24.8%
Rail	3.31	8.1%
Standoff	0.01	0.0%
Terminal Block	0.05	0.1%
Wires	0.17	0.4%
Packaging	0.49	1.2%
Bolts and nuts	0.05	0.1%
Transport, freight	1.02	2.5%
Transport, freight, lorry 16-32 metric ton, euro5	0.11	0.3%
Total	**40.92**	100.0%

The bookplate and the rail are steel parts with a great life expectancy, and due to their static nature in the product's design, they have minimal chances of failure and can be used multiple times. The environmental impact would be much less if no powder coating were applied to the components, as seen in Figure 5.12, which depicts the LCA network of the whole product.

The diffuser has an impact that is equal to 12% of the total manufacturing impact, and according to Figure 5.12, the selected polycarbonate granulate is the culprit. The use of recycled materials once again could significantly limit the component's environmental impact.

The results of this analysis have been used to estimate the environmental impact of each remanufacturing scenario.

5.5 Circular Economy Design Analysis (CEDA) for the case study

This section introduces the CEDA for this case study. The 32 scenarios have been identified in Table 5.4, where the reader can identify which components are replaced in each remanufacturing scenario. The cost for each scenario has been calculated based on the financial functions described in the economic model description in Chapter 3.6. The environmental impact per scenario has been calculated based on the data from the LCA and the environmental impact per remanufacturing process for each of the 32 scenarios. The CEDA for the Strathclyde is illustrated in Figure 5.13.

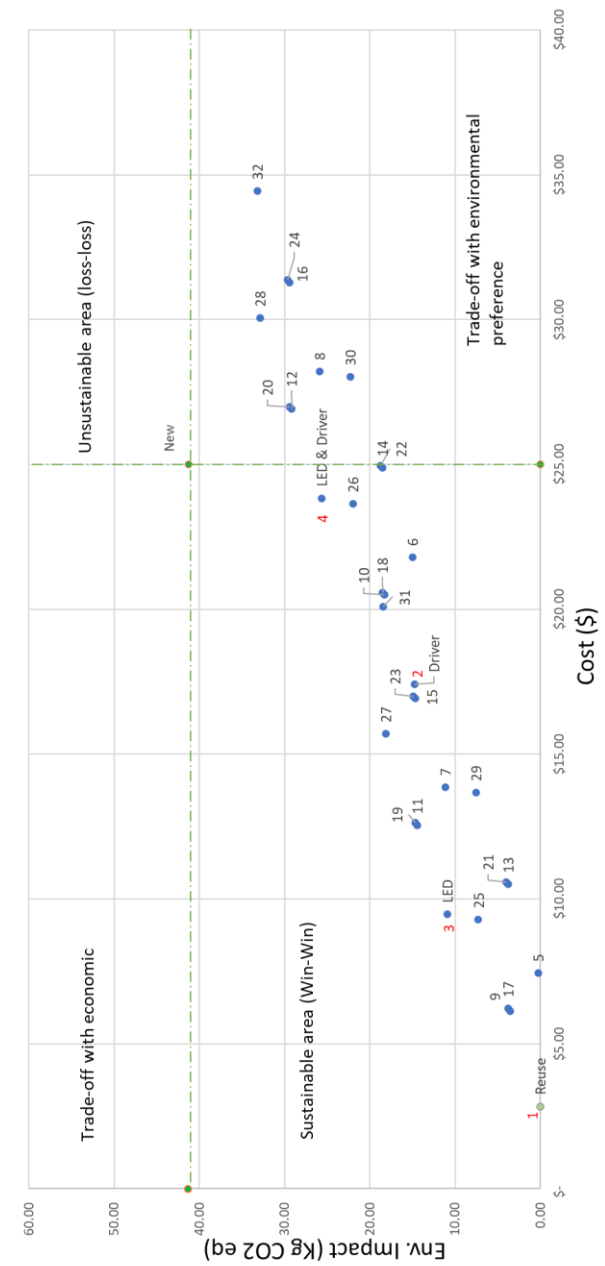


Figure 5.13: CEDA Strathclyde

Analysis of Figure 5.13 yields several key insights, the foremost being that the luminaire design is conducive to remanufacturing, as most potential scenarios fall within the sustainable (win-win) area. Specifically, Scenario 1, which involves no component replacement and is thus categorized as direct reuse, leaves 31 viable remanufacturing scenarios.

In the sustainable area, 23 out of the 31 scenarios (or 74.2%) demonstrate that remanufacturing offers significant economic and environmental benefits. On average, remanufacturing costs $19.25, representing a 23% reduction from the price of a new product. Excluding economically unfeasible scenarios where costs exceed those of a new product, the average remanufacturing cost decreases to $15.63, reflecting a 37% price reduction.

From an environmental standpoint, the average remanufacturing process results in 17.15 kg of CO2 equivalents, a substantial 59% reduction compared to a new product. Notably, none of the remanufacturing scenarios based on the five key components selected create more environmental impact than purchasing a new product.

However, within the trade-off area favouring environmental benefits, eight scenarios (25.8%) are more expensive than buying a new product. The average cost of these scenarios is $28.97, 16% higher than a new product. Despite the higher costs, the positive environmental impact of these scenarios suggests that remanufacturing could still be a viable option, particularly for companies prioritizing environmental objectives.

The company has identified several remanufacturing scenarios of particular interest, which will be further analysed in the subsequent paragraphs.

A) Direct reuse- Remanufacturing Scenario 1

Direct reuse, which entails no component replacement, is a viable option the proposed method offers. Its environmental impact is calculated at a minimal 0.04 kg CO2 equivalent, and the cost is estimated at $2.83. These figures are comparable to Scenario 5, where only the end caps are replaced. While direct reuse appears to be the most environmentally and financially advantageous, it's not always the optimal choice. This is because, after the usage stage, the luminaire's efficiency diminishes. Therefore, the quality of lighting it provides might not meet the standards of new customers, although it could be sufficient for a secondary market.

Importantly, direct reuse or remanufacturing profitability is not solely determined by the costs involved. The selling price of the luminaire plays a crucial role in the overall profitability of each scenario. Hence, it's essential to consider not just the cost savings from reuse or remanufacturing but also the market value of the refurbished product.

B) Replacement of solely the Driver- Remanufacturing Scenario 2

The driver is the most environmentally critical component, emitting 35% of the total carbon emissions. Replacement of the driver results in a total cost of $17.41 and 14.78 kg CO_2 eq. Those numbers are translated into a cost reduction of 30.35% and a reduction of carbon emissions equal to 64.24%. According to the company's engineers, the driver is the most prone to failure components, and replacement of drivers is a widespread practice.

C) Replacement of solely the LED- Remanufacturing scenario 3

Another scenario of special interest for the company is the exclusive replacement of the LEDs with newer ones after the usage stage. This scenario of remanufacturing results in reductions of 62.15% to the economic cost and 73.53% to the carbon emissions. This scenario reveals the massive potential for environmental and financial gains with remanufacturing over multiple usage stages. Additionally, the idea of replacing the component that has the biggest role in the efficiency of the product for the consumer and upgrading it after every usage stage will result in mitigating the environmental impact of that product during the usage stage as well, since new LED technologies will be much more efficient. Thus, with each added usage stage, the total environmental impact will be lessened while the efficiency of the product will either remain the same or be upgraded.

D) Replacement of the LED and the driver- Remanufacturing scenario 4

The final scenario that is of special interest to the company requires the replacement of both the LED and the driver. The financial cost in that case is equal to $23.83, which is only 4.69% less than buying a new one; thus, the difference is not that important. On the contrary, environmentally, the reduction is equal to 37.86%, with only 25.68 kg CO_2 eq produced. As described before, in these scenarios, the components are replaced with new identical ones; thus, the cost and environmental impact remain the same.

This scenario is crucial for identifying the product's suitability for remanufacturing since the driver and the LEDs are the two components responsible for the product delivering its value to the customer. Replacement of those two components will produce a product that will be ‘as good as new’ and will have the same lifespan as a new one, fulfilling completely the definition of remanufacturing (W. L. Ijomah et al., 2005). This scenario is also considered one of the worst-case scenarios since both those crucial components have failed and need replacement. In the end, remanufacturing the product has a small financial benefit for the company and a great environmental benefit that can be used in various ways and delivers the same value proposition to the customer. Thus, this scenario proves that remanufacturing can be profitable even when all the critical components need replacement, promoting further the company's adoption of a circular model.

As seen in the CEDA from Figure 5.13, for this product’s design, there are no scenarios that are either in the Unsustainable area (loss-loss) or in the area of Trade off with economic preference. The absence of scenarios from those areas, especially the unsustainable, proves even further that the product’s design is suitable for large-scale remanufacturing since, based on the assumptions made and the model’s development, the predictions show that there will always be at least environmental benefit.

One of the assumptions of the proposed method is that the replacement of components is identical to the ones used before. This assumption is used to simplify the model and develop an interdisciplinary method that can be implemented across multiple industries. When the model is used for further analysis of the future potentials of a product, the progress of technology should also be considered. In the lighting sector specifically, Haitz's law, which is the LED counterpart to Moore's law, dictates that for every decade, the cost of a lumen (unit of useful light emitted) is reduced by a factor of 10 while the amount of light produced per LED is improved by a factor of 20, for a given colour or wavelength (Nature Photonics, 2007). Moore's law describes a similar principle for integrated circuits that are used in the luminaire's driver. Thus, technological progress will mitigate those components' environmental impact and cost, moving the CEDA graph more to the sustainable area (win-win) and establishing remanufacturing as an even better solution at that time.

5.6 Decision Making

This section identifies the solution constraints and presents the proposed models as described in section 3.11. After that, the decision factors considered for the luminaire case study are analysed and weighted for the final solution proposition.

5.6.1 Practitioner's input and solution's constraints

As described in section 3.11, the practitioner must provide input to the proposed method. This input will be used to identify the solution constraints that are applicable to this specific case study. In this case study, we consider that an EGG customer has a total of 500 Strathclyde luminaires that they want to replace. The luminaires have been in use for the past five years. The case study implementation will be described in the following paragraphs, and the practitioner's input will be analysed and used to identify any solution constraints.

5.6.1.1 Guarantee and lifespan process

According to the remanufacturing definition, the remanufactured goods are required to be 'as new' if not even in better condition. Thus, the practitioner's input for the guarantee process is crucial in capturing any possible risk with a compromised guarantee. As guarantee in this study, is described the period that the product will be used in the future while the company is confident that it will be functional in 'as new' condition. This chapter will present the application of the guarantee process for the remanufactured luminaires.

According to the case study assumptions, the returned batch equals 500 ‘Strathclyde’ luminaires that have been used for five years, two shifts per day and were bought new. The critical electronic components in the ‘Strathclyde’ LED luminaire are the driver and the LED strips. The other components are only subject to mechanical wear, and their life expectancies can be considered known with good certainty and are equal to a specific number of expected lifespans. The life expectancy values for mechanical wear have been selected based on feedback from the practitioner. The company provides a 3-year guarantee when the product is used for two eight-hour daily shifts. Since the company provides guarantees for their remanufactured products, the inequalities that will be used for performing the life expectancy checks are described in section 3.11.2. Table 5.9 contains the guarantee check input data both in years and hours, as seen below:

Table 5.9: Guarantee Check input data

		(hours)
Up, Past use of product (in years)	5	**29200**
Guarantee (in years)	3	**17280**
Number of Shifts (in past USE-Up)	2	16
Number of Shifts (in the future USE-U_f)	2	16
U_f-future use (in years)	5	29200

The future shifts per day are predicted to be equal to 2, and the guarantee given by the company for the correct product operation is three years. The model uses those data to perform a check based on Equation 13 to determine if any component could compromise this guarantee period.

Table 5.10 contains the lifespan for each key component and a replacement check based on Equation 13, which describes the key components' generic wear.

Table 5.10: Generic replacement check of components based on guarantee period

		check 1 L-Up>=0		check 2	Replace Check (L-Up-Uf<G)
Key Component	**L (hours)**	**(L-Up)**	**Uf (hours)**	L-Up-Uf<G	
Diffuser A	87600	58400	29200	29200	No replace
Bookplate	131400	102200	29200	73000	No replace
End caps	87600	58400	29200	29200	No replace
LED strips	50000*	20800	29200	-8400	*see *Specified check 1-LED*
Driver	50000*	20800	29200	-8400	*see *Specified check 2-Driver*
Up-Past use (hours)	**29200**				
Guarantee (hours)	**17280**				

The driver and LED strips have unique models that check for any potential compromise of the functionality of the product during the guarantee period. The next paragraphs describe each of those two models.

Specified check 1- LED

For the LEDs in this framework, we followed an approach that captures the way LEDs mostly ‘fail’ by degrading over time. Thus, using an exponential distribution will not have the optimum impact on the decision of whether or not the guarantee is compromised if they are remanufactured. The expected service life of an LED ‘*describes the time until the mean light output of an LED luminaire has dropped to a specified percentage of the initial light output’* (Zumtobel Lighting GmbH, 2018). In our study, we adopt this service life definition for the LEDs and refer to it as lifespan for reasons of easiness.

According to The Lighting Handbook (Zumtobel Lighting GmbH, 2018), a label on the product of “L80 50,000 h” is equal to 80% of the output light that was initially designed to emit, after 50000 hours of operation time as depicted in Figure 5.14.

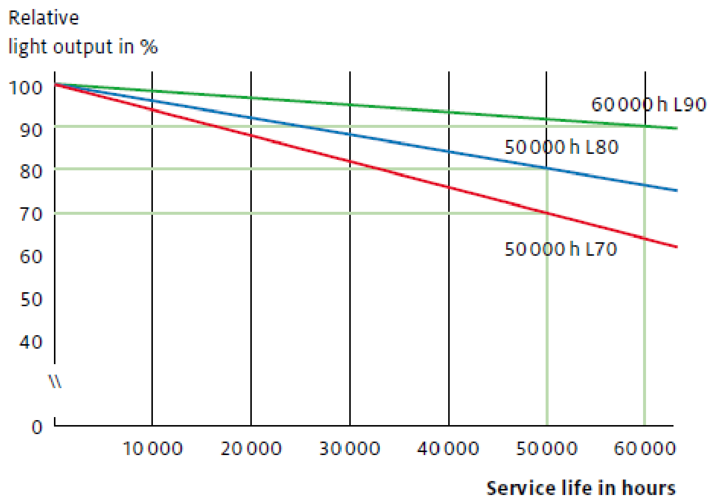


Figure 5.14: Service life data for LEDs

The flowchart of the process for checking if the LEDs have enough lifespan for reuse or replacement is mandatory, as depicted in Figure 5.15.

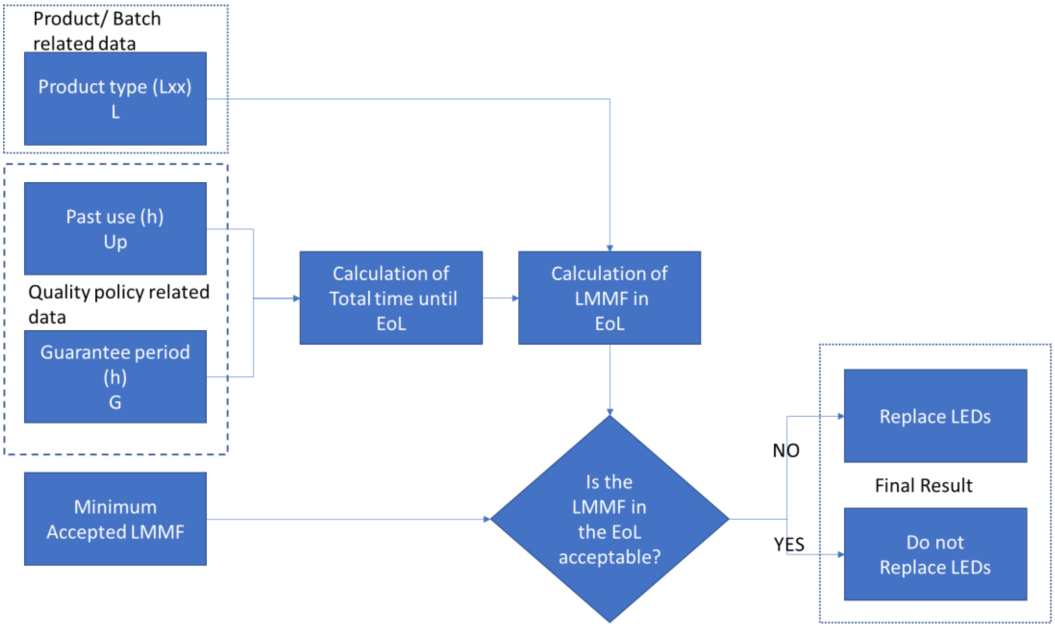


Figure 5.15: Flowchart of the LED lifespan check

The first inputs from the practitioner are the L-value of the returned products and the past use (Up) per hour. Those data are product-related data, which will be similar to the whole batch of returned products. If operational data are unavailable, a maximum of 50.000 hours should be considered. Table 5.11 presents the LED check's inputs, calculations, and outputs for the replacement model for the batch of 500 L80 LEDs Strathclyde luminaires.

Table 5.11: Process for LED replacement checking

Product Type	80	LXX	input
Up-past use (h)	29200	hours	input
Guarantee time	17280	hours	input
Up plus guarantee	46480	hours	calculated
Round up	50000	hours	calculated
Accepted use in EoL (minimum LLMF)	0.7	LLMF	input
Result (LLMF)	**0.8**	**NO Replace**	calculated

As presented in Table 5.11, the outcome of the analysis explicitly concludes that considering the LED's past use (Up) and the guarantee time for maintaining good efficiency, along with the accepted Lamp Luminous Flux Maintenance Factor (LLMF) at the EoL and the product's type, the LEDs will not require replacement. This ensures that the LEDs will remain above the efficiency threshold (minimum accepted LLMF of 0.7) even after their second life (remanufacturing), thus not compromising the guarantee of good working conditions provided by the company.

The minimum accepted LLMF of 0.7 means that the threshold value for the efficiency of the light is 70% of its efficiency when new. The 0.7 has been selected based on the fact that the Strathclyde luminaire is suitable for offices and schools, and according to '*The Ligthing Hanbook'*, for such working areas, the baseline of the LLMF is 0.67 (Zumtobel Lighting GmbH, 2018). Finally, the LLMF has been selected as an appropriate index for capturing the efficiency of the LEDs since it is the standard practice in the lighting sector.

For an L80 luminaire, according to the manufacturer's data, that value is reached in 70.000 hours of operation, as seen in Table 5.12. The company has selected the LLMF of 0.7 based on its policy and may differ based on the target market, company's goals, and services.

Table 5.12: Lamp luminous flux maintenance factor (LLMF) for LED comparison (Zumtobel Lighting GmbH, 2018)

LLMF	L95	L90	L85	**L80**	L75	L70	L65	L60	L55	L50
Service life in hours										
1000	1	1	1	1	1	0.99	0.99	0.99	0.99	0.99
5000	1	0.99	0.99	0.98	0.98	0.97	0.97	0.96	0.96	0.95
10000	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.9
15000	0.99	0.97	0.96	0.94	0.93	0.91	0.9	0.88	0.87	0.85
20000	0.98	0.96	0.94	0.92	0.9	0.88	0.86	0.84	0.82	0.8
25000	0.98	0.95	0.93	0.9	0.88	0.85	0.83	0.8	0.78	0.75
30000	0.97	0.94	0.91	0.88	0.85	0.82	0.79	0.76	0.83	0.7
35000	0.97	0.93	0.9	0.86	0.83	0.79	0.76	0.72	0.69	0.65
40000	0.96	0.92	0.88	0.84	0.8	0.76	0.72	0.68	0.64	0.6
45000	0.96	0.91	0.87	0.82	0.78	0.73	0.69	0.64	0.6	0.55
50000	0.95	0.9	0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5
55000	0.95	0.89	0.84	0.78	0.73	0.67	0.62	0.56	0	0
60000	0.94	0.88	0.82	0.76	0.7	0.64	0.58	0.52	0	0
65000	0.94	0.87	0.81	0.74	0.68	0.61	0	0	0	0
70000	0.93	0.86	0.79	0.72	0.65	0.58	0	0	0	0
75000	0.93	0.85	0.78	0.7	0.63	0.55	0	0	0	0
80000	0.92	0.84	0.76	0.68	0	0	0	0	0	0
85000	0.92	0.83	0.75	0.66	0	0	0	0	0	0
90000	0.91	0.82	0.74	0.64	0	0	0	0	0	0
95000	0.91	0.81	0.72	0.62	0	0	0	0	0	0
100000	0.9	0.8	0.7	0.6	0	0	0	0	0	0

After analysis of the practitioner's inputs, it is confirmed that the LEDs do not compromise the guarantee period, and replacement is not mandatory. In the case that replacement is needed, the result is translated into the pre-screening process and the quality grades of the cores, thus directly impacting the pre-screening decision for the remanufacturability of the batch.

This automated tool is based on Excel modelling and was developed specifically for the luminaire case study. It is focused on identifying if all the LEDs will need replacement independently of their quality condition. A direct conclusion from this tool is that LEDs of higher quality, L95 to L80, are much more suitable for a circular business model of multiple usage stages since their efficiency remains high for much longer periods of operation. On the contrary, LEDs of lesser quality from L65 and below seem to be unsuitable for a second usage stage and, thus, remanufacturing.

Specified check 2- Driver

The driver is an electrical component that usually fails catastrophically; thus, it is a non-repairable component. To analyse the driver, we use quality data shared with the manufacturer and apply the basic principles of reliability. According to the manufacturer and practitioner data, the driver's life expectancy is 50.000 hours with a failure rate of 10% when the operating temperature is 75 degrees Celsius and 100.000 hours at 65 degrees Celsius with the same failure rate of 10%. To analyse those statements, we use the exponential distribution since it is the most commonly used distribution in reliability engineering and can model the behaviour of products with a constant failure rate, as seen in Equation 14:

Equation 14: Driver failure rate

$$\lambda = \frac{\#\ of\ failures}{total\ time\ of\ operation * \#\ of\ sample}$$

The practitioner, using data from previous batches that had the same type of driver, identified that in a sample of 100 drivers, there are ten failures, so:

$$\lambda = \frac{10}{50.000 * 100} = 2 * 10^{-6}\ failures\ per\ hour\ of\ operation$$

The reliability in the exponential distribution is defined as shown in Equation 15:

Equation 15: Reliability based on exponential distribution

$$R(t) = e^{-\lambda t}$$

Thus, the reliability for the 50.000 hours that aggregate the past use Up and Guarantee period is:

$$R(50.000\ hours) = e^{-2*10^{-6}*50000} = 0.9048\ or\ 90.48\%$$

The analysis of reliability provides a solid case for the decision of whether or not the driver should be replaced and what the probability of compromising the guarantee associated with the remanufactured product is. According to the driver's manufacturer data, this is considered an acceptable reliability value since the base value has been set for 81.87%, corresponding to 100000 hours of operation.

Implementation of the case-specific models of the driver and the LEDs has now concluded the Guarantee and lifespan process, and the total result is that none of the key components need to be replaced at risk of compromising the guarantee period given by the company. Thus, any component replacement will occur due to its quality and not as a part of a mass replacement process for this specific batch of 500 Strathclyde luminaires. Additionally, since there is no need for mass replacement of any component, the batch could still be considered for the direct reuse scenario. In conclusion, the direct reuse scenario was not excluded due to the guarantee and lifespan process.

5.6.1.2 Legislation restrictions

Based on the regulations outlined in the Waste Electrical and Electronic Equipment (WEEE) Directive, the lighting product manufacturer is obligated to collect and transport the used luminaires to a recycling facility. Consequently, in this context, disposal is not an option, and recycling becomes the sole viable alternative when direct reuse or remanufacturing is not feasible. It's important to note that the recycling scenario also factors in the costs of purchasing a new batch of luminaires. Including replacement costs is essential as the primary goal is to fulfil the customer's needs.

5.6.1.3 Obsolescence and market prediction

In this step, the practitioner will have to predict the market demand for the remanufactured goods and grade the obsolescence of the product’s design. Both the future demand and the obsolescence are graded based on linguistic values. The grades for the demand prediction and obsolescence combinations have been tuned based on the practitioner’s input. In this case study, only when both the demand is ‘decreasing’ and the obsolescence of the design is valued as ‘outdated’ is the result of a *hard* constraint that directly excludes the scenarios of direct reuse and remanufacturing. The ‘Strathclyde’ luminaire has a wide variety of applications in both offices and schools, so the market is very stable. As seen in Table 5.13, The practitioner has decided that there is a *stable demand (X2)* for the Strathclyde luminaire even if the design is considered *outdated (O3)*. The result of such a combination is a soft constraint, which will be taken into consideration in the decision-making as a decision factor, but it means that there are no scenarios exclusion, such as reuse or remanufacturing, due to limited market demand. The scale of the final result is from value '1', corresponding to no remanufacturing, to '5', which corresponds to the highest and better grade suitability for remanufacturing.

Table 5.13: Obsolescence and future demand factors table

Demand Prediction	**Obsolescence**	**EoL scenario impact**	**Final grade (1 no reman- 5 the best score)**	**Constrain**
decreasing (X1)	relatively new (O1)	Reuse or Rem/re	3	soft
decreasing (X1)	Ok (O2)	Reuse or Rem/re	2	soft
decreasing (X1)	outdated (O3)	Recycle or Disposal	1	Hard
stable (X2)	relatively new (O1)	Reuse or Rem/re	4	soft
stable (X2)	Ok (O2)	Reuse or Rem/re	3	soft
stable (X2)	outdated (O3)	Reuse or Rem/re	2	soft
increasing (X3)	relatively new (O1)	Reuse or Rem/re	5	soft
increasing (X3)	Ok (O2)	Reuse or Rem/re	4	soft
increasing (X3)	outdated (O3)	Reuse or Rem/re	3	soft

5.6.1.4 Product Materials

The product under analysis is composed of materials that can be both recycled and landfilled. Some materials may need special waste treatment. Thus, due to legislation relating to the WEEE, disposal of this specific product is not allowed. Therefore, disposal is excluded from the EoL scenarios.

5.6.1.5 *Pre-screening process*

The generic model of the pre-screening process has been tailored to the specific case study of the luminaire. In this section, the model will be presented alongside its implementation for the returned batch of 500 luminaires.

One of the first steps is that the Guarantee and lifespan process will be used to identify if there is any component that needs to be replaced independently of its quality condition. Based on previous findings, there are no such components.

The next step would be for the practitioner to enter the values of the two identified quality dimensions: the visual condition and the performance. The practitioner allocated the relative components for each of those two groups, as shown in Figure 5.16.

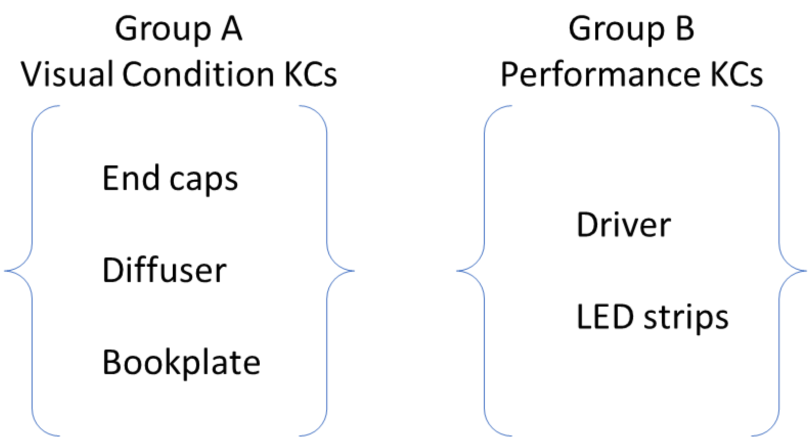


Figure 5.16: Key components quality dimensions

The grading for each of the KCs conditions is based on simple linguistic captions (Excellent, OK, Bad), as illustrated in Table 5.14, and are directly linked with the mean number of key components that may need to be replaced.

When a product is graded based on its visual condition as ‘A’, that means that linguistically, it is ‘Excellent’, which translates to a possibility of 68.2% that 0 components will need replacement. The linguistic value ‘Excellent’ also refers to the mean value of zero components being replaced. The rest of the possibilities are calculated based on the normal distribution as expressed in Table 5.14.

Table 5.14: Pre-screening case study grading and analysis of the system

	Quality dimension	***Grade symbol***	***Grade (linguistically)***	***linguistic correlation***	***Number of components to be replaced***	***Explanation of the grade (%possibility to be true)***
1	Visual Condition	A	Excellent		0	62.80%
				mean=0	1	27.20%
				components replaced	2	4.20%
					3	0.20%
		B	OK		0	15.80%
				mean=1	1	68.20%
				components replaced	2	13.60%
					3	2.40%
		C	Bad		0	2.20%
				mean=2	1	13.60%
				components replaced	2	68.20%
					3	15.80%
2	Performance	A	Excellent		0	62.80%
				mean=0	1	27.20%
				components replaced	2	4.60%
		B	OK		0	15.90%
				mean=1	1	68.20%
				components replaced	2	15.90%

			0	2.20%
C	Bad	mean=2	1	13.60%
		components replaced	2	84.20%

Based on the technician's feedback, half of the luminaires looked and performed 'excellent', while the rest of them were either 'OK' or in 'Bad' condition, either aesthetically or performance-wise, as depicted in Table 5.15.

Table 5.15: Batch condition based on technician's input

visual condition is	**% of the batch**
excellent	50%
OK	25%
Bad	25%
Performance is	
excellent	50%
OK	40%
Bad	10%

One of the key results from Table 5.15 is that only half of the luminaires of the batch are in excellent condition both visually and performance-wise. The company of the case study has set a threshold value for direct reuse. For acceptance of direct reuse of a batch, 95% of the luminaires of the batch must be in excellent condition, both visually and performance-wise. Thus, the direct reuse of the batch is opted out from the available EoL pathways.

The pre-screening model uses the data from Table 5.15; the model results are visible in Table 5.16.

Table 5.16: Results of the pre-screening process

% of products that will need replacement of # components	# of components replaced	Average Cost ($)	Average env. Imp. (CO_2)	Average time (eDiM)
14.6%	0	2.83	0.04	0.00
29.0%	1	9.33	6.67	508.00
29.7%	2	15.61	13.30	741.90
17.2%	3	21.89	19.93	879.01
5.8%	4	28.16	26.55	955.08
0.8%	5	34.44	33.18	991.50
Average product (97.2%)	**-**	**13.44**	**11.13**	**582.55**
Batch size 500		**$ 6718.8**	**5565 kgCO_2 eq**	**80.9 hours**

Table 5.16 presents the results from the pre-screening process, indicating that, on average, a product is likely to have a 97.2% chance of incurring a cost of $13.44 and generating 11.13 kg of CO_2 emissions per unit. According to the condition of the batch, 14.6% of the products will not require any component replacements, costing $2.83 each for remanufacturing. Conversely, a small portion of the same batch (0.8%) will necessitate the replacement of all key components. Therefore, these average cost and environmental impact figures are based on the varied conditions of the returned products.

Additionally, the average eDiM score, calculated at 582.55 seconds, can be utilized to estimate the average cycle time for remanufacturing each product. This translates to an estimated total cycle time of approximately 80.9 hours for the entire batch of 500 luminaires.

Additional information deriving from the pre-screening process is captured in Figure 5.17, where the average values for cost and environmental impact are depicted alongside the distribution of the returned batch.

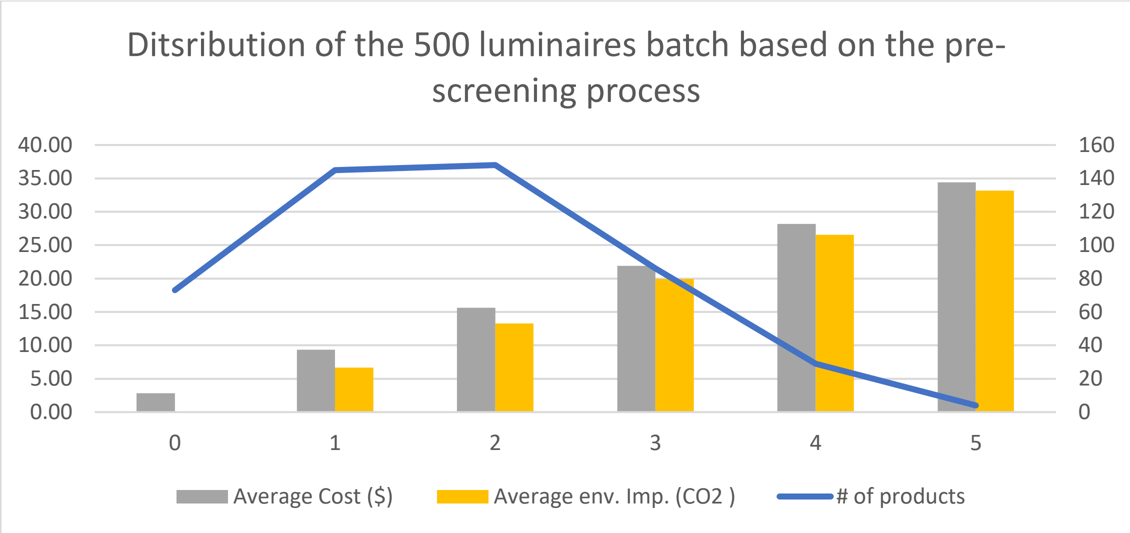


Figure 5.17: Distribution of the batch under analysis

From Figure 5.17, it becomes evident that most of the products will probably need 1 or 2 components to be replaced, while much less might need more than three new components, revealing a good quality condition of the batch.

5.6.1.6 Difficulty factor

The difficulty factor expresses the complexity of the dis- and re-assembly process due to the joints' connections for a specific product design. For the Strathclyde luminaire, the practitioner's input is captured in Table 5.17.

Table 5.17: Product's joints connection grading

CODE	CONNECTORS DESCRIPTION	GRADING AND TIME					
-	Strongly agree (A)- Strongly disagree (E)	A	B	C	D	E	Grade
C1	The joints are standardised	1	5	10	15	25	1
C2	The joints can be disassembled, and they are not fixed joints	1	5	10	15	25	5
C3	The screws have the same metrics	1	5	10	15	25	10

C4	The number of joints is low	1	5	10	15	25	10
C6	The joints are easily accessible	1	5	10	15	25	5
C7	Size components are easy to handle	1	5	10	15	25	15
C8	The tools needed are available	1	5	10	15	25	1
C9	The tools are standardised	1	5	10	15	25	1
	Difficulty factor (average value)						**6**

Table 5.18 contains the result of the sub-process, which is a multiplier for the average time for remanufacturing a product. It aims to recalibrate the economic prediction model by inserting an additional risk net by computing the possible delays on average per product due to product design.

After discussions with the company engineers, the multiplier values corresponding to each result range, depicted in Table 5.18, were selected based on the specific case study.

Table 5.18: Ranges of results

RANGE OF RESULT	RESULT	MULTIPLIER OF AVERAGE TIME
(1,10)	Good	1
[10,20)	Ok	1.5
[20,25]	Bad	2

Finally, for the luminaire case study, the difficulty factor lies between the (1,10) range; thus, the multiplier will be equal to one time the average time to remanufacture. That is interpreted as a design in which its dis- and re-assembly process is straightforward with no additional complexity that could delay the estimated times. Finally, that means the remanufacturing cost will stay as predicted by the pre-screening process, equalling $ 13.44.

5.6.1.7 Functionality constraints factor

The functionality constraints factor is a multiparameter factor aimed to capture the complexity of the remanufacturing process and identify any potential area of risk related to the process that might jeopardise the viability of the suggested solution. It consists of sub-factors such as the inventory levels, remanufacturing capacity, and components availability, all of which have binary GO and NO GO results. A model performs checks based on each of those factors and returns either a GO or a NO GO result, identifying which factor did not qualify as a pass, as seen in Figure 5.18.

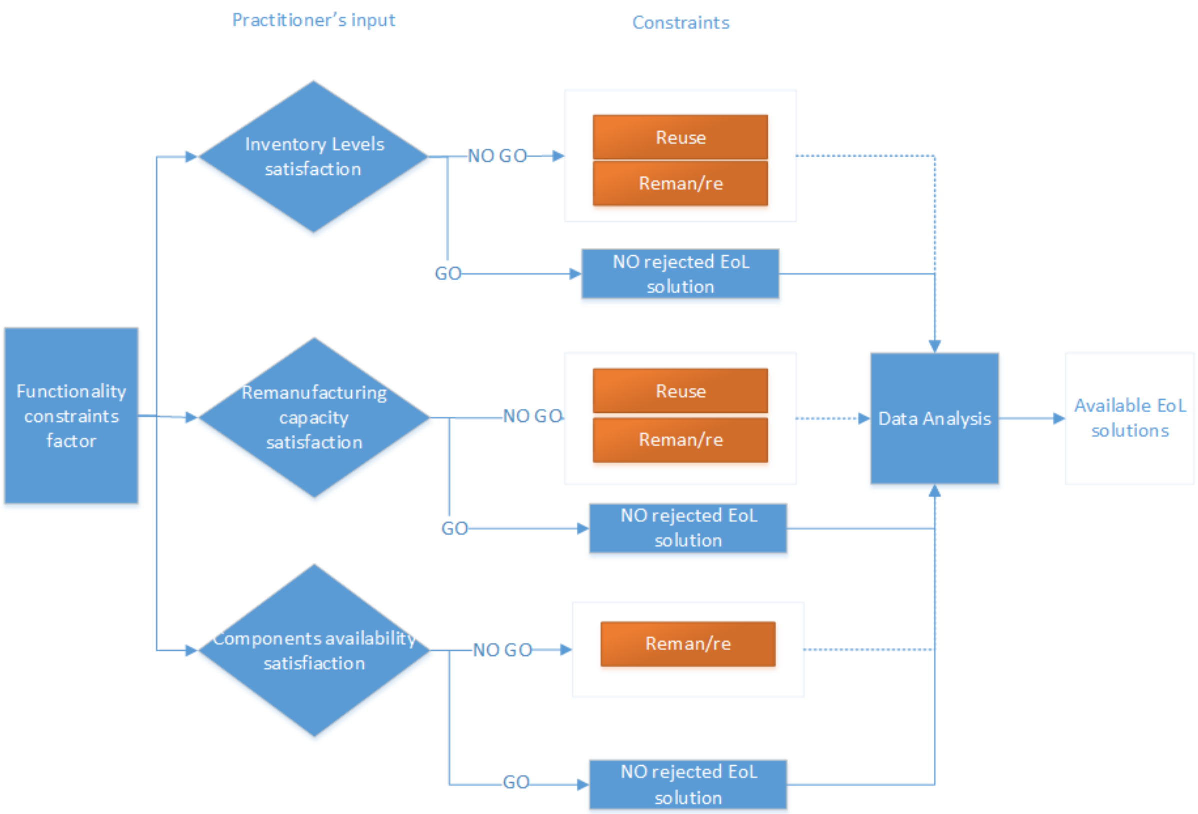


Figure 5.18: Functionality factor sub-process

Based on Table 5.15, which contains the input from the technician for the pre-screening process, the majority of the luminaires are in great condition. Regarding the visual condition, approximately 250 luminaires are in 'Excellent' condition; thus, they will not need any component replacement from the list of components responsible for the visual condition of the product, the diffuser, the bookplate, and the end caps. Applying the same process for the performance results in approximately 250 luminaires being in 'Excellent' condition. The practitioner can consider this analysis alongside other data, such as delivery times of replacement components, availability and remanufacturing capacity and have a good estimation if any of those factors cannot be met for remanufacturing this specific batch of 500 Strathclyde luminaires.

In our case study, the practitioner identifies that the inventory has the capacity to store 500 more luminaires. Additionally, with a total cycle time of 80.9 hours, the facilities have the remanufacturing capacity to work on the returned batch. Finally, the components that may be needed are all in production by the suppliers, and the delivery times are within acceptable ranges; thus, the component availability factor is also satisfied.

Thus, in this case study, no constraints would restrict one of the EoL solutions due to the functionality factor.

5.6.2 Solutions constraints overview

This section analyses all the input from the practitioner and the potential solution constraints, resulting in Table 5.19.

Table 5.19: Solution Constraints Results

Practitioner's input and constraints	EoL restricted pathways	Reasoning	Result
Guarantee Process	Reuse	Product's reliability compromises direct reuse	No restriction
Legislation Restrictions	Reuse	Legislation prohibits direct reuse	No restriction
	Remanufacture	Legislation prohibits remanufacturing	No restriction
	Recycle	Legislation prohibits recycling	No restriction
	Disposal	Legislation prohibits disposal	Restriction of Disposal

Obsolescence and Market predictions	Reuse	Product's obsolescence compromises direct reuse	No restriction
	Remanufacture	Product's obsolescence compromises remanufacturing	No restriction
Pre-screening Process	Reuse	Product's quality compromises direct reuse (less than 95% excellent condition)	Restriction of Direct Reuse
	Remanufacture	Product's quality compromises remanufacturing	No restriction
		Average cost per product	**$ 13.44**
		Average CO_2 emissions per product	**11.13 kgCO2 eq**
Product Materials	Recycle	Product's materials cannot be recycled	No restriction
	Disposal	Product cannot be disposed	Restriction of Disposal
Functionality Factor	Reuse	Product's functionality rating prohibits direct reuse	No restriction
	Remanufacture	Product's functionality rating prohibits remanufacturing	No restriction

According to Table 5.19, based on the analysis of the practitioner's input, there are only two viable solutions for this returned batch of luminaires: remanufacturing and recycling. Recycling includes buying a new batch of similar products with the same properties.

Disposal was opted out due to Legislation Restrictions, Product Materials constraints, and direct reuse due to the Pre-screening process and low percentage of excellent visual and performance-wise luminaires, less than 95%, which was the threshold value for the company.

5.6.3 Decision factors

The decision factors identified based on literature and industrial input have been thoroughly analysed in section 3.11. This section includes the practitioner's decision factors for this specific case study. The factors and their weights are represented in Figures 5.19- 5.23 and are used in the MCDA Promethee model developed for delivering the final decision support to the practitioner.

Figure 5.19 contains the average values for each of the four pillars of decision factors applied to this work. Although this work aims to support the implementation of CE, according to the practitioner's input and weighting of the decision factors, the most critical decision factors for applying a CE pathway to a returned batch are the financial ones. Second, the technical factors describe how suitable a product's design is for using a CE solution. Finally, social and environmental factors are part of the decision-making factors but are not identified as the main drivers.

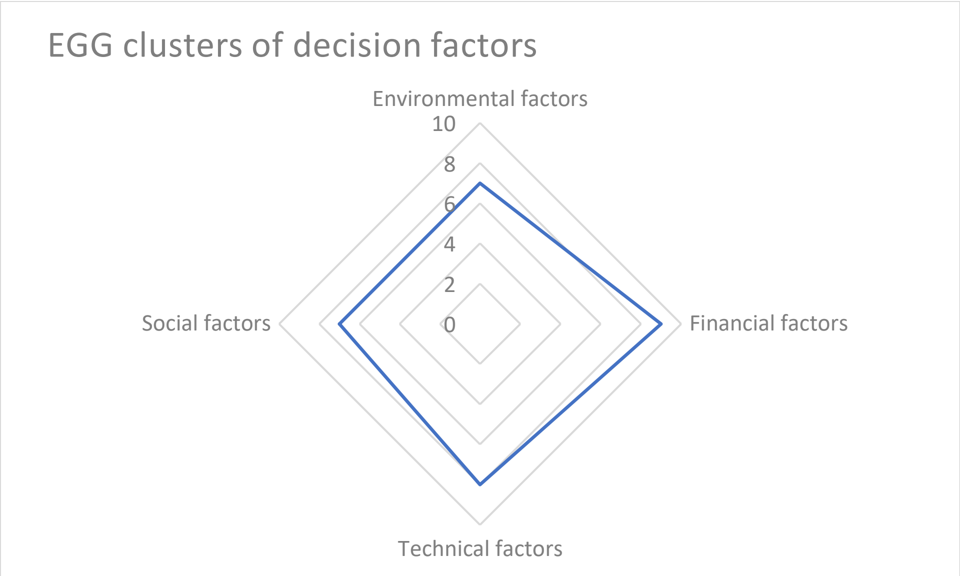


Figure 5.19: EGG clusters of decision factors

Figure 5.20 illustrates the environmental factors identified by the practitioner. Material waste and carbon emissions seem to be the most important, while water consumption and hazardous or toxic materials do not stand out. Water consumption is not as crucial due to the location of the main client of the business, Scotland, where water scarcity is not an issue. Moreover, after discussion with the practitioner, the hazardous or toxic materials used in the LEDs are limited and, thus, not a crucial decision factor.

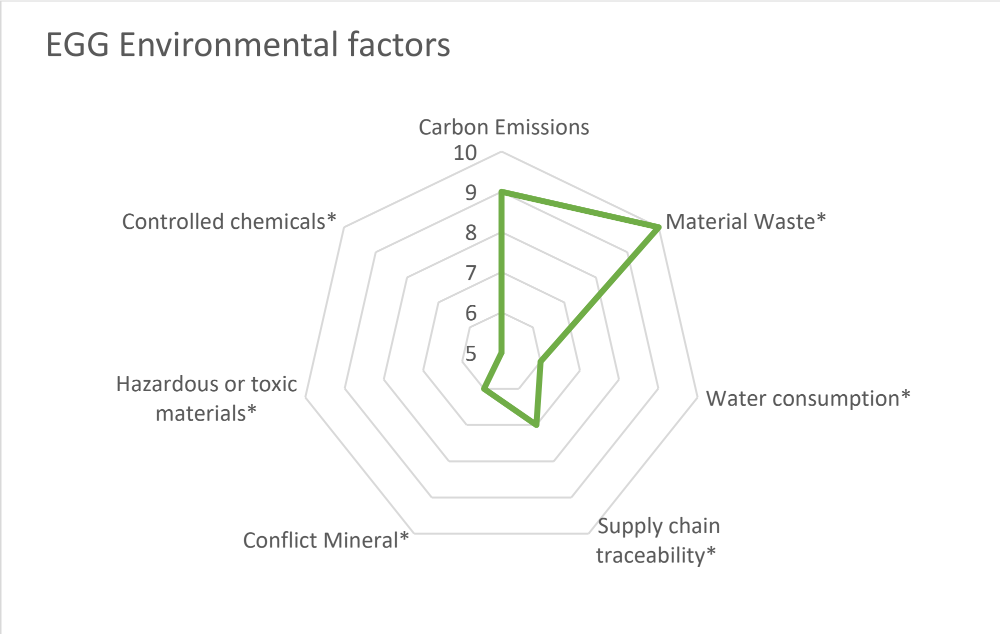


Figure 5.20: EGG Environmental factors

Figure 5.21 contains the financial factors, and it is evident that all of them are critical for decision-making. The practitioner commented that low costs are slightly more important than profits due to the stable demand and the servitisation business model.

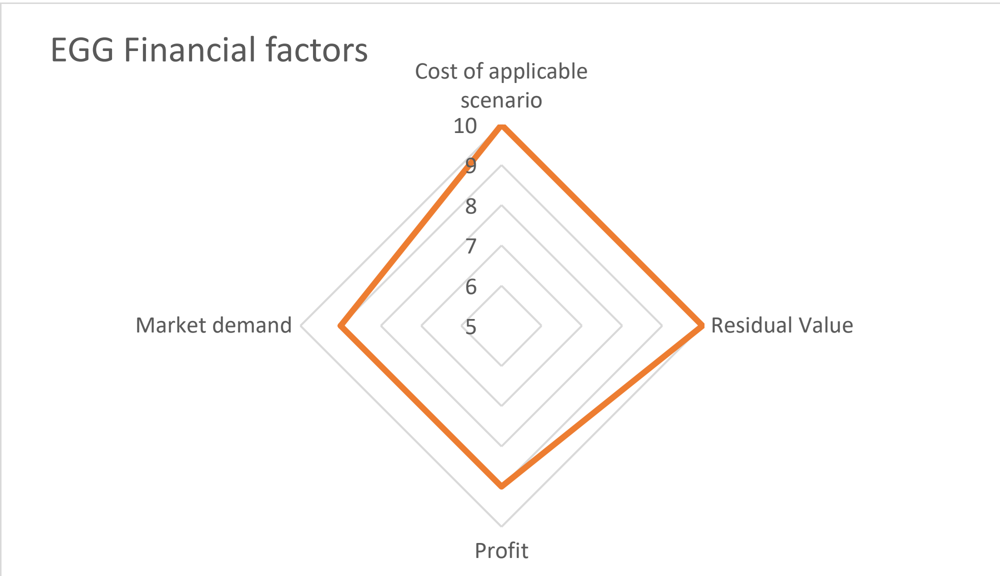


Figure 5.21: EGG Financial factors

Figure 5.22 includes the technical decision factors that describe the suitability of the returned batch for remanufacturing. Interestingly, the batch quality is not a critical issue for the returned batch; the practitioner claimed that since the business model applies remanufacturing to a great extent, as long as the batch quality is within the profitable margins, the quality stops being critical. On the contrary, the availability of components is crucial, as well as eDiM, a metric used to express the ease of dis- and re- assembly.

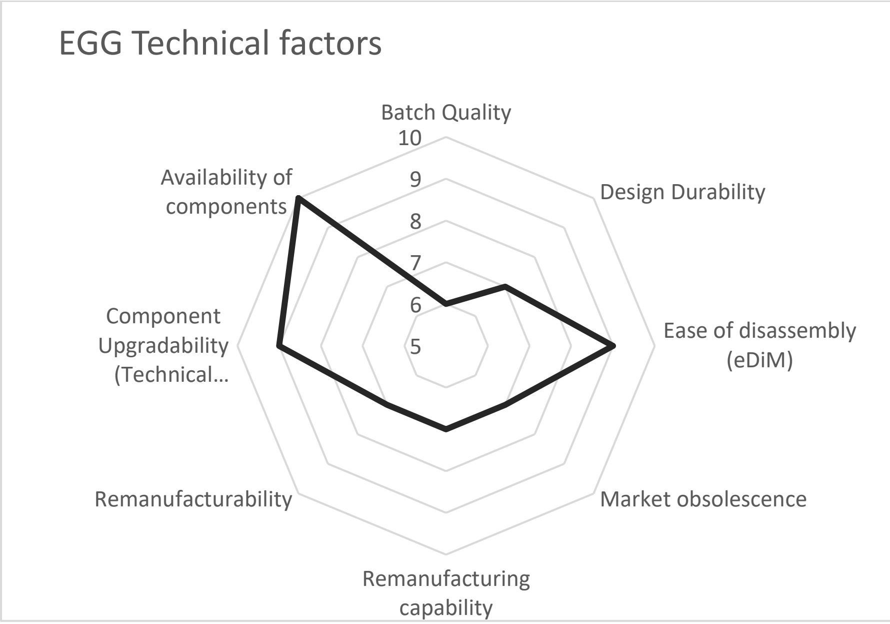


Figure 5.22: EGG Technical factors

Figure 5.23 illustrates the social factors taken into consideration in this study. As depicted, their importance is limited for the company in their decision-making for remanufacturing or not returning a batch.

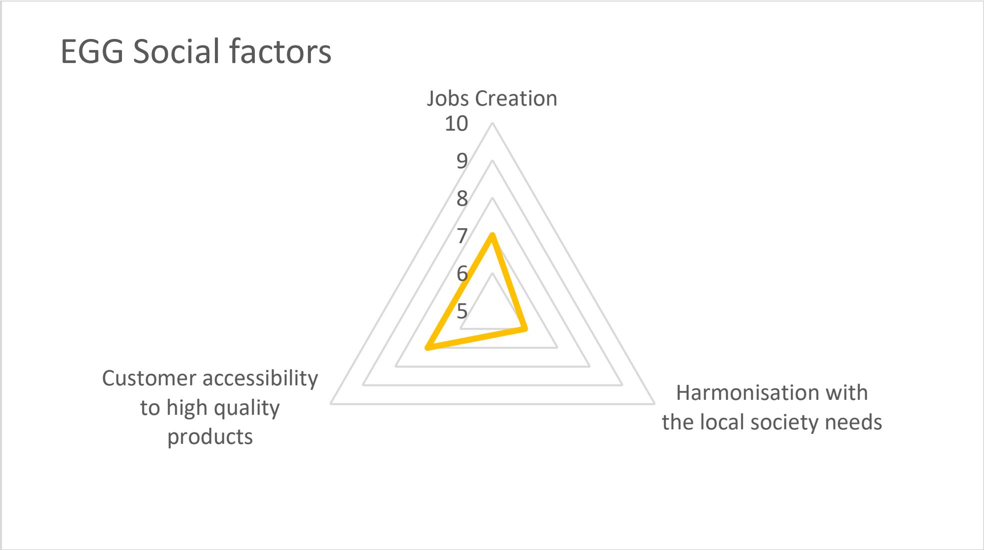


Figure 5.23: EGG Social factors

All the factors and their weights are fed into the Visual Promethee II full-ranking method, and that software provides the final solution of the method.

5.6.4 Solutions Ranking

The solutions ranking emerges from Visual Promethee II by feeding the model the decision factors: the criteria, their weights and the available pathways (actions).

Figure 5.24 illustrates some of the decision factors that act as criteria in the Visual Promethee MTDM model developed for this case study, more specifically, the design's cost, carbon emissions and obsolescence. The cost and carbon emissions factors are quantitative, and their values for the EoL pathways (described as actions in Visual Promethee) have been calculated based on the pre-screening process and the financial and environmental analysis described in the previous chapters. The rest of the factors, such as the obsolescence, are qualitative, and their evaluation for each EoL scenario (actions) is based on a 5-point qualitative scale. The practitioner inputs the evaluation values. It is crucial to remind the reader that recycling and disposal include, as part of the solution, purchasing a batch of new products to satisfy the market needs, and that purchase is captured in all the factors.

Scenario1	Cost	Carbon Emis...	Obsolescense
Unit	unit	unit	5-point
Cluster/Group			
Preferences			
Min/Max	min	min	max
Weight	46.00	15.43	19.29
Preference Fn.	Linear	Linear	Linear
Thresholds	absolute	absolute	absolute
- Q: Indifference	$ 1.00	1.00	1.00
- P: Preference	$ 2.00	2.00	2.00
- S: Gaussian	n/a	n/a	n/a
Statistics			
Minimum	$ 2.83	0.04	3.00
Maximum	$ 25.10	42.20	5.00
Average	$ 16.59	22.21	4.00
Standard Dev.	$ 9.25	17.25	1.00
Evaluations			
Reuse	$ 2.83	0.04	average
Remanufacture	$ 13.44	11.13	average
Recycle*	$ 25.10	35.49	very good
Disposal*	$ 25.00	42.20	very good

Figure 5.24: Decision Factors (Criteria) Analysis

For greater ease, the factors considered in the study have been grouped into four main categories: environmental, social, technical, and financial. The relative importance of each category is represented in Figure 5.25, where the weights assigned to each cluster reflect the average weights of the individual decision factors within that cluster. The weighting process involved each factor being rated on a scale from 1 to 10 based on practitioner input through a questionnaire. On this scale, a rating of 10 indicates the highest importance. These ratings were then translated into weighted values to denote the significance of each factor within its respective category.

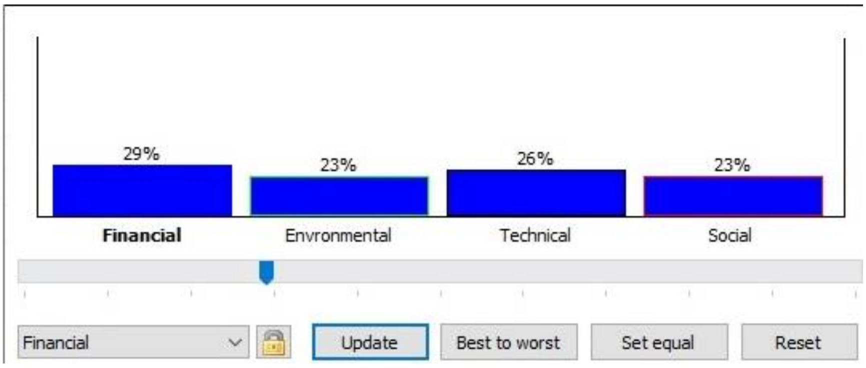


Figure 5.25: Weights of the decision clusters

The results of the MTDM model are presented in Figure 5.26 for the weights described in Figure 5.25. Using the GAIA illustration tool, the practitioner can learn how each of the available EoL pathways (or actions in visual Promethee) performs for each cluster of decision factors. As a rule of thumb, the closer a decision cluster is located to an available solution (action), the better that solution performs for that cluster.

As depicted, the best-ranked solution from the available ones is remanufacturing the batch. Technical criteria are best satisfied through recycling since a new product will be bought. Remanufacturing performs much better in social and environmental criteria. Interestingly, the environmental and financial criteria are perfectly aligned; thus, the financial criteria are not illustrated in the graph depicted in Figure 5.26.

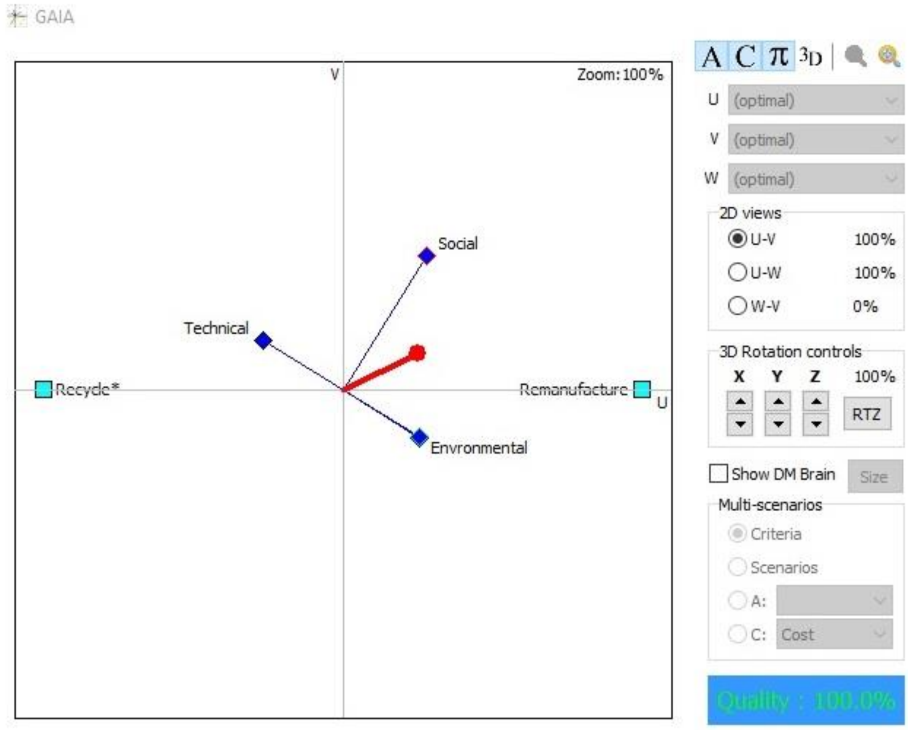


Figure 5.26: GAIA results of the MTDM model

Thus, the final result of the developed method for the batch of the 500 returned luminaires would be to remanufacture them with the details included in Table 5.20:

Table 5.20: Final result of the method and best-ranked solution

			Batch size	500	
	per luminaire		**whole batch**		
EoL pathways	**Cost**	**Env. Impact (kgCO2 eq)**	**Cost**	**Env. Impact (kgCO2 eq)**	**Result**
Remanufacture	$13.44	11.13	$6,720.00	5565	Best ranked
Recycle	$25.10	35.49	$12,550.00	17745	2nd best ranked
Reuse	$2.83	0.04	$ 1,415.00	20	Not applicable
Disposal	$25.00	42.2	$12,500.00	21100	Not applicable

5.6.5 Sensitivity analysis of the results

a) Decision factors and weighting

One of the most interesting tools Visual Promethee software provides is the ability to perform a 'walking weights' analysis. This sensitivity analysis provides insights into the weights for each decision cluster and how their impact could alter the proposed solution. In the following paragraphs, some scenarios of great interest have been selected for further analysis. In all the scenarios and all the EoL pathways, the batch data, financially and environmentally, have been the same as predicted from the pre-screening process.

One of the initial scenarios analysed involves assigning equal weights to all decision clusters (criteria), each set at 25%, as illustrated in Figure 5.27. This particular scenario was chosen to facilitate an understanding of how each EoL pathway performs across the various decision factor clusters. The analysis utilized the GAIA method, also depicted in Figure 5.27, which enables a comprehensive evaluation of the performance of EoL pathways in relation to each cluster of decision factors.

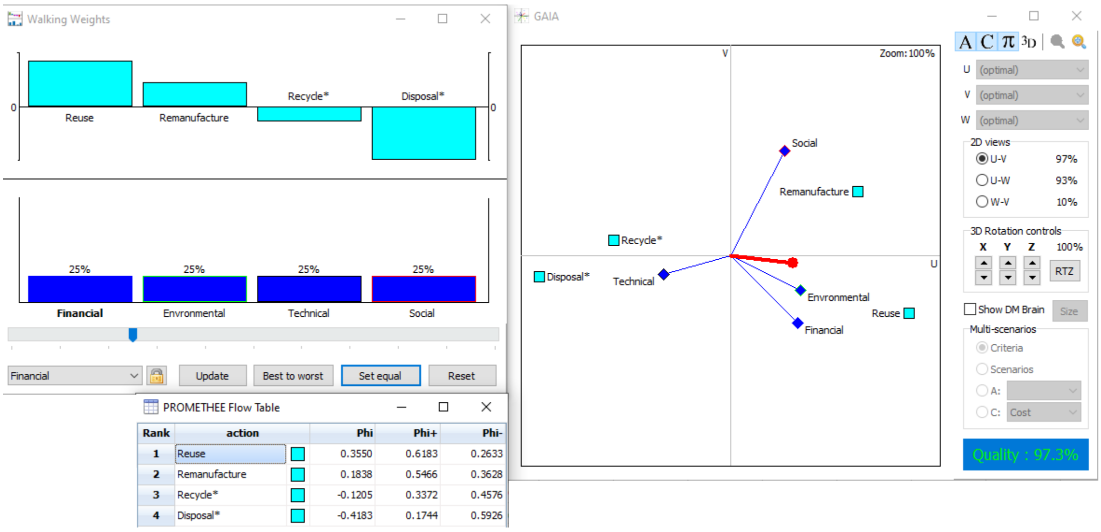


Figure 5.27: Walking weights & GAIA, batch data same, all clusters have equal importance

In the analysis presented in Figure 5.27, reuse emerges as the highest-ranked pathway, particularly in the figure's 'walking weights' section. This ranking is further supported by the data from the flow table in the same figure. Direct reuse is particularly effective in satisfying the financial and environmental decision clusters. Direct reuse entails minimal costs, primarily associated with inspection and cleaning, and does not require component replacement, resulting in a very low environmental impact. However, what reuse lacks is efficiency in technical performance, an aspect better addressed by disposal and recycling. Both these scenarios involve purchasing a new product, either identical or similar, to meet demand, ensuring superior technical characteristics compared to direct reuse.

Remanufacturing, on the other hand, stands out in the social cluster. It contributes positively to the local community by providing employment opportunities and reducing environmental impact. Furthermore, remanufacturing aligns well with the goals of harmonizing the community's needs and aspirations, making it a socially beneficial EoL pathway.

An additional insight from this analysis is the impact of assigning zero importance to one of the decision clusters. In such a scenario, the EoL pathway that previously performed best in the de-emphasized cluster will be disadvantaged compared to the other pathways. This is demonstrated in Figure 5.28, where social factors are given almost no weight in the decision-making process, shifting the focus predominantly to financial considerations. This scenario mirrors a significant aspect of reality, as observed during the evaluation workshop, where many companies engaged with the research seemed to prioritize financial factors over social ones.

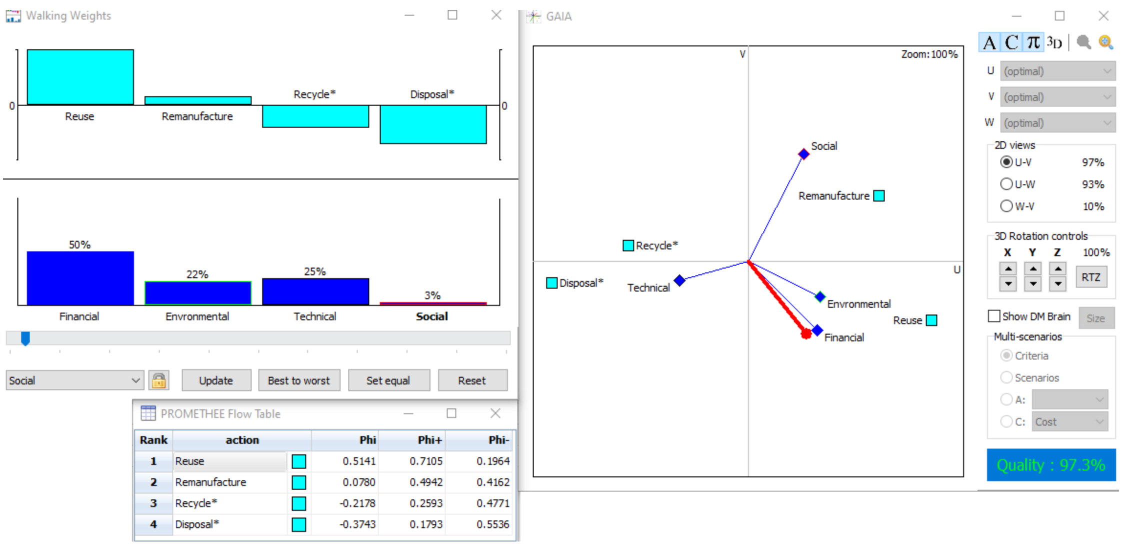


Figure 5.28: All EoL pathways, social cluster almost of zero importance

Interestingly, in these scenarios, the cost of remanufacturing the batch and environmental impact is kept the same as calculated from the pre-screening process: \$13.44 and 11.13 kgCO_2 eq on average per product, raising the question of what the threshold value for that cost is for remanufacturing to be third in ranking and recycling to be a more viable solution. After some analysis, it appears that when environmental impact is kept the same at 11.13 $kgCO_2$ eq as before when the cost of remanufacturing is set to $26.2 and above, recycling is a better option than remanufacturing. That reveals the great advantage of remanufacturing from a holistic point of view since the rest of the decision factors tip the scale towards remanufacturing than recycling, promoting a much greener solution. Additionally, only 8 of the 31 (or 26%) remanufacturing scenarios have an estimated cost above the threshold value of $26.2, which means that such a cost is not so common, strengthening the case for remanufacturing being a viable solution for this existing product design.

Another interesting scenario for further analysis is when the technical decision factors, which include technical obsolescence and outdated products, are the most important. Such a case could happen for products such as smartphones or other products with limited shelf-life, as consumers are more prone to changes due to upgrades or trends. Following the same analysis pattern and keeping all EoL pathways available, when the weight of the technical factors is above 46%, recycling is a better solution than direct reuse and remanufacturing, as indicated by the action profile and the flow table in Figure 5.29.

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	Recycle*	0.0922	0.4217	0.3295
2	Reuse	0.0804	0.4490	0.3686
3	Remanufacture	-0.0505	0.3935	0.4440
4	Disposal*	-0.1222	0.3045	0.4267

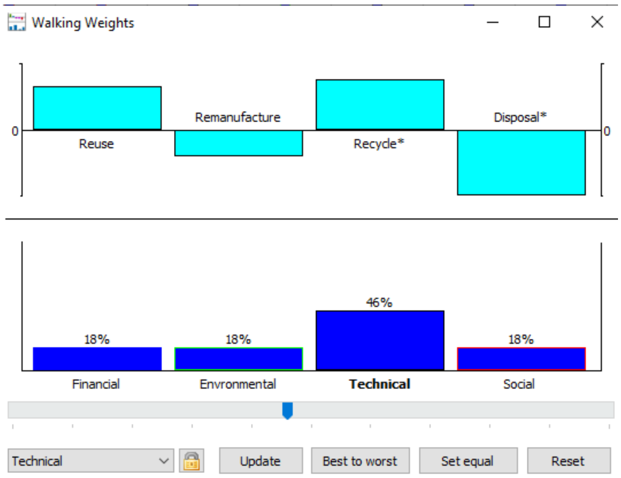


Figure 5.29: Walking weights, all EoL solutions, break point for technical factors

That reveals that a luminaire with an outdated technical capability might be better recycled than remanufactured based on the practitioner's input. Such a case can be supported by an LCA that includes the usage stage as well since it can calculate the environmental impact and running cost of usage of the product during the usage stage, which might be significantly different from a more updated product. This observation underscores that in order to achieve a lower overall environmental impact, the usage stage must be included in the analysis, particularly when remanufacturing is considered a feasible EoL pathway. This inclusion is critical because the efficiency of the product during its use is a key factor in determining its carbon emissions.

5.7 Discussion of the results

Following the case study description, the developed method was applied to a batch of 500 luminaires that had been in use for the past five years. The decision support for the batch's EoL treatment was provided based on the luminaire's condition, practitioner inputs, and a detailed analysis of its design using the proposed method. This analysis concluded that remanufacturing was this batch's most appropriate EoL pathway. Recycling was the only other feasible option, as direct reuse and disposal were not viable due to specific solution constraints. In the evaluation, remanufacturing outperformed in the social, financial, and environmental clusters, whereas recycling had an advantage only in the technical cluster. For recycling to be ranked higher than remanufacturing in this scenario, the technical decision cluster would need to be assigned significantly more importance – specifically, a threshold value of 46% importance for the technical cluster, with the remaining three clusters at 18% each, when considering all EoL pathways. The sensitivity analysis provided a deeper understanding of the method's outcomes and how the weights assigned to different decision clusters influenced the final ranking of the EoL options.

From a structural representation perspective, the application of HALG for the luminaire and its integration with the eDiM tool provided a standardised approach to estimating the time needed for dis- and re-assembly of the product. In this case study, the key components were easily allocated in a hierarchy due to a clear sequence of tasks required to access each component. The time distribution, as measured by the eDiM tool across its different categories, offered insights into potential design optimization areas. For instance, 'snap-fit' connectors that required no tooling significantly expedited the disassembly and reassembly processes, indicating a clear opportunity for optimizing the luminaire design to better align with *Design for Remanufacturing* principles.

The development of CEDA allowed the practitioner to assess the suitability of the luminaire’s existing design for implementing a CEBM. Remanufacturing seems greatly advantaged from CEDA since it links the component replacement scenarios with quantified environmental data and costs. The creation of the four areas, as depicted in Figure 5.13, provides the practitioner with a quantified answer on how well a product is designed for remanufacturing. The luminaire proves to be a highly suitable product for remanufacturing since 74.2% of the remanufacturing scenarios belong to the sustainable area, and the remaining 25.8% belong to the trade-off with environmental preference area.

Additionally, through the CEDA, the practitioner can identify scenarios of high interest or probability of occurrence and measure their performance. In this case study, those scenarios replaced the LEDs and the driver in any possible combination. The proposed method was able to quantify the impact of those scenarios among 29 more remanufacturing scenarios and provide the basis for a ‘*rule of thumb’* core acceptance strategy.

In this case study, the ability to assign weights to decision clusters and individual decision factors emerged as a significant advantage of the proposed method. The practitioner was afforded the flexibility to determine the weights for each decision cluster, with the results being promptly displayed. Moreover, sensitivity analysis techniques like 'walking weights' from the visual PROMETHEE software allowed the practitioner to observe how changes in the weights of decision clusters impacted the final ranking of the available EoL pathways.

When these findings were presented to the decision-maker, they recognized the potential of using predefined weight profiles for decision clusters to streamline the process in future applications. Examples of such profiles include a 'neutral' profile, where all decision clusters are weighted equally; a 'strongly positive environmental' profile, where environmental considerations are given substantial precedence; or a profile emphasizing the technical cluster. These profiles offer a quicker and more efficient approach to decision-making by predetermining the weight distribution based on specific priorities or objectives.

5.8 Chapter Summary

This chapter presented the findings that emerged from applying the developed method in a fully operating context through the case study of the 'Strathclyde' luminaire from EGG Lighting. Multiple objectives were addressed through this technique since the industry provided feedback on the method and tailored it to its needs, and the utility of the method was evaluated, as well as its accuracy and applicability.

The case study from the lighting sector pushed the method to be more sector-specific with, tailoring the solution constraints to their needs and developing a guarantee and lifespan process that covered the key components' main quality criteria. Additionally, the implementation of the HALG method provided the company with a clear dis- and re-assembly process and the use of eDiM as a metric of dis- and re-assembly timing offered a standardised way to predict the time for each process based on the type of connectors type, tools used, the size of the product and the handling that it requires. Based on a detailed LCA and financial analysis of the remanufacturing process, the CEDA analysis assessed the remanufacturability of the existing product design and communicated that result in an unambiguous way to the practitioner. The pre-screening process developed for this case study created a prediction model that can be used to estimate the costs and environmental impact of returned batches after their usage stage. The solution constraints identified the main pillars of adverse factors that might make one or more of the EoL pathways unviable. Finally, the decision factors questionnaire and weighting in the Promethee model provided the practitioner with a deeper understanding of the main enablers for remanufacturing a batch.

After capturing the practitioner's input through each stage, some results emerged. Firstly, based on the LCA, the driver and the LED strips were the main contributors to environmental impact. Thus, reusing the driver will result in a significantly reduced environmental impact. Additionally, based on the financial analysis of the remanufacturing scenario, the existing design of the 'Strathclyde' luminaire is considered very promising for the application of a service-based business model, thus achieving circularity, since almost 75% of those scenarios are financially preferable to buying a new product. From the solutions constraints process, it was identified that there is a lot of potential, both financially and environmentally, by implementing direct reuse in a secondary market where the efficiency of the LEDs is not the primary customer demand. Due to the quality of the returned batch, direct reuse and disposal were not feasible in this case study due to the legislation restrictions. Finally, the decision factors and their weights provide the Promethee model with the prerequisite input for calculating the ranking of the available EoL pathways, with remanufacturing the batch being the most favourable over recycling and purchasing a new identical or similar batch.

In the discussion, further analysis was provided on scenarios of special interest. For each EoL pathway, the best-performing cluster of decision factors was identified, allowing the practitioner to gain additional knowledge on the main drivers for each pathway. It revealed that obsolescence is not a key issue in the lighting industry, where products have a long shelf life and are not considered outdated relatively fast, and manufacturing and reusing have a significant edge over recycling or disposal. That edge alters when the main decision factors are the technical factors, which include obsolescence, with a significance greater than 46%, while the rest of the clusters have equal significance to 18%. In this scenario, recycling is the favourable EoL pathway since purchasing the new batch satisfies the need for an updated product much better. This is identified as one of the most adverse contributors to applying circular business models to products that are prone to fashion changes or quick technological developments.

In the next chapter, another application of the developed method from the oil and gas industry will be presented to illustrate how the method is sector agnostic, as well as an evaluation of the method through another practitioner and its results.

6 Case Study B: Bladder Accumulator

This chapter presents the second case study of the proposed method to illustrate the applicability of the proposed framework to a sector utterly different from the previous one. The product of choice is the generic 20-litre bladder accumulator from the Oil and Gas industry. This chapter will use the same methodological approach as Chapter 6 and will use the data received from the collaborating company in a detailed step-by-step application of the proposed method. After an overview of the case study found in Chapter 6.1, Chapters 6.2 and 6.3 contain the product characteristics and the structural analysis of the product, respectively. In greater detail, chapter 6.4 includes the product's environmental assessment and 6.5 the CEDA analysis. Chapter 6.6 describes the decision-making process, the practitioner's input regarding the constraints of the solution, the weights of the decision factors and the solution raking, which is the final output of the developed method. Chapter 6.7 discusses the application of the method in this case study, and chapter 6.8 summarises the content of chapter 6.

6.1 Case study overview

6.1.1 Company Introduction

The company collaborating with the second case study and applying the proposed method will remain anonymous and be named the '*Accumulator Company' or 'AC'* from this point on. This medium-sized company is part of one of the world's leading manufacturers of gas-loaded bladder, piston and diaphragm accumulators. Their offerings range from standardised products to bespoke solutions, and applications of their products can be found in multiple industries such as offshore, subsea and petrochemical to mining, mobile and defence.

AC, as a 'B2B' OEM, is part of the supply chain for multiple companies and diversified sectors. Their customers, driven by their dedication to limiting their environmental impact across their organisation, have initiated conversations about applying a CEBM regarding the accumulators purchased from AC. AC's goal for participating in this study is to gain knowledge on the remanufacturability of their selected product and holistically explore the EoL CE pathways.

6.1.2 *The company's current and CEBM operation*

AC applies a linear B2B model where the product's EoL stage is the final customer's responsibility. According to discussions with the company, AC is currently unaware of the EoL pathway that the client selects. Moreover, the criticality of the product's applications has acted as a discouraging factor for applying CE pathways, such as remanufacturing, reconditioning, or even repairing. Nevertheless, the company has shown interest in understating the potential of their products in their EoL and testing a CEBM similar to the one illustrated in Figure 6.1.

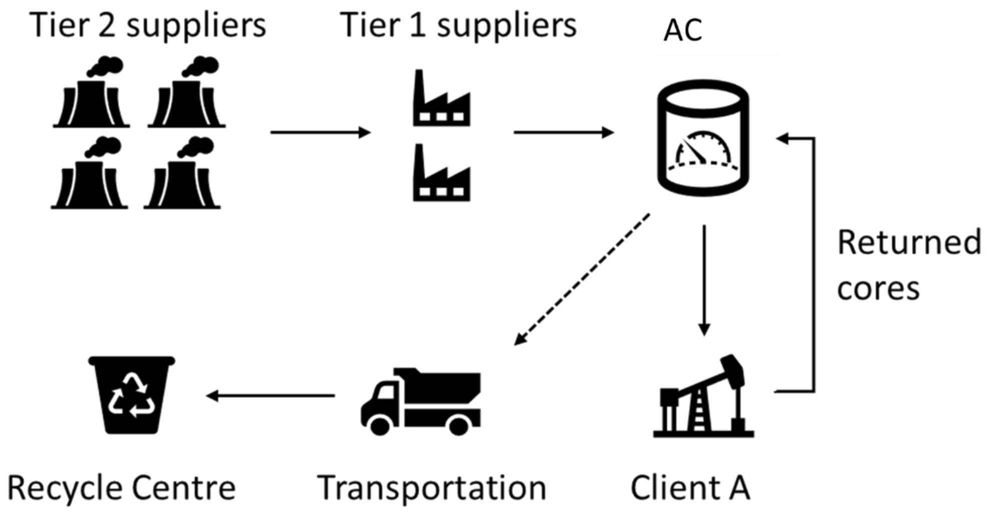


Figure 6.1: Circular Economy Business Model (CEBM) of the company

6.1.3 *Case Study Assumptions*

Similarly to the case study presented in Chapter 5, the proposed method will provide decision support after the end of the usage stage and answer whether a returned batch of accumulators should be remanufactured or directly recycled.

Additionally, the following assumptions have been made for the second case study, with many of them stemming from discussions with the company:

- As an OEM contemplating integrating remanufacturing into its operations, AC will take on the role of an Original Equipment Remanufacturer (OER). AC's properly trained engineers will handle all remanufacturing processes in this capacity. This arrangement necessitates the return of End-of-Use stage accumulators from the customers to AC. Given specific customer preferences, such as the exterior colour of the accumulators, the remanufactured units will be designated for use by the same clients who originally owned them.

- Accumulators that fail to meet the established quality standards for remanufacturing will not be processed further by the OER. Instead, these units will be sent directly to a recycling centre, ensuring that they are dealt with responsibly and in line with sustainability practices.
- A client has 100 accumulators they would like to replace with either new or remanufactured ones. The batch of 100 gas-loaded accumulators has been used for seven years in a process environment with a fluid that may be corrosive. The OER will use the proposed method to identify the most suitable EoL pathway for these end-of-usage stage cores.
- All the final products will be tested (100% testing).
- All the returned products have been used for the same time and in similar conditions.
- Selected assemblies will be considered as components, thus made of one material, and replaced fully. The selected material is based on the most dominant material of the assembly's sub-components.
- Only the selected key components are subject to replacement based on the decision support method. All other non-critical components are considered to have a significantly longer operational lifetime; thus, there is no need for replacement. Therefore, the replacement scenarios do not consider them.
- Some parts are considered consumables per usage and thus are always replaced no matter the condition of the core. Those are referred to as ‘always replaceable components’. Those components are replaced even in the ‘direct reuse’ EoL pathway.
- The components of the accumulator have been produced in China. The assembly of the accumulators has also taken place in China. Within the country, transportation has not been considered due to the limited impact and lack of accurate data.
- The EoL estimated values for each component of interest of the accumulator had been based on feedback from the company’s engineer.

- Due to the international nature of the supply chain, all the prices are expressed in U.S. dollars.
- The scrapping prices per material originate from experts (*Scrap Metal Prices*, n.d.) and the average values based on the year 2020 were selected after being converted to US dollars to kg (with a conversion rate of £1= $1.41).
- The average values between the highest and lower market prices were selected after converting U.S. dollars to kg (with a conversion rate of £1= $1.41).
- A used component is always replaced with a new identical, or similar one of equal functionality and monetary value when new.
- For materials for which recycling is not an option, the disposal rate per kilo of disposed material is set to $0.10 per kilo. This simplification of the recycling cost is based on discussions with companies from the Electrical and Electronic Equipment industry, and the same principles have been expanded to this case study.
- Direct reuse includes replacing the always-replaceable components, cleaning, and inspection costs per unit.
- We consider an average transportation of 50km per trip to the customer. The vehicle we considered was a small lorry transport, Euro 0, 1, 2, 3, 4 mix, 7,5 t total weight, 3,3 t max payload, which results in 0.000133 kgCO2 eq per 1 kgkm, as data captured in Ecoinvent 3.6 database.
- In the scenario of direct reuse, we consider two trips: the product recovery from the customer to the company's facilities and the trip to the new customer's facilities. For those trips, the average transportation of 50 km is applied.
- The environmental impacts of recycling and landfilling the product have been calculated for the whole product and then distributed to its components based on their weights and total weight.
- For a component of a lower disassembly level to be reached, all the components of the previous disassembly level must be disassembled.
- The accumulator components were produced in the same country where the assembly takes place; thus, no additional transportation has been calculated for each component or the raw materials.

- For the LCA results analysis, only components that have a contribution of one per cent or more (≥1%) to the manufacturing environmental impact will be considered for the EoL study, as stated in ISO 14040, which defines that the critical environmental issues arise when their contribution is more significant than 1% (K.-M. Lee & Inaba, 2004).
- The energy consumption of the electric tools used in the dis- and re-assembly processes have been integrated into the final environmental impact of remanufacturing. At the same time, the cleaning and testing of the product are considered to have zero effect based on input from the company's engineers.
- The eDiM calculation is based on average values after three trials and feeback from the AC's engineers.
- The weights of the components are equal to the weights of the raw materials since no data was available on the efficiency of the manufacturing processes.
- For assemblies that are interpreted as a component, the most suitable material has been selected to represent the assembly during this analysis, as advised by the company's engineer.
- The average inspection time is 7.5 minutes per accumulator.
- The average labour cost is £12.5 or $14.13 based on the transaction rate of 1 Pound sterling, which equals 1.1304 United States Dollars as of 22/10/2022 (Anon., n.d.).
- Regarding profit, we consider the following pricing model: reused or remanufactured accumulators are sold at 90% of the price of a new accumulator. The new accumulator is sold at $350.

Finally, all the assumptions regarding how the LCA was conducted are described in the relative chapter when defining the scope, system boundaries, functional units, etc.

6.2 Product Characteristics

The product selected for the second case study is a hydraulic bladder accumulator with a nitrogen-filled bladder for use in hydraulic systems. It is defined as a pressure vessel based on the pressure equipment directive 2014/68/E.U. Its primary function is to store pressure and then discharge that fluid to keep pressure stable in a hydraulic system. All work done in bladder accumulators requires well-trained, competent personnel since specific safety regulations must be met. Figure 6.2 illustrates the standard bladder accumulator and its key components selected for this case study.

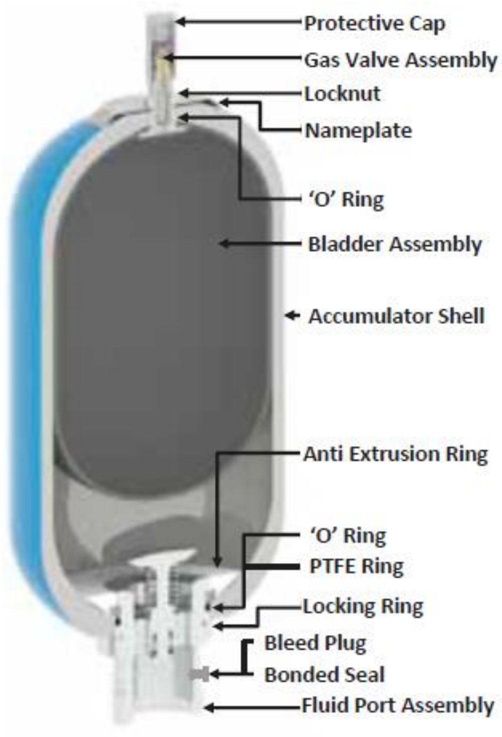


Figure 6.2: Selected standard bladder accumulator

6.3 Structural analysis of the product

In this case study, similar to the previous one, the first point of analysis is structural analysis. After selecting the specific product to apply the proposed method, the practitioner must submit the data related to the product's structure. These data are used for structural analysis and to develop the BOM, HALG, and eDiM, as in the first case study in Chapter 5. The application for each tool is presented in the following sections.

6.3.1 Bill of Materials (BOM)

The practitioner first uses a multilevel bill of materials (BOM) based on the product's components. Table 6.1 contains all the components of the accumulator and their weights, as seen below in a BOM format:

Table 6.1: Accumulator BOM

Component	Material	Weight (Kg)
Fluid Port 'O' Ring	Nitrile	0.005
Stem 'O' Ring	Nitrile	< 0.01
Gas valve assembly	EN 10088 1.4401/ Nitrile	0.05
Nameplate	1.4301 Stainless Steel	0.13
Fluid port backup Ring	PTFE	0.005
Accumulator Shell	34CrMo4	50
Bladder	Nitrile	1.25
Fluid port	17-4PH DH1150 Stainless Steel	3.4
Locking Ring	EN 10272 1.4401/1.4404	0.5
Poppet Valve	P460 NH	0.07
M6 Nyloc Nut	A2 Stainless Steel	< 0.01
Piston	17-4PH DH1150 Stainless Steel	0.005
Gas Valve Stem	EN 10088 1.4305	0.15
Filler Ring	Nitrile	0.45
Protective cap	EN 10088 1.4305	0.085
Gas valve Locknut	316 Stainless steel	0.04
Spring	BS2056 302S26 G2	0.01

Some of the parts presented, such as the gas valve assembly, are not a single component but an assembly and, thus, are not composed of a single material. Based on feedback from the case study company, the most suitable material has been selected to represent the assembly during this analysis. Additionally, during remanufacturing, these assemblies will be replaced at their full if needed and cannot be broken into smaller components. These are assumptions made during the BOM stage and verified by the company’s engineer. Using the list of materials, the practitioner moved to the next step, the development of the HALG graph, which will be presented in detail in the next paragraph.

6.3.2 Hierarchical Attributed Liaison Graph (HALG)

Table 6.2 contains the three main types of components for the accumulator: the *key*, the *always-replaceable* and the *consumables*. As defined in section 3.4, *key components* are the components, or assemblies acting as components, that the financial and environmental analysis of the proposed method is based upon for supporting the decision of which is the most suitable EoL pathway for an EoU product. Those components have been identified as '*key*' due to their functionality or cost importance.

The second category of components refers to the ones that are always replaced in the case of remanufacturing or direct reuse. Those, referred to as *always-replaceable*, are components related to faster erosion, safety, and critical aspects of the product's functionality. Those components' environmental impact and cost have been added to all the remanufacturing scenarios and the direct reuse.

Finally, the last category of product components refers to components with no significant cost, function, or complexity or are sub-components of an assembly. These components are considered consumables, and their replacement with new ones does not affect the remanufactured core's cost or environmental impact during the proposed method's analysis. Even though they are defined as consumables, this does not mean that they are short-lived components that need maintenance. On the contrary, due to their limited functionality, those components might be able to be used multiple times with no signs of fatigue.

In Table 6.2, *always-replaceable* components have a grey background, *key components* are light blue, and the *consumables* have a white background. The numbers in the first row of Table 6.2 refer to the accumulator's component number in the HALG. The bladder assembly includes the components 'bladder' as well as other components.

Table 6.2: Accumulator components categorisation

No	Part/ Assembly	Status
0	**Accumulator Assembly**	
1	Fluid Port 'O' Ring	Always replaceable
2	Stem 'O' Ring	Always replaceable
3	Gas valve assembly	Key Component
4	Nameplate	Always replaceable
5	Fluid port backup Ring	Always replaceable
6	Accumulator Shell	Key Component
7*	Bladder Assembly	-
7	Bladder	Always replaceable
8	Fluid port Assembly	Key Component
9	Locking Ring	Key Component
10	Retaining ring	Consumable
11	Poppet Valve Assembly	Part of the Fluid Port assembly
12	M6 Nyloc Nut	Part of the Fluid Port assembly
13	Piston	Part of the Fluid Port assembly
14	Gas Valve Stem	Key Component
15	Filler Ring	Always replaceable
16	Protective cap	Consumable
17	Gas valve Locknut	Consumable
18	Spring	Part of the Fluid Port assembly

Figure 6.3 demonstrates the HALG for the accumulator of choice. The figure was developed based on the information from the BOM in Table 6.1 and input from the practitioner. Keys or assemblies defined as components have been highlighted in red. According to the HALG, the accumulator has four distinct structural levels, while each line between levels, components, and assemblies represents a connection between them. A critical difference between the HALG and the multilevel BOM representation is that a BOM focuses on the components of an assembly. In contrast, a HALG focuses on hierarchically illustrating the connections between components and assemblies.

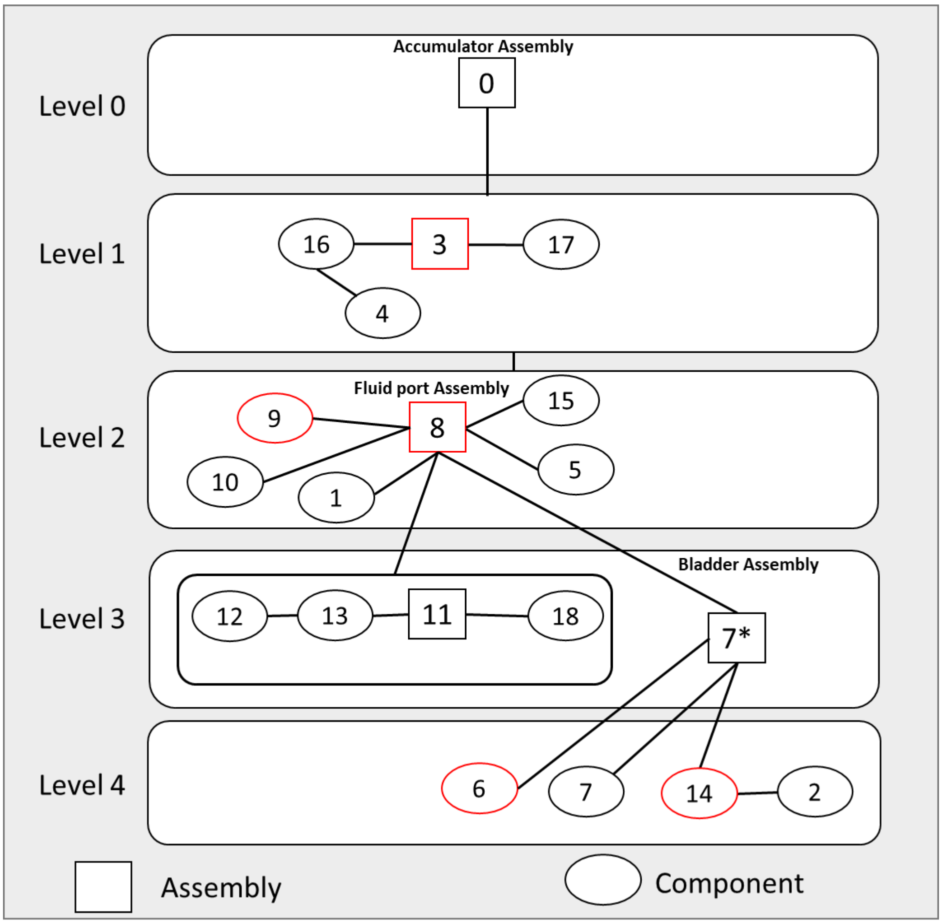


Figure 6.3: Accumulator HALG

Level 0, as depicted in Figure 6.3, refers to the accumulator assembly as a whole as a product. In the following analysis, the numbers in parentheses next to the components refer to their numbers in the HALG, as depicted in Figure 6.3.

Level 1 is the first step of disassembling the accumulator, which contains the protective cap (16), gas valve locknut (17), gas valve assembly (3), and nameplate (4). Components (16) and (17) are considered consumables due to their limited function and cost, while component (4) is regarded as always replaceable. The gas valve assembly (3) is a key component, and whether it will be replaced is part of the proposed method's decision analysis.

Level 2 is linked to level one and requires the disassembly of its components for the level 2 components to be accessible. Level 2 includes the key components, fluid port assembly (8), and locking ring (9). Additionally, level 2 consists of the always replaceable components: the fluid port 'O' ring (1), the fluid port backup ring (5), and the filler ring (15). Finally, it includes a retaining ring (10). Although the fluid port is an assembly, the decision to replace it or not refers to it as a whole; thus, it acts as a component in this method.

Level 3 is the following stage of the disassembly of the accumulator. It includes sub-components of the fluid port assembly. As discussed before, the practitioner considers that the decision for the fluid port to be taken is if it is replaced at its full; thus, no sub-components are part of this decision individually. Moreover, level 3 includes the bladder assembly (7*).

Finally, level 4 contains the always replaceable bladder (7), stem ‘o’ ring (2) and the key component accumulator shell (6). It also has the key component of the gas valve stem (14).

At this point, the practitioner has gained knowledge of the product's structure and the connections between its components and identified the key components that will focus on the remanufacturing process and its financial and environmental analysis. A critical outcome from the development of the HALG is the realisation that the always replaceable component of the stem ‘o’ ring is placed in the final level of the graph. Thus, remanufacturing of the accumulator will require disassembly up to level 4, regardless of the condition of the rest of the key components. Such a practice impacts the calculation of eDiM, as will be presented in the next chapter.

6.3.3 Ease of disassembly (eDiM)

This section describes the application of the eDiM to the accumulator as a method to estimate the disassembly and re-assembly time for each of the cores being processed. Quantifying the time needed through the standardised method of eDiM provides a basis for calculating labour costs. Similar to the case study described in Chapter 5, eDiM offers a transparent and comparable index on the effort needed to access and replace the selected key components and other components that might need replacing.

Table 6.3 contains the eDiM analysis for the disassembly, and Table 6.4 includes the re-assembly analysis.

Table 6.3: eDiM analysis for the disassembly

eDiM disassembly														
Component number	Side/ component	Disassembly sequence of components	Disassembly sequence of connectors of components	Number of connectors	Number of product manipulations	Tool type	Cleaning **(sec)**	**Tool change (sec)**	**Identification of connectors**	**Manipulation (sec)**	**Positioning (sec)**	**Disconnection (sec)**	**Removing (sec)**	**eDIM(dis) (Sec)**
		Initial positioning									60			
3*		Gas valve assembly	**LEVEL 1**											**273**
16		Remove Protection Cap (16)		1	0	Hand	5		14.4				1.4	20.8
3		Remove Gas Valve Cap (3)		1	0	Hand	5			15	2.8	2.8	1.4	27
	Gas Side	Fit portable charging set to discharge any gas until it reads zero		2	0	1 x 19mm spanner 1 x 16mm spanner		5.6		15	2.8	2.8	15	41.2
		View through Fluid Port to see the position of the Poppet Valve to see if there is any trapped gas (Health and Safety)		0	0	Endoscope		2.8	15	15	2.8	0	1.4	37
		Remove Charging Set		2	0	1 x 19mm spanner		5.6	14.4	15	2.8	5.6	1.4	44.8

						1 x 16mm spanner								
17			Remove Locknut (17)	1	0	1 x 22mm spanner	5	2.8			2.8	2.8	14	27.4
4		Remove nameplate (4)		1	0	Hand	5				5.6	2.8	1.4	14.8
		Fluid Port Assembly	**LEVEL 2**											**205.6**
9			Remove Locking ring (9)	1	0	1 x C spanner 1 x hammer	5	5.6	14.4		2.8	2.8	1.4	32
		Push Fluid Port inside of the Shell		0	0	Hand	5	2.8		25	2.8	14	1.4	51
5		Remove Back-up ring (5)		0	0	Hand					2.8	5.6	1.4	9.8
1		Remove Fluid Port "O" Ring (1)		0	0	Hand					2.8	2.8	1.4	7
15	Fluid Side	Remove Filler Ring (15)		0	0	Hand				14.4	2.8	2.8	1.4	21.4
8		Remove Fluid Port from Shell (8)		0	0	Hand	5			14.4	2.8	2.8	1.4	26.4
10			Remove Retaining ring (10)	1		Hand				14.4			14.4	28.8
12			Remove Nyloc Nut (12)	1	0	6mm socket	5	2.8	14.4		2.8	2.8	1.4	29.2
			LEVEL 3											**70**
13		Remove Piston (13)		0	0	Hand	5	2.8		14.4	2.8	14	1.4	40.4
11		Remove Poppet Valve (11)		0	0	Hand	5			8.4	2.8	2.8	1.4	20.4
18		Remove Spring (18) from Poppet Valve		0	0	Hand	5				2.8	0	1.4	9.2
			LEVEL 4											**167.6**
7	Bladder	Remove Bladder (7) from Shell		0	0	Hand					2.8	14	1.4	18.2

2		Remove Stem 'O' Ring		0	0	Hand					2.8	8.4	1.4	12.6
14		Remove Gas Valve Stem		0	0	Hand					2.8	8.4	1.4	12.6
6	Accumulator Shell	Shell (6) is now empty of all components		0	0		120				2.8	0	1.4	124.2
		Total					175	30.8	72.6	151	118.8	98	70	**716.2**

Based on data from Table 6.3, a pie chart was developed to visualise the main disassembly tasks and their percentage of time for the accumulator, as depicted in Figure 6.4. The additional time for cleaning each part has been added to the total eDiM per component but is not captured in Figure 6.4. eDiM aims to standardise actions, but it does not include cleaning time. As a result, it was decided that the time needed for cleaning should not be captured in Figure 6.4 but still be a part of the total eDiM time and Table 6.3.

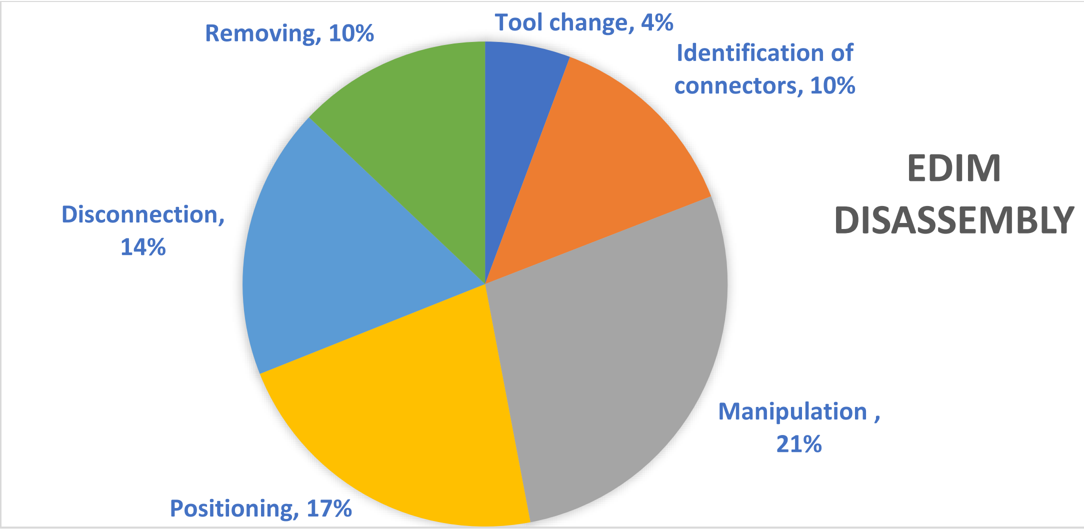


Figure 6.4: Percentage of the duration of disassembly tasks for the accumulator

According to Figure 6.4, most of the time is needed to manipulate the components. This aligns with the experience of the company's practitioners since most of the components are bulky and positioned tightly, requiring specific actions for the component to be freed. As a result, the second most time-consuming task is *positioning*, which refers to correctly positioning the tool. This is because of the tight space inside the accumulator's shell and the limited space to provide faster access to the connectors. *Removing* refers to the time needed to remove and place the unfastened component in the trays/ bins. In contrast, *Disconnection* refers to the time required for performing the task of disconnecting a connector. That is why disconnecting the connectors is 14% of the total eDiM time while removing is only equal to 10%.

Similarly to Table 6.3, Table 6.4 has been developed to illustrate the time needed for each standardised task using the eDiM methodology when re-assembling the accumulator. The actions and components in Table 6.4 are captured in a reverse sequence than in disassembly expressed through Table 6.3 since that would be their sequence during re-assembly. The final eDiM for each of the components of interest is calculated based on the eDiM for dis- and re-assembly, and it is equal to the sum of the eDiM(dis) and eDiM(re) assembly for that component.

Table 6.4: eDiM re-assembly of the accumulator

eDiM re-assembly													
Component number	Side/ component	Re-assembly sequence of components	Re-assembly sequence of connectors of components	Number of connectors	Number of product manipulations	Tool type	**Tool change (sec)**	**Identification of connectors**	**Manipulation (sec)**	**Positioning (sec)**	**Connection (sec)**	**Installing (sec)**	**eDiM(rea) (sec)**
	Gas Side									60			
6	Accumulator Shell	Shell is now empty of all components		1	0	Water/ lubricant pressure machine	11.2		60	2.8		60	134
2		Insert Stem 'O' Ring		0	0	Hand				2.8	8.4	1.4	12.6
14		Attach Gas Valve Stem		0	0	Hand				2.8	8.4	1.4	12.6
7	Bladder	Place Bladder (7) to Shell		0	0	Assembly guide	11.2		60	42	28	120	261.2
			LEVEL 4										**420**
18		Install Spring (18) from Poppet Valve		0	0	Lubricant gun	11.2			28	0	1.4	40.6
11	Fluid Side	Install Poppet Valve (11)		0	0	Lubricant gun	11.2		120	2.8	0	1.4	135.4
13		Insert Piston (13)		0	0	Hand			60	2.8	2.8	1.4	67
			LEVEL 3										**283**
8	Fluid Side	Fluid Port		0	0	Hand				2.8	2.8	28.8	34.4

10			Install Retaining ring (10)	1		Hand			14.4			14.4	28.8
8		Push Fluid Port inside the Shell		0	0	Hand				2.8	10	1.4	14.2
15		Install Filler Ring (15)		0	0	Hand				2.8	2.8	28.8	34.4
1		Install Fluid Port "O" Ring (1)		0	0	Hand				2.8	2.8	28.8	34.4
5		Install Back-up ring (5)		0	0	Hand				2.8	2.8	28.8	34.4
12			Install Nylon lock Nut (12)	1	0	6mm socket	1.4	0		2.8	7.6	1.4	13.2
9			Install Locking ring (9)	1	0	1 x C spanner 1 x hammer	22.4	0		14.4	11.2	11.2	59.2
			LEVEL 2										**536**
4	Gas Side	Install nameplate (4)			0	Hand				2.8	11	1.4	15.2
17	Gas Side		Install Locknut (17)	1	0	1 x 22mm spanner	2.8			2.8	2.8	14	22.4
	Gas Side	Install Charging Set		1	0	1 x 19mm spanner 1 x 16mm spanner	2.8	0		2.8	2.8	1.4	9.8
	Gas Side	View through Fluid Port to see the position of the Poppet Valve to see if there is any trapped gas (Health and Safety)		0	0	Endoscope	1.4		15	2.8	0	1.4	20.6
	Gas Side	Fit portable charging set to discharge any gas until it reads zero		2	0	1 x 19mm spanner 1 x 16mm spanner	22.4			2.8	5.6	15	45.8
3	Gas Side	Install Gas Valve Cap (3)		0	0	Hand				2.8	0	2.8	5.6
16	Gas Side	Install Protection Cap (16)		1	0	Hand						2.8	2.8
		Gas valve assembly	**LEVEL 1**										**122**
		Total					98	0	329.4	192	110	369	**1361**

Comparably to the previous analysis, Table 6.4 is the basis for creating the pie chart that visualises the time spent in each task category. Figure 6.5 illustrates that visualisation. In Figure 6.5, *removing* has been replaced by the word *installing* since this term better expresses the actions of placing components from the tray to the remanufactured product. Similarly, the term ‘connection’ has replaced ‘disconnection’ to convey the nature of re-assembly more efficiently.

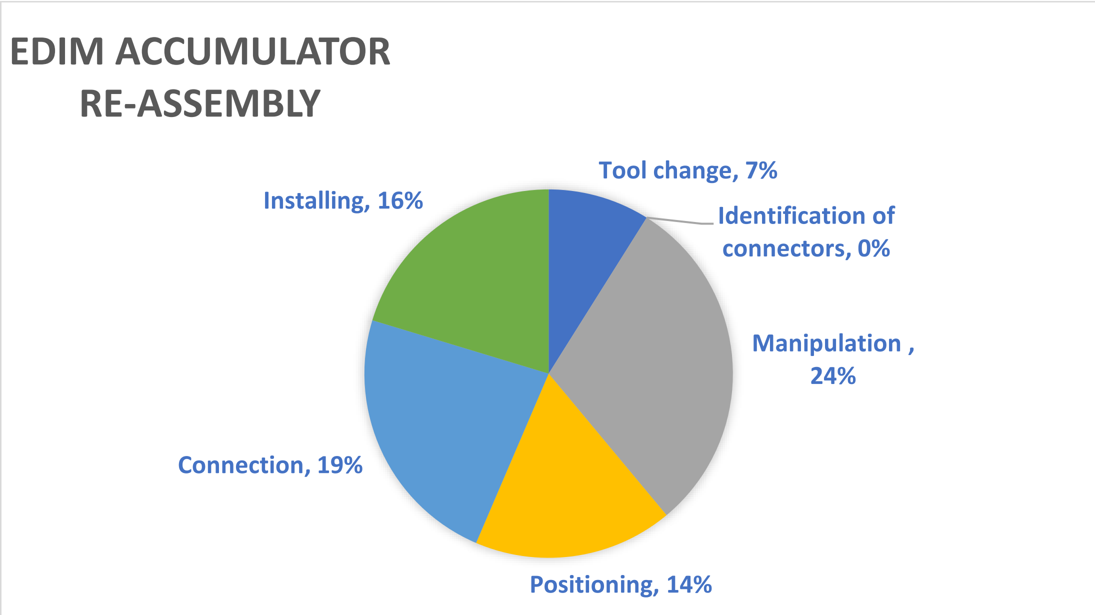


Figure 6.5: Percentage of the duration of Re-assembly tasks for the accumulator

Based on Figure 6.5, manipulation is again the most time-consuming action, with 24% of the total time, while connection follows with 19%. The reasons for this allocation of time stay the same. *Identification of connectors* is 0% since the re-assembly requires backtracking the disassembly steps; thus, no connectors are unknown to the practitioner at this stage.

The eDiM analysis provides a powerful tool for evaluating the time spent across the key tasks when dis- and re-assembling a product. Such results can spark the conversation about whether specific tools can be used to support the manipulation of the multiple components to mitigate the time needed for this task. Finally, the categorisation is also used to illustrate to the upper management the time spent by the operators in the dis- and re-assembly process. It can be used to develop the remanufacturing process and its further optimisation.

6.3.4 Components replacement scenarios

As described in Chapter 3, this study uses an approach that creates multiple remanufacturing scenarios based on what combination of the identified key components are replaced. The accumulator has been identified to have five key components; thus, 32 distinct scenarios have been developed. As described in section 6.3.2, some assemblies have been defined as components due to their functionality. Table 6.5 contains the 32 scenarios where the value "0" equals the component not being replaced and "1" is being replaced.

Table 6.5: Scenarios of components replacement for the accumulator

Scenarios	Gas valve assembly	Fluid port	Locking Ring	Gas Valve Stem	Accumulator Shell
1	0	0	0	0	0
2	0	0	0	0	1
3	0	0	0	1	0
4	0	0	0	1	1
5	0	0	1	0	0
6	0	0	1	0	1
7	0	0	1	1	0
8	0	0	1	1	1
9	0	1	0	0	0
10	0	1	0	0	1
11	0	1	0	1	0
12	0	1	0	1	1
13	0	1	1	0	0
14	0	1	1	0	1
15	0	1	1	1	0
16	0	1	1	1	1
17	1	0	0	0	0
18	1	0	0	0	1
19	1	0	0	1	0
20	1	0	0	1	1
21	1	0	1	0	0
22	1	0	1	0	1
23	1	0	1	1	0
24	1	0	1	1	1
25	1	1	0	0	0
26	1	1	0	0	1
27	1	1	0	1	0
28	1	1	0	1	1
29	1	1	1	0	0

30	**1**	**1**	**1**	**0**	**1**
31	**1**	**1**	**1**	**1**	**0**
32	1	1	1	1	1

Particular interest applies to scenario 1, from Table 6.5 since no key component needs to be replaced. This scenario is defined as *direct reuse* for this case study. The rest of the 31 scenarios fall under the term of *remanufacturing*.

6.4 Environmental Assessment of the product

This section describes the environmental assessment of the selected product. The method chosen for calculating the environmental impact is the simplified LCA as described by Christiansen (1997). The main reason for selecting the simplified LCA approach against the traditional LCA is the balance between its complexity and the identification of environmental hotspots in the product. Finally, the usage of carbon emissions equivalent to the quantification expression of the environmental impact is another reason for selecting the simplified LCA approach since there will be no focus on the other environmental impact categories.

6.4.1 Lifecycle Assessment

In this section, all the stages of the lifecycle assessment will be described as those identified in Chapter 3.5. Although this study conducts a simplified LCA, the main guidelines for applying an LCA have been applied as those are expressed through standards of practice from the series ISO 14040.

Goal and scope definition

The selected product is a hydraulic bladder accumulator with a nitrogen-filled bladder for hydraulic systems. The simplified LCA was conducted on the accumulator to identify each component’s environmental impact based on the existing design of the product. The results of this study will be used to quantify the product's environmental impact across a much more extensive analysis that examines the product’s suitability for the application of circular solutions after its EoL stage. The audience for this study is the user of the suggested method, and the results are kept internal and are not comparative to any similar product; thus, no third-party verification is needed.

Functional Unit

The selected functional unit occurs from the fact that this LCA's goal is not to compare to other similar products or support design decisions but to quantify the environmental impact of the existing product. Thus, the functional unit is one unit of the product defined as an 'accumulator'.

System boundaries

The boundaries of this simplified LCA are dictated from the 'cradle to grave' approach, as depicted in Figure 3.4. The stages considered were the raw material extraction, production of basic materials and components, transportation, usage stage and EoL stages of the accumulator. The product was manufactured and assembled in China, as well as its components and raw materials, as described in the assumptions of the case study; thus, no additional transportation has been calculated for each component. The datasets used for material processing include the raw material extraction and processing, defined from the Ecoinvent 3.6 and Industry 2.0 databases. Realistic assumptions have been made regarding the manufacturing processes and the materials where no data were available, and only components with equal to or more than one per cent (1%) contribution to the manufacturing environmental impact will be considered for the EoL study. The components that are not part of the study are less than five per cent (5%) of the total product's weight.

Life cycle Inventory (LCI) data

Data regarding the materials and their weights have been collected through interviews with the company engineers and managers and the disassembly of an existing product. For the estimation of the usage stage, it was considered that the accumulator is installed in operation and then only used to regulate the pressure; thus, no additional inputs from nature are captured during that stage.

Table 6.6: Accumulator composition used for LCA

Component	Material assumption in LCI	weight (kg)
Gas valve assembly	Steel engineering steel in Asia/Butadiene {RER}| market for butadiene	0.05
Protective cap	Steel, stainless 304, flat rolled coil/kg/RNA	0.085
Gas valve Locknut	Steel, stainless 304, flat rolled coil/kg/RNA	0.04
Nameplate	Steel, stainless 304, quarto plate/kg/RNA	0.13
Fluid port	Steel, stainless 304, quarto plate/kg/RNA	3.4
Locking Ring	Steel, stainless 304, flat rolled coil/kg/RNA	0.5
Fluid port backup Ring	Tetrachloroethylene {RER}| market for tetrachloroethylene	0.005
Fluid Port 'O' Ring	Butadiene {RER}| market for butadiene | APOS, S	0.005
Filler Ring	Butadiene {RER}| market for butadiene | APOS, S	0.45
M6 Nyloc Nut	Steel, stainless 304, flat rolled coil/kg/RNA	0.01
Piston	Steel, stainless 304, flat rolled coil/kg/RNA	0.005
Poppet Valve	Steel, stainless 304, flat rolled coil/kg/RNA	0.07
Spring	Steel, stainless 304, flat rolled coil/kg/RNA	0.01
Bladder	Butadiene {RER}| market for butadiene | APOS, S	1.25
Stem 'O' Ring	Butadiene {RER}| market for butadiene | APOS, S	0.01
Gas Valve Stem	Steel, stainless 304, flat rolled coil/kg/RNA	0.15
Accumulator Shell	Steel, chromium steel 18/8 {GLO}| market for | APOS, S	50

Table 6.6 differs from Table 6.1, which contains the accumulator BOM, because it includes the assumptions made in the Lifecycle Inventory (LCI) as those validated by the company engineers. Figure 6.6 illustrates the manufacturing tree for the accumulator. It includes the LCI material, weight, LCI manufacturing processes for each component, and the accumulator's final assembly. The raw materials refer to the upstream of manufacturing the accumulator, while the final transportation refers to the downstream.

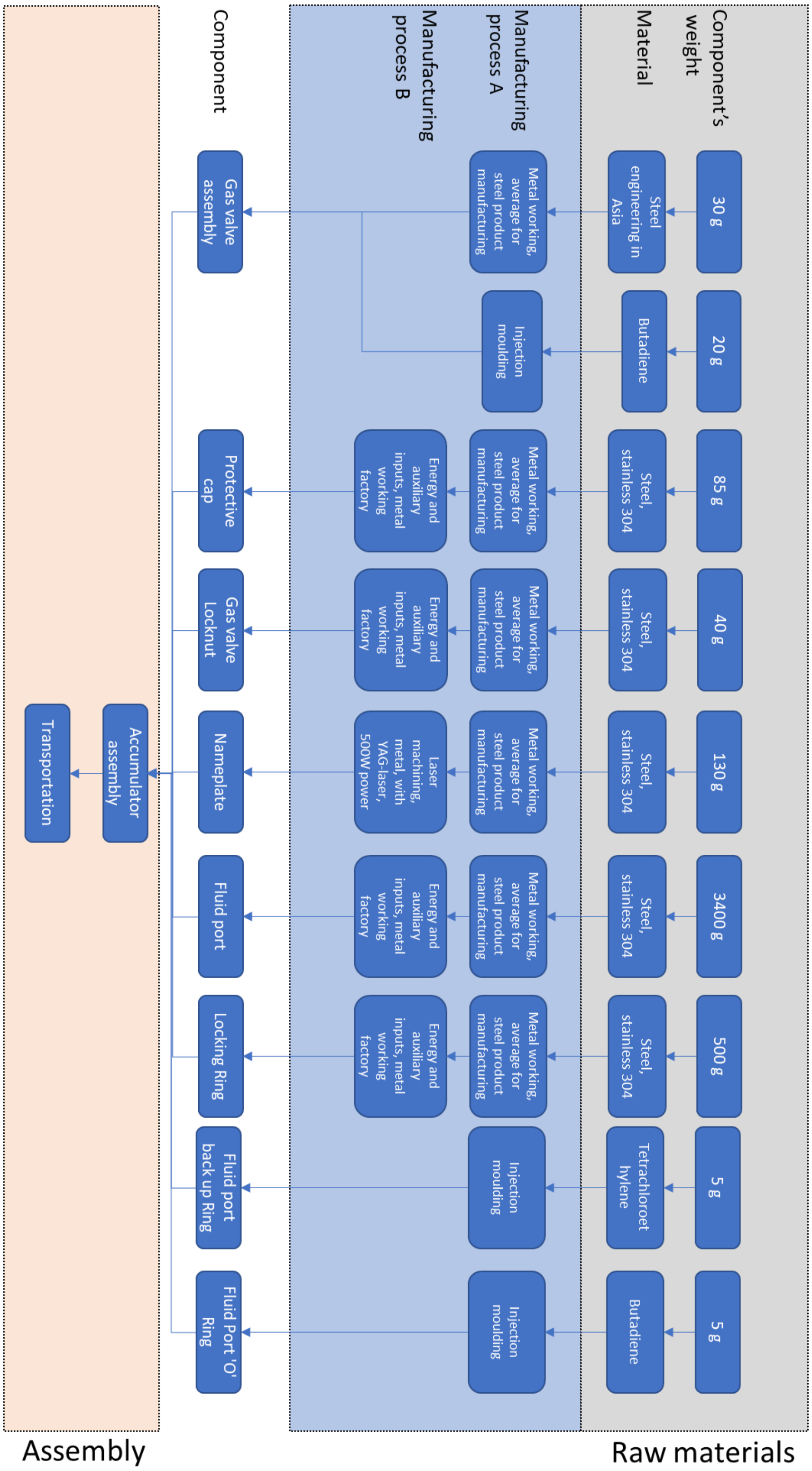


Figure 6.6: Accumulator Process tree

LCIA method of choice

The LCIA method of choice was the ReCiPe Midpoint 2016 (H) V1.04 / World (2010) (H) because it provides 18 midpoint impact categories with Climate Change as the focus. Climate change is expressed in kilograms of Carbon emissions equivalent (kgCO_2 eq) as described in Chapter 3.

6.4.2 LCA Results Analysis

In this part, there will be an analysis of the results of the LCA with a focus on delivering the goals and the scope as described before.

'Cradle to Grave' approach

During the previous sections, it was described that the approach of this simplified LCA is the *'Cradle to Grave'* approach, which includes all the stages from raw material extraction to EoL. Figure 6.7 depicts the network up to the manufacturing stage for the accumulator. The environmental impact is expressed in the network illustration of Figure 6.7 through the global warming category and is expressed in kg of CO_2 equivalent. The cut-off value for illustration purposes is that only sources that depict more than 0.3% of the total impact are represented in Figure 6.7. The width of each line in the network corresponds to the environmental impact of that source in the total impact calculated by the LCA, with thicker lines being responsible for greater impact and vice versa.

In the conducted analysis, the usage phase of the accumulator is assumed to have no environmental impact. This decision stems from the challenges associated with acquiring data about the accumulator's installation and operation in its functional environment. Furthermore, during its operational phase, the accumulator does not require resources like electricity or other consumables, nor does it emit substances into its environment. These factors collectively contribute to the rationale behind considering the usage phase as environmentally neutral in this specific analysis.

The EoL options for the product, specifically recycling and landfilling, have been simulated using the SimaPro software. The determination of which components are recyclable was informed by the expertise of the company's engineers. When the accumulator is sent to a landfill, the environmental impact is quantified at 2.05 $kgCO_2$ equivalent. In contrast, recycling the recyclable components results in a negative environmental impact of -40.21 $kgCO_2$ equivalent, indicating a reduction in overall emissions.

It's important to highlight that while the environmental impact of landfilling appears low, this assessment considers the separation of materials, as defined in the landfill scenario within the Ecoinvent 3.6 database. This factor plays a significant role in the comparatively lower environmental footprint of the landfilling option.

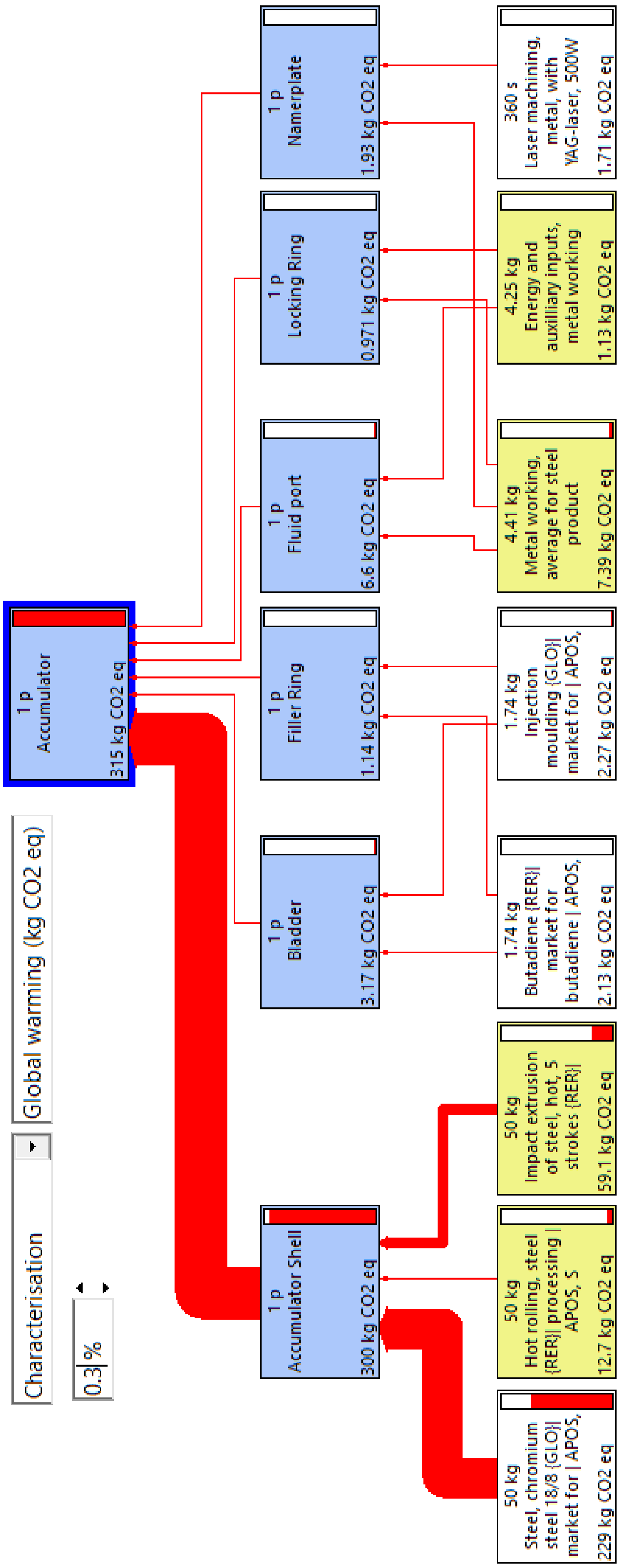


Figure 6.7: Network of the Accumulator, Global warming (characterisation), cut off at 0.3 %

Table 6.7 includes the environmental impact of the accumulator expressed through the global warming potential and quantified in kg CO_2 equivalent. It is obvious that the accumulator's shell is responsible for the highest impact, equal to 95.23% of the total impact

Table 6.7: Components of environmental impact (global warming)

Accumulator	Flow	Comp./ total %	Unit
Stem 'O' Ring	0.00254	0.00%	kg CO2 eq
Spring	0.0201	0.01%	kg CO2 eq
Protective cap	0.165	0.05%	kg CO2 eq
Poppet Valve	0.136	0.04%	kg CO2 eq
Piston	0.00971	0.00%	kg CO2 eq
Namerplate	1.93	0.61%	kg CO2 eq
M6 Nyloc Nut	0.00194	0.00%	kg CO2 eq
Locking Ring	0.971	0.31%	kg CO2 eq
Gas Valve Stem	0.291	0.09%	kg CO2 eq
Gas valve Locknut	0.0777	0.02%	kg CO2 eq
Gas valve Assembly	0.138	0.04%	kg CO2 eq
Fluid port backup Ring	0.0268	0.01%	kg CO2 eq
Fluid Port 'O' Ring	0.0127	0.00%	kg CO2 eq
Fluid port	6.6	2.10%	kg CO2 eq
Filler Ring	1.14	0.36%	kg CO2 eq
Bladder	3.17	1.01%	kg CO2 eq
Accumulator Shell	300	95.24%	kg CO2 eq
Total	**315**	**100.00%**	**kg CO2 eq**

An important consideration in the remanufacturing of the accumulator, as detailed in Table 6.2, is that certain components necessitate replacement in each cycle. For these components, the only feasible EoL options are recycling or landfilling. Collectively, these components amount to a total of 1.71 kg of mixed steel. Table 6.8 presents a comparative analysis of the two scenarios - recycling and landfilling. It reveals that recycling these components results in a negative environmental impact of -3.21 kg CO2 equivalent, whereas landfilling them leads to an impact of 1.33 kg CO2 equivalent. Therefore, the net difference in environmental impact between recycling and landfilling is calculated to be 4.54 kg CO2, equivalent to a total of 1.71 kg of mixed steel components. This translates to an impactful 2.65 kg CO2 equivalent per kilogram of EoL mixed steel components.

Table 6.8: Impact assessment accumulator recycling, landfilling comparison for always replaceable components

Impact category	Recycling the always-replaced components	Landfill the always-replaced components	Unit
Global warming	-3.21	1.33	kg CO2 eq
Stratospheric ozone depletion	0.00	0.00	kg CFC11 eq
Ionising radiation	-0.03	0.01	kBq Co-60 eq
Ozone formation, Human health	-0.01	0.00	kg NOx eq
Fine particulate matter formation	-0.01	0.00	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	-0.01	0.00	kg NOx eq
Terrestrial acidification	-0.01	0.00	kg SO2 eq
Freshwater eutrophication	0.00	0.00	kg P eq
Marine eutrophication	0.00	0.00	kg N eq
Terrestrial ecotoxicity	-2.75	0.83	kg 1,4-DCB
Freshwater ecotoxicity	-0.04	0.74	kg 1,4-DCB
Marine ecotoxicity	-0.06	0.97	kg 1,4-DCB
Human carcinogenic toxicity	-0.07	0.03	kg 1,4-DCB
Human non-carcinogenic toxicity	-1.63	15.93	kg 1,4-DCB
Land use	-0.53	0.01	m2a crop eq
Mineral resource scarcity	-0.13	0.00	kg Cu eq
Fossil resource scarcity	-0.51	0.02	kg oil eq
Water consumption	-0.01	0.00	m3

The analysis above shows that the accumulator's shell is the most dominant component of the whole accumulator assembly. It is responsible for 89% of the entire assembly's weight (when empty) and 95.24% of the product's total environmental impact. The CEDA graph presented in the following section also captures this magnitude difference between the accumulator shell and the rest of the components.

6.5 Circular Economy Design Analysis (CEDA) for the accumulator

This section introduces the CEDA for this case study. The 32 scenarios have been identified in 3.4, where the reader can identify which components are replaced in each remanufacturing scenario. The cost for each scenario has been calculated based on the financial functions described in the financial model described in 3.6. The environmental impact per scenario has been calculated based on the data from the LCA and the environmental impact per remanufacturing process for each of the 32 scenarios. The CEDA graph for the accumulator is illustrated in Figure 6.8. The dotted lines on the CEDA graph refer to a new identical product's environmental and financial impact (cost).

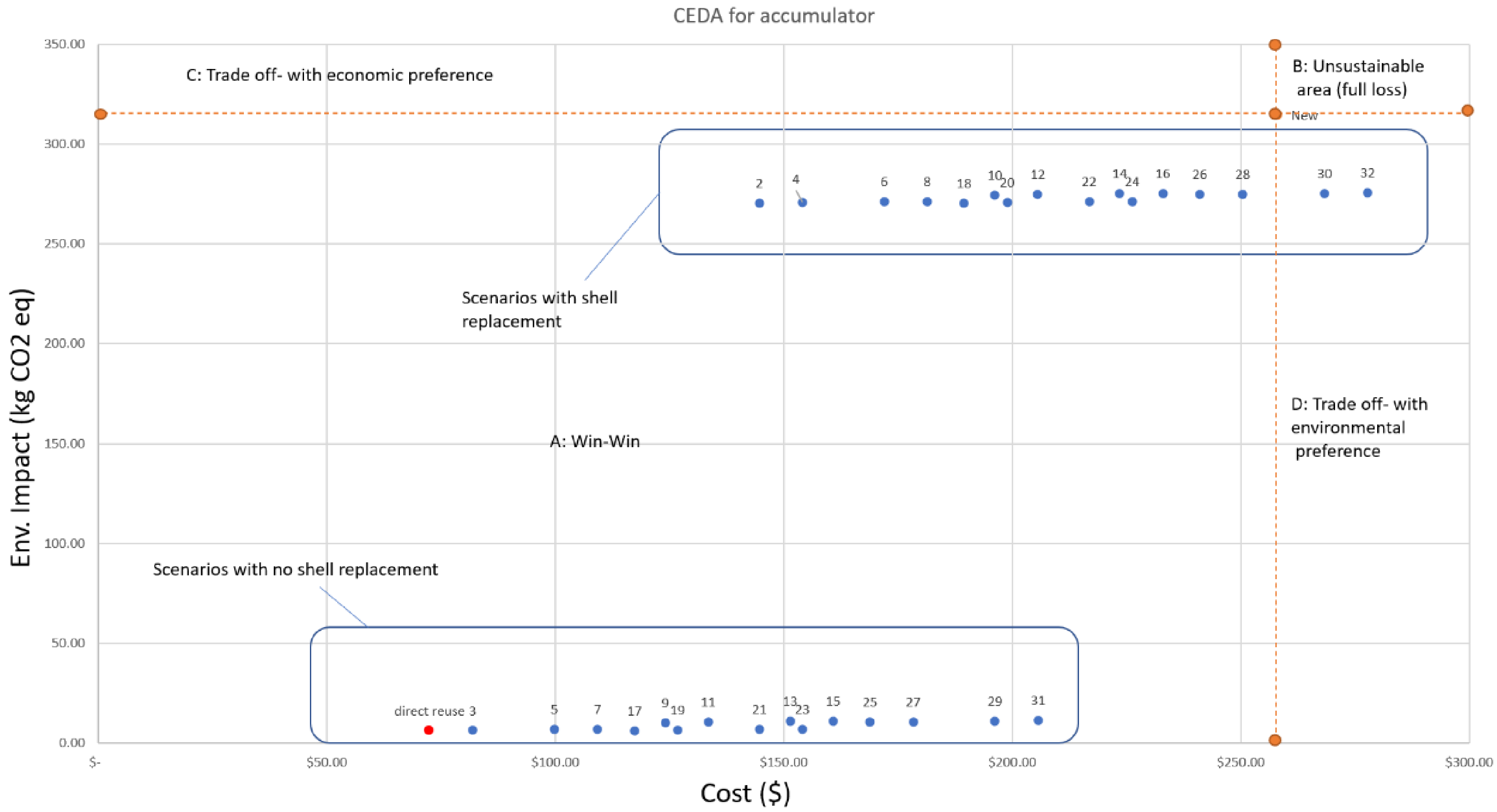


Figure 6.8: Accumulator CEDA

From Figure 6.8, there are many conclusions to draw, with the key conclusion being that there are two distinct groups of remanufacturing scenarios based on the condition of the shell and whether it needs replacing. The reason behind this creation of the two groups is the magnitude of the difference between the shell and every other component expressed in the environmental aspect. The dominance of the part in the CEDA graph reveals that significant ecological gains can be achieved if the company designs the product so that the shell will not need replacement after the usage stage. Additionally, the CEDA graph could support decision-making for core acquisition by creating a rule of thumb based on the shell's condition. Although the shell is clearly a dominant component from an environmental point of view, this is not the case financially. Based on Figure 6.9, the cost of replacing different components is greater when more key components are replaced.

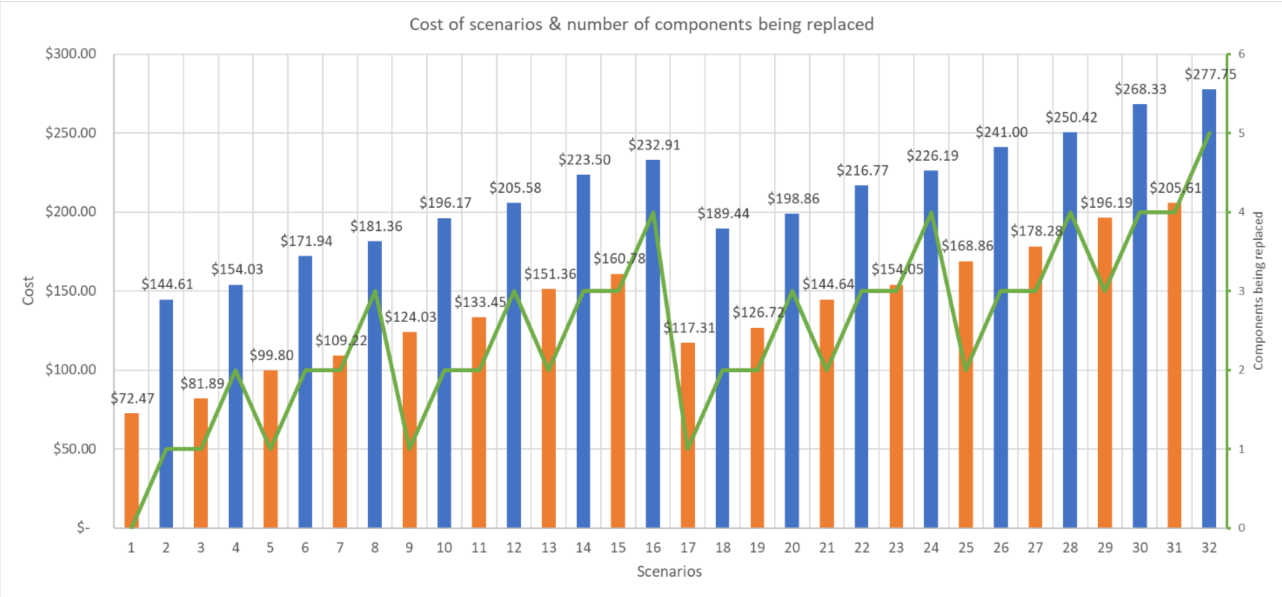


Figure 6.9: Cost per scenario and number of components being replaced

The same information is also captured from CEDA (Figure 6.8) since the cost is growing towards the *x*-axis named cost and expressed in USD ($), leading to the same conclusion.

Based on the CEDA, in greater detail, 93.75% of the remanufacturing scenarios belong to the 'win-win' area of the CEDA graph. As expected, scenario 1 refers to direct reuse with no key component being replaced. However, in all scenarios, all the mandatory replaceable components have been replaced, as in the scenario of direct reuse. Direct reuse, as expected, is the scenario with the lowest cost and environmental impact. The cost for scenarios that don't require the shell to be replaced grows as different or more components are being replaced.

However, their environmental impact remains practically the same due to their lightweight and the lack of energy-intensive remanufacturing processes when replaced.

The remaining 6.25% of the scenarios (2 out of the 32) belong to the *trade-off with environmental preference* area. Those two scenarios refer to when all five key components are replaced (scenario 32) or when all are replaced except the gas valve stem (scenario 30). That means those scenarios have a higher cost when compared to buying a new accumulator. Additionally, their environmental impact gain from remanufacturing is limited, as they belong to the group of scenarios that require shell replacement; thus, their global warming potential equivalent is similar.

Finally, no remanufacturing scenarios belong to the *Trade-off- with economic preference* area, where the cost of remanufacturing the core is lower, but the environmental impact is higher. Similarly, no scenarios belong to the *Unsustainable area (full loss)* zone. A key conclusion from the lack of scenarios in those two zones is that the product's design provides a significant opportunity for remanufacturing.

One of the assumptions of the proposed method is that the replacement of components is identical to the ones used before. This assumption simplifies the model and develops an interdisciplinary method that can be implemented across multiple industries. When the model is used for further analysis of the future potentials of a product, technological progress should also be considered. Thus, technological progress can potentially mitigate those components' environmental impact and cost, moving the CEDA graph towards the sustainable area (win-win) and providing remanufacturing as an even more significant opportunity.

6.6 Decision Making

The specific usage scenario developed for this case study assumes that a customer possesses a batch of 100 gas-loaded accumulators. These accumulators have been in use for seven years within a process environment where they have been exposed to potentially corrosive fluids. This section delves into the solution constraints relevant to these accumulators, with detailed discussions and the presentation of proposed models for addressing these constraints. The practitioner's input will be captured and assessed to develop the solution constraints. Following this, the decision factors specific to the accumulator case study are thoroughly analyzed and weighted. The culmination of this analysis is the presentation of the final solution for handling this particular batch of accumulators.

6.6.1 *Practitioner's input and solution's constraints*

Similar to case study A, the practitioner will have to provide input to the proposed method to identify the solution constraints that apply to this application of the method. The case study implementation will be described in the following paragraphs, and the practitioner's input will be analysed and used to identify any solution constraints.

6.6.1.1 Guarantee and lifespan process

Based on the remanufacturing definition, a remanufactured product must be in at least '*as new*' condition. In this section, the guarantee and lifespan process of the proposed method will be applied.

In line with the assumptions of this case study, the batch of 100 accumulators under consideration has been operational for seven years and was initially installed as new units. The accumulators were used in a process environment that involved exposure to potentially corrosive fluids. According to the industry's guidelines, these accumulators' bladders must be replaced at least every five years. Therefore, all the bladders in this batch are due for replacement.

Consistent with the practices of the remanufacturer, certain components are always replaced in every remanufacturing cycle of an accumulator, regardless of their current condition. In this case, apart from the bladder, the components slated for replacement include the fluid port backup ring, the fluid port 'O' ring, the filler ring, and the stem 'O' ring.

For the next usage stage of the accumulators, we consider a high-humidity environment of application with a corrosive fluid and an operation time of 5 years. According to the manufacturer's guidelines, the service check period is set at two years due to the harshness of the environment. Thus, the remanufacturer will provide a guarantee only for those two years of future use.

Table 6.9 includes the application analysis of the guarantee process and calculates, for each key component, the life expectancy (L), the difference between the life expectancy and the past usage of the component (Up), the future usage of the component (Uf) in the new application. Then, it conducts a check to estimate if the future usage and the remaining life expectancy of the component will violate the guarantee period (G) that the remanufacturer is willing to provide. According to the check application results, the fluid port assembly and gas valve stem will need to be replaced, independent of their condition.

Table 6.9: Guarantee check for the accumulator

Key Component	L (hours)	(L-Up)	Uf (hours)	L-Up-Uf<G	Replace Check (L-Up-Uf<G)
Gas valve assembly	131400	70080	17520	52560	No replace
Accumulator Shell	131400	70080	17520	52560	No replace
Fluid port Assembly	87600	26280	17520	8760	**Replace**
Locking Ring	131400	70080	17520	52560	No replace
Gas Valve Stem	87600	26280	17520	8760	**Replace**
Up-Past use (hours)	61320				
Guarantee (hours)	17520				

In conclusion, the scenario of direct reuse with only the replacement of the always-replaceable components cannot be applied due to the guarantee period of two years. Thus, direct reuse is excluded from the available EoL pathways.

6.6.1.2 Legislation restrictions

Concerning the accumulators, based on the author's and the company's engineers' best knowledge, it is understood that there is no specific legislation governing the disposal or recycling of these accumulators. Consequently, in the context of this case study, both disposal and recycling are considered viable EoL pathways for the accumulators.

6.6.1.3 Obsolescence and market prediction

Similar to the previous case study, in this step, the practitioner predicts the market demand for the remanufactured goods and the obsolescence of the product's design, both graded based on linguistic values. The demand prediction and obsolescence combinations grades have been tuned based on the practitioner's input.

The accumulators are products with very stable demand. Additionally, their design has been developed based on efficiency and functionality and has remained unaltered for the past decades. Thus, as a product, they are well in their maturity stage.

In this case study, according to the practitioner, only when the demand is 'decreasing', and the obsolescence of the design is valued as 'outdated' is the result of a *hard constraint* that directly excludes the scenarios of direct reuse and remanufacturing. This would be translated into a grade of 1 according to the parameters of Table 6.10. As seen in Table 6.10, the practitioner has decided that the accumulator has a stable demand (X2). The design is considered *OK (O2)*. The result of such a combination is a soft constraint and graded with three (3) on a scale from 1 to 5, with 5 being the best result.

Table 6.10: Obsolescence and future demand factors table

Demand Prediction	**Obsolescence**	**EoL scenario impact**	**Final grade (1 no reman- 5 the best)**	**Constraint**
decreasing (X1)	relatively new (O1)	Reuse or Rem/re	3	soft
decreasing (X1)	Ok (O2)	Reuse or Rem/re	2	soft
decreasing (X1)	outdated (O3)	Recycle or Disposal	1	Hard
stable (X2)	relatively new (O1)	Reuse or Rem/re	4	soft
stable (X2)	Ok (O2)	Reuse or Rem/re	3	soft
stable (X2)	outdated (O3)	Reuse or Rem/re	2	soft
increasing (X3)	relatively new (O1)	Reuse or Rem/re	5	soft
increasing (X3)	Ok (O2)	Reuse or Rem/re	4	soft
increasing (X3)	outdated (O3)	Reuse or Rem/re	3	soft

This result means that its grade of obsolescence will be considered during the decision-making as a deciding factor, but there will be no scenario exclusion due to it. As a result, direct reuse or remanufacturing is not excluded from the available EoL pathways.

6.6.1.4 Product Materials

The product under analysis is composed of materials that can be both recycled and landfilled. There are no dangerous materials that may need special waste treatment. Thus, there is no EoL scenario exclusion.

6.6.1.5 Pre-screening process

The generic model of the pre-screening process has been tailored to the specific case study of the accumulator. This section will present the model alongside its implementation for the returned batch of 100 same-model accumulators from the oil and gas industry.

The first step is to use the *Guarantee and lifespan process* to identify if there is any component that needs to be replaced independently of its quality condition. The findings from this analysis stage indicate that the fluid port assembly and the gas valve stem must be replaced, irrespective of their condition. The necessity of these replacements will subsequently have a notable impact on the outcomes of the pre-screening analysis, which will be elaborated upon in the following sections.

The next step would be for the practitioner to enter the values of the two quality dimensions: the visual condition and the performance. The practitioner has allocated the relative components for each of those two groups, as shown in Figure 6.10.

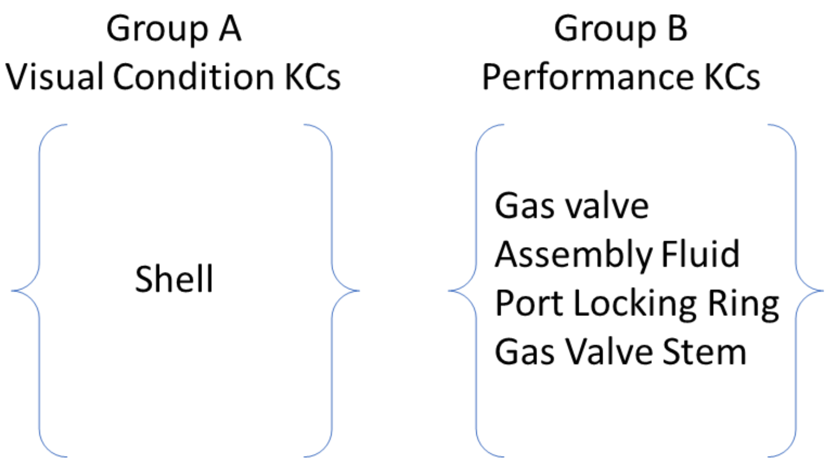


Figure 6.10: Key components quality dimensions

Before the practitioner inputs those values into the pre-screening process model, some changes had to be made to allocate the pre-screening possibilities to align perfectly with this case study. The model follows all the principles described in section 5.6.1.5, but it is tailored to have one visually inspected key component and four performance-related key components. Similar to the previous case study, linguistic values were used to describe the dimensions of visual and performance quality. Additionally, the allocation of components that must be replaced based on those linguistic values has been altered to capture the ratio of the one visual and four performance key components. Finally, allocating the possibilities for each linguistic value to the number of components needed to be replaced has followed the same distribution principles described in section 5.6.1.5.

Table 6.11 includes the analysis of the linguistic grading system for this case study. The quality dimensions of visual aesthetics and performance are used. The linguistic values of *excellent, OK,* and *Bad* are used, and each of them is linked to a mean value of components that belong to that quality dimension, which will need to be replaced. The probabilities in the last column express the possibility of that statement being true, thus considering the uncertainty of using linguistic values.

Table 6.11: Pre-screening case study grading and analysis of the system

	Quality dimension	***Grade symbol***	***Grade (linguistically)***	*linguistic* ***correlation***	***Number of components to be replaced***	***Explanation of the grade*** **(%possibility to be true)**
1	Visual Condition	A	Excellent	mean=0	0	62.8%
				components replaced	1	37.2%
		B	OK	mean=0.5	0	50%
				components replaced	1	50%
		C	Bad	mean=1	0	37.2%
				components replaced	1	62.8%
2	Performance	A	Excellent	mean=0 components replaced	0	62.8%
					1	27.2%
					2	4.2%
					3	0.4%
					4	0.0%
		B	OK	mean=1 components replaced	0	25.7%
					1	33.0%
					2	25.7%
					3	12.1%
					4	3.5%
		C	Bad	mean=2 components replaced	0	11.2%
					1	23.6%
					2	30.4%
					3	23.6%
					4	11.2%

The practitioner will input the values based on visual inspection and feedback from the customer who installed the accumulators. Table 6.12 captures this input:

Table 6.12: Quality condition input

visual condition is	% of the batch
excellent	50%
OK	30%
Bad	20%
Performance is	
excellent	40%
OK	40%
Bad	20%

According to the visual inspection, 50% of the sample seemed to be in excellent visual condition. The only key component related to the visual quality dimension of the accumulator is the shell. Thus, these percentages that describe the visual quality status of the product are linked directly to the possibility that the accumulator shell might need to be replaced.

Regarding the performance of the accumulators, according to the customer, 40% of them work perfectly, 40% have a minimal drop in pressure, and 20% have to be replaced by new accumulators that are not part of the returned batch. The key components linked to the accumulator's performance are the gas valve, the assembly fluid, the port locking ring, and the gas valve stem.

The pre-screening model uses the practitioner’s input and the data from Table 6.11 to calculate the average cost, environmental impact and time needed for remanufacturing. Additionally, the practitioner inputs the fact that two of the key components related to the performance of the accumulator will need to be replaced due to guarantee restrictions. Table 6.13 includes the results of the pre-screening process. According to it, the average accumulator from this batch will cost $180.27, emit 130.83 kg$CO_2$ eq and need 36.93 minutes to be remanufactured.

Table 6.13: Results of the pre-screening process

% of products that will need replacement of # components	# of components replaced	cost (avg)	env imp (kgCo2)	avg time (edim) minutes
0.00%	0		not applicable	
0.00%	1		not applicable	
78.30%	2	$ 68.86	113.89	36.93
13.57%	3	$ 205.16	167.74	36.93
6.45%	4	$ 241.45	221.59	36.93

1.67%	5	$ 277.75	275.44	36.93
99.99%	-	**$ 180.27**	**130.83**	36.93
Batch size 100		**$ 18,027.00**	**13,083**	**36.93**

The whole batch of 100 accumulators will cost $18,027, emit 13,083kg$CO_2$ eq and need 65.55 hours of cycle time to be remanufactured. Based on Table 6.13, most of the products will need replacing two components. The reason behind this is that the percentages of products that would need 0 or 1 component to be replaced, based on data from the pre-screening process, have cascaded to the percentage of products that will need two components to be replaced. This occurs because the guaranteed process requires replacing two key components regardless of their condition.

Finally, the company has set a direct reuse acceptance threshold value. This value is established as '*at least 95% of the returned batch will be rated as excellent visually and performance-wise*'. Since this is not happening in our case study, direct reuse is excluded from the available EoL pathways for this batch.

6.6.1.6 Difficulty factor

The difficulty factor expresses the complexity of the dis- and re-assembly process due to the joints' connections for a specific product design. The factor aims to recalibrate the economic prediction model by inserting an additional risk net by computing the possible delays on average per product due to product design. The multiplier values corresponding to each of the results ranges are depicted in Table 5.18 and have been selected based on the previous case study after discussions with the company engineers. Similarly, in this case study, the company engineers found this additional step helpful for identifying potential difficulties in the remanufacturing process emerging from unpredictable joints in the product. For the accumulator, the practitioner's input is captured in Table 6.14.

Table 6.14: Product's joints connection grading

Code	**Connectors description**	**Grading and time**					
-	Strongly agree (A)- Strongly disagree (E)	A	B	C	D	E	Grade
C1	The joints are standardised	1	5	10	15	25	1

C2	The joints can be disassembled, and they are not fixed joints	1	5	10	15	25	1
C3	The screws have the same metrics	1	5	10	15	25	5
C4	The number of joints is low	1	5	10	15	25	5
C6	The joints are easily accessible	1	5	10	15	25	5
C7	Size components are easy to handle	1	5	10	15	25	25
C8	The tools needed are available	1	5	10	15	25	5
C9	The tools are standardised	1	5	10	15	25	1
	Difficulty factor (average value)						**6**

Based on the ranges from Table 5.18, the accumulator's difficulty factor equals six (6), thus laying between the (1,10) range. In this case, the multiplier is equal to one. This means that the values from the pre-screening process of cost and average time to remanufacture will remain the same.

6.6.1.7 Functionality constraints factor

The functionality constraints factor is a multiparameter factor aimed to capture the complexity of the remanufacturing process and identify any potential area of risk related to the process that might jeopardise the viability of the suggested solution. Similar to the previous case study, the model (illustrated in Figure 5.18.) will perform checks regarding the inventory level satisfaction, the remanufacturing capacity satisfaction, and the components' availability satisfaction. The results from those checks will be expressed through a *GO*, *NO GO* answer, impacting the availability of specific EoL pathways.

Based on the practitioner's input, the inventory levels are considered satisfactory for a returning batch of 100 accumulators. The remanufacturing capacity is related to the available personnel to conduct remanufacturing activities. Using the pre-screening process, the practitioner has identified that each accumulator will have an average lead time of 36.93 minutes. Finally, through the guarantee and pre-screening process, the practitioner knows that each accumulator will need replacement of the Fluid port Assembly and Gas Valve Stem, independently of their condition. Thus, remanufacturing the batch will require adequate components availability for the key and always replaceable components. Table 6.15 includes the necessary number of components that should be available for remanufacturing the returned batch of the accumulators. The numbers occur from the implementation of the pre-screening model and the guarantee model.

Table 6.15: Inventory of components needed for remanufacturing the batch of accumulators

	batch size of 100 accumulators	**inventory on the component**
Components that are always replaced	Fluid port backup Ring	100
	Fluid Port 'O' Ring	100
	Filler Ring	100
	Bladder	100
	Stem 'O' Ring	100
Key components	Fluid port	100
	Gas Valve Stem	100
	Gas valve assembly	20
	Locking Ring	20
	Accumulator Shell	50

In greater detail, the accumulator's shell is the only component related to the accumulator's visual quality dimension. Based on the practitioner's input, 50% is considered to be in excellent condition; thus, no replacement is needed. The remaining 50% might need a replacement; thus, the inventory is set to be 50% of the batch size for safety reasons. The same principles apply to the gas valve assembly and the locking ring, where, based on the practitioner's input and the pre-screening process, the safety threshold value for the inventory is set to 20% of the total batch size.

According to the practitioner, the average lead time of 39.33 minutes for each accumulator of this batch, the inventory levels for storing both the returned cores and the remanufactured ones and finally, the components inventory for replacing old components are considered satisfactory. Thus, all of them are a GO, based on Figure 5.18, and no EoL pathway has been rejected. Consequently, in this case study, no constraints would restrict one of the EoL solutions due to the functionality factor.

6.6.2 Solutions constraints overview

In this section, all the input from the practitioner and the potential solution constraints are analysed, resulting in Table 6.16:

Table 6.16: Solution Constraints Results

Practitioner's input and constraints	EoL restricted pathways	Reasoning	Result
Guarantee Process	Reuse	Product's reliability compromises direct reuse	Restriction of Direct Reuse
Legislation Restrictions	Reuse	Legislation prohibits direct reuse	No restriction
	Remanufacture	Legislation prohibits remanufacturing	No restriction
	Recycle	Legislation prohibits recycling	No restriction
	Disposal	Legislation prohibits disposal	No restriction
Obsolescence and Market predictions	Reuse	Product's obsolescence compromises direct reuse	No restriction
	Remanufacture	Product's obsolescence compromises remanufacturing	No restriction
Product Materials	Recycle	Product's materials cannot be recycled	No restriction
	Disposal	Product cannot be disposed	No restriction
Pre-screening Process	Reuse	Product's quality compromises direct reuse (less than 95% excellent condition)	Restriction of Direct Reuse
	Remanufacture	Product's quality compromises remanufacturing	No restriction
		Average cost per product	**$ 180.27**
		Average CO_2 emissions per product	**130.83 kgCO2 eq**
Functionality Factor	Reuse	Product's functionality rating prohibits direct reuse	No restriction
	Remanufacture	Product's functionality rating prohibits remanufacturing	No restriction

According to Table 6.16, based on the analysis of the practitioner's input, the only restricted EoL pathway is that of direct reuse, as defined for this case study.

Remanufacturing an accumulator includes replacing the components needed with identical or similar comments and recycling and disposal of the old components.

Recycling and disposal of the accumulator include replacing the accumulator with an identical/ similar one to satisfy customer demand.

6.6.3 Decision factors

This section includes the practitioner's rating of the decision factors for this specific case study. The factors and their weights are represented in Figures 6.11 to 6.15, and those factors are used in the MCDM Promethee model developed for delivering the final decision support to the practitioner. Initially, the scoring of all the decision clusters is presented. Later, the environmental factors are discussed in greater detail, followed by the financial, technical, and social factors.

Figure 6.11 contains the average values based on the practitioner's input for each of the four pillars of decision factors applied to this work. According to the practitioner, the environmental, financial, and technical factors have almost the same importance, making them all the main drivers of decision-making. Social factors have much less significance and, thus, are much more challenging to impact decision-making for which EoL pathway a returned batch should follow.

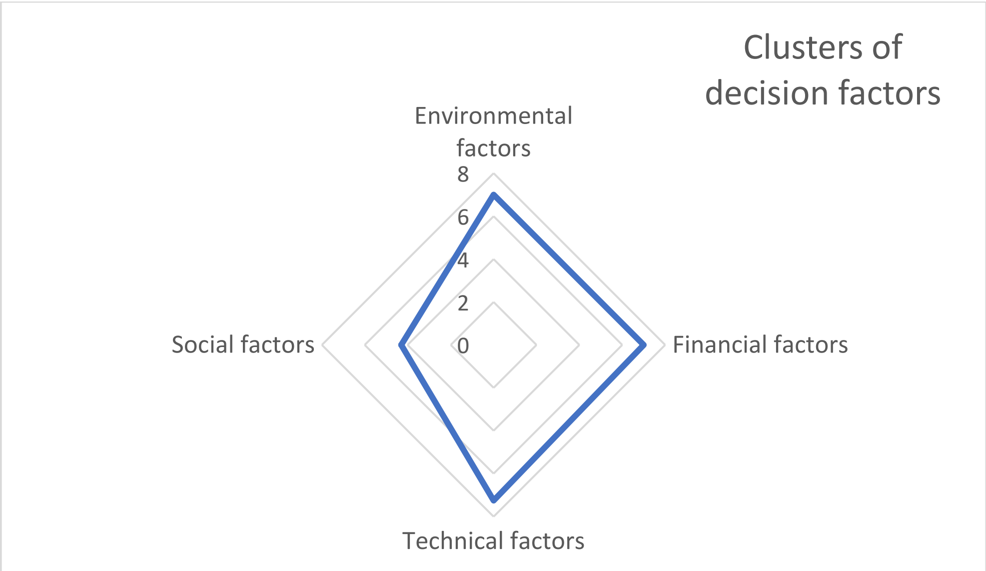


Figure 6.11: Clusters of decision factors

Figure 6.12 illustrates the environmental decision factors the practitioner rated based on their importance. The main areas of interest for the case study company are that the customer's environmental requirements are the key decision factors in the area. During a discussion with the company's practitioner stated the following:

'Customers are now asking us about CO2 (very early stages). We have identified 2.1(Carbon Emissions) as a five at the moment (2021-2022). In 2020, this value would have probably been 2. In the future, maybe as a guess, we believe we may be asked to state CO2 values for our products, and we may have to charge extra for our products to reduce the CO2 costs from our supply sources.'

L.M. Graduate Quality Administrator

Thus, it becomes evident that the company has understood that quantifying its environmental impact through its operational and product-focused direct emissions will be of greater significance in the future. Another interesting aspect is that although expressing their environmental impact through the carbon emissions equivalent seems to be of secondary importance for that period, the company considered that disposal of their products is much more important and should be avoided. Unfortunately, during the conducted research, the company had a limited overview of how their customers disposed of or recycled their products.

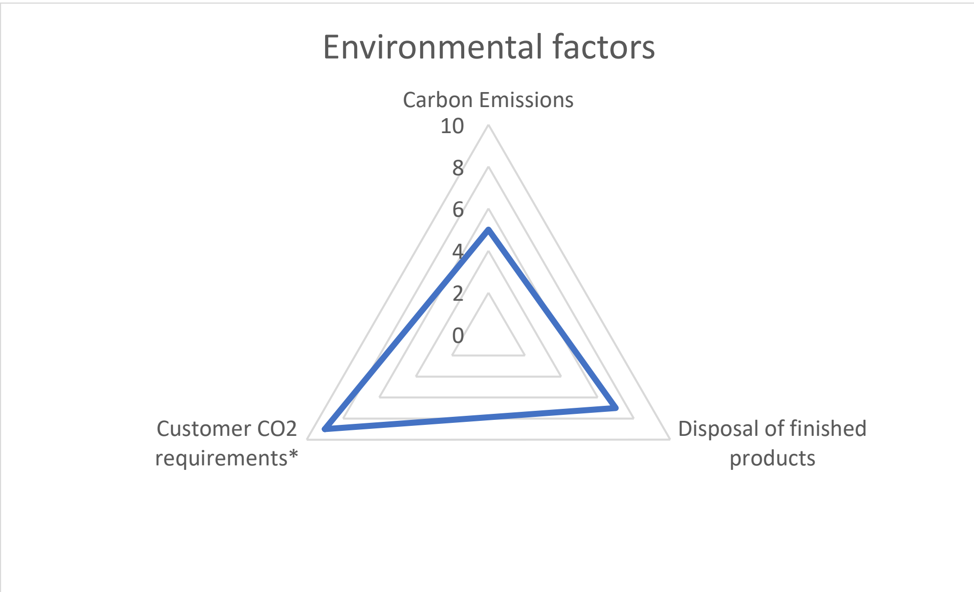


Figure 6.12: Environmental factors

Figure 6.13 contains the financial factors part of the multicriteria decision-making model. According to the practitioner, the most important factors are profit and market demand.

The cost of remanufacturing and the residual value have an importance of 5/9, which defines them as important but not critical. On the contrary, the profit and the market demand are rated with 9/9. One of the conclusions that may be driven from this analysis is that as long as there is profit and a market for the remanufactured products, the products' costs and residual values are of secondary significance.

Additionally, the company has identified an underlying financial opportunity for the remanufacturing sector from a government subsidies perspective. The practitioner added two factors that aim to capture the importance of government subsidies and financial aid while minimising the cost and risk of remanufacturing. More specifically, the Community Infrastructure Levy and 'Grants and subsidies' were added. This addition will be addressed in the proposed multicriteria decision-making model by adding an '*access to governmental grants*' criterion, where reuse and recycling will have an *average* evaluation, remanufacturing a *good* evaluation and disposal a *bad* one. These evaluations are based on a 5-point linguistic scale.

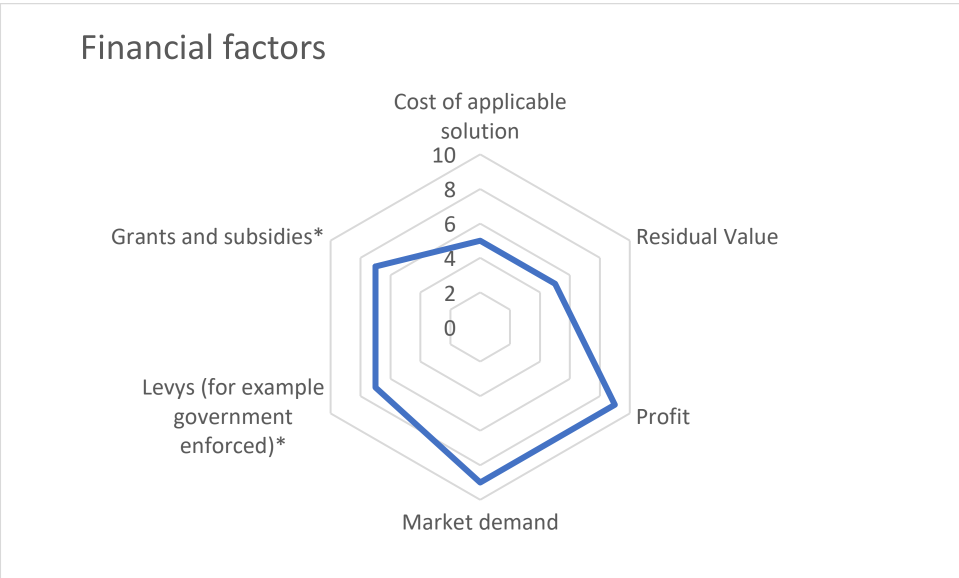


Figure 6.13: Financial factors

Figure 6.14 includes the technical factors identified and weighted in this study. The main contributors were the batch quality, the core's remanufacturability, and the components' availability, all rated 9/9. The participant commented that:

'*Our product range would be classed as a mature product, and we have approximately 4500 individual designs, but mainly based on variations on a theme.*'

L.M. Graduate Quality Administrator

Such a variation in the products may cause some difficulties in the remanufacturing process from a technical perspective since not all the models will be equally suitable for remanufacturing. Further analysis of the most dominant models in the market, types of variations, value-adding and main core characteristics may be needed to identify the most prominent cores for extended remanufacturing. Such an analysis could be a potential application of the proposed work since the CEDA graph can support the identification of the most suitable product designs for remanufacturing.

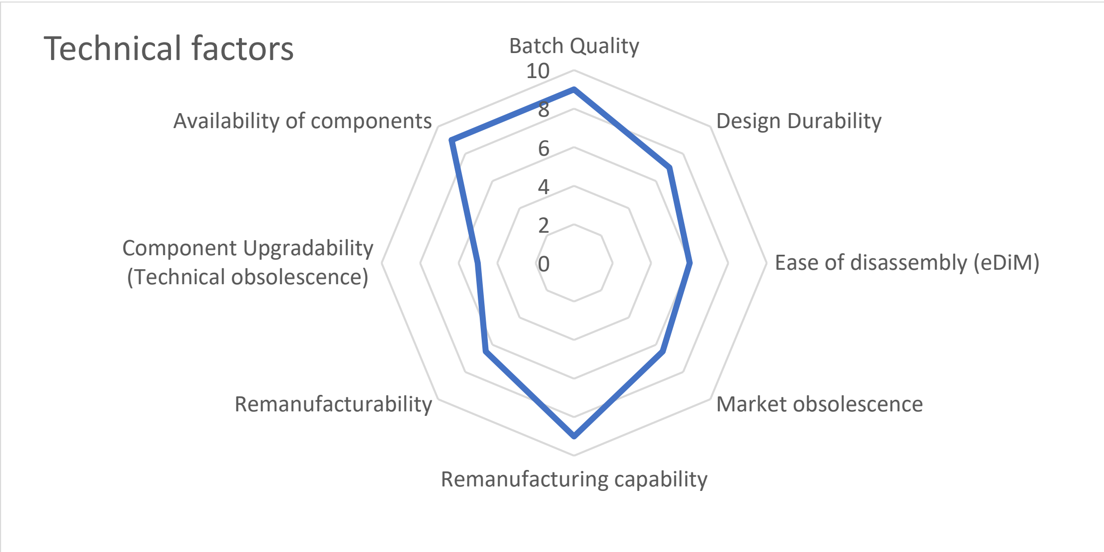


Figure 6.14: Technical factors

As seen in Figure 6.15, the factors '*jobs creation'* and '*Harmonisation with the local society needs'* are rated with 2/8, thus not important for the company and their remanufacturing decision drivers. On the contrary, '*customer accessibility to high-quality products'* is rated with 9/9, which once again reveals the company's customer focus. The latter factor can also be interpreted through a financial lens and relates to the market and customer satisfaction.

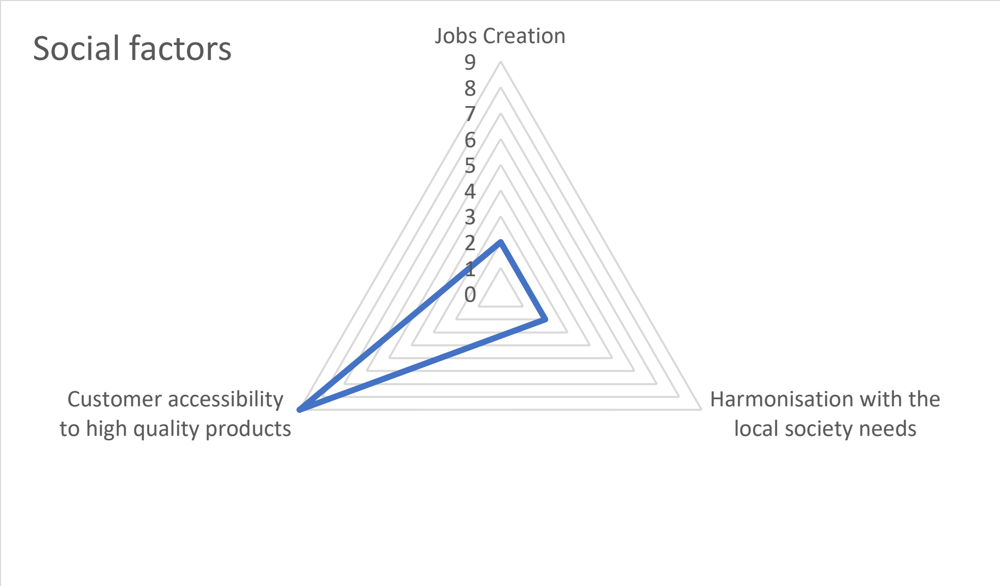


Figure 6.15: Social factors

All the factors presented in this section and their weights are fed into the Visual Promethee II full-ranking method and the software provides the final solution of the proposed method.

6.6.4 Solutions Ranking

The solutions ranking occurs by using the Visual Promethee II. The software's inputs are the decision variables (criteria), the weights for each of the criteria, the available EoL scenarios (actions) and the values that describe the performance of each criterion against the actions.

Figure 6.16 illustrates eight of the 19 decision factors that act as criteria in the Visual Promethee MTDM model developed for this case study. As seen in Figure 6.16, the decision factors are quantitative and qualitative. Each of the available actions (EoL pathways) has been assessed based on their performance against the decision factor. For quantitative factors, the numeric values have been used to identify the impact of each EoL scenario. For qualitative decision factors, a 5-point linguistic scale has been used. As a reminder to the reader, the scenarios of recycling and disposal include buying a new accumulator to satisfy the customer's need.

Scenario1	Cost	Carbon Emis…	(Market) Ob…	Creation of J…	Harmonisatio…	Durability of …	eDIM index	Profit
Unit	unit	unit	5-point	5-point	5-point	5-point	5-point	5-point
Cluster/Group								
Preferences								
Min/Max	min	min	max	max	max	max	max	max
Weight	6.09	7.32	4.56	3.16	3.40	4.57	4.57	10.94
Preference Fn.	Linear	Linear	Linear	Linear	Linear	Linear	Usual	Usual
Thresholds	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	$ 1.00	1.00	1.00	1.00	1.00	1.00	n/a	n/a
- P: Preference	$ 2.00	2.00	2.00	2.00	2.00	2.00	n/a	n/a
- S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Statistics								
Minimum	$ 72.47	6.19	3.00	2.00	1.00	3.00	4.00	€ 86.40
Maximum	$ 263.60	316.74	5.00	5.00	5.00	5.00	5.00	€ 172.53
Average	$ 184.13	175.36	4.25	3.00	3.25	4.25	4.50	€ 130.00
Standard Dev.	$ 70.88	118.13	0.83	1.22	1.48	0.83	0.50	€ 30.46
Evaluations								
Reuse	$ 72.47	6.19	average	bad	very good	average	good	€ 172.53
Remanufacture	$ 180.27	130.83	good	very good	good	good	good	€ 131.23
Recycle*	$ 220.17	247.69	very good	average	average	very good	very good	€ 129.83
Disposal*	$ 263.60	316.74	very good	bad	very bad	very good	very good	€ 86.40

Figure 6.16: Decision Factors (Criteria) Analysis

The factors of cost, profit, and carbon emissions are quantitative, and each of their values for the EoL pathways (described as actions in Visual Promethee) have been calculated based on the pre-screening process and the financial and environmental analysis described in the previous chapters. Specifically for the profit, we consider the following pricing model: reused or remanufactured accumulators are sold at 90% of the price of a new accumulator. The new accumulator is sold at $350. Finally, the final profit value has considered any costs related to disposal or profits from recycling the accumulators.

Each of the decision factors has been allocated to one of the four main decision clusters: the financial, the environmental, the technical and the social. Using the weighting assistant tool that Visual Promethee provides, the factors have been weighted, while the decision clusters' weights are calculated based on the practitioner’s input by using absolute percentages. The weights for each cluster of factors are depicted in Figure 6.17, and they are the averaged weights of the decision factors under the umbrella of the cluster.

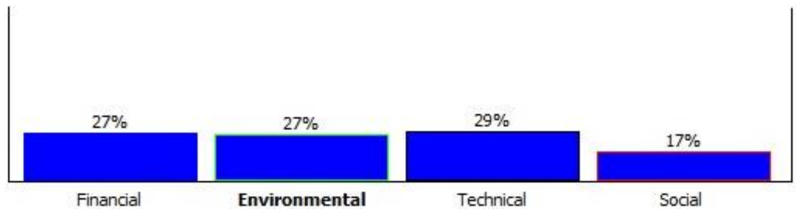


Figure 6.17: Weights of the decision clusters

As expected from the analysis of the practitioner's input regarding the decision factors, the social cluster of decision factors is not equally important to the rest of the clusters.

The results of the MTDM model are presented in Figure 6.18 for the weights described in Figure 6.17. Using the GAIA illustration tool, as depicted in Figure 6.18, the practitioner can learn how each of the EoL pathways (or actions in visual Promethee) performs for each decision factor cluster. Reuse is still an available action at this point for a better illustration of the model. As a rule of thumb, the closer a decision cluster is located to an available solution (action), the better that solution performs for that cluster. Technical criteria fall on the recycle action, so the action's description has been added manually.

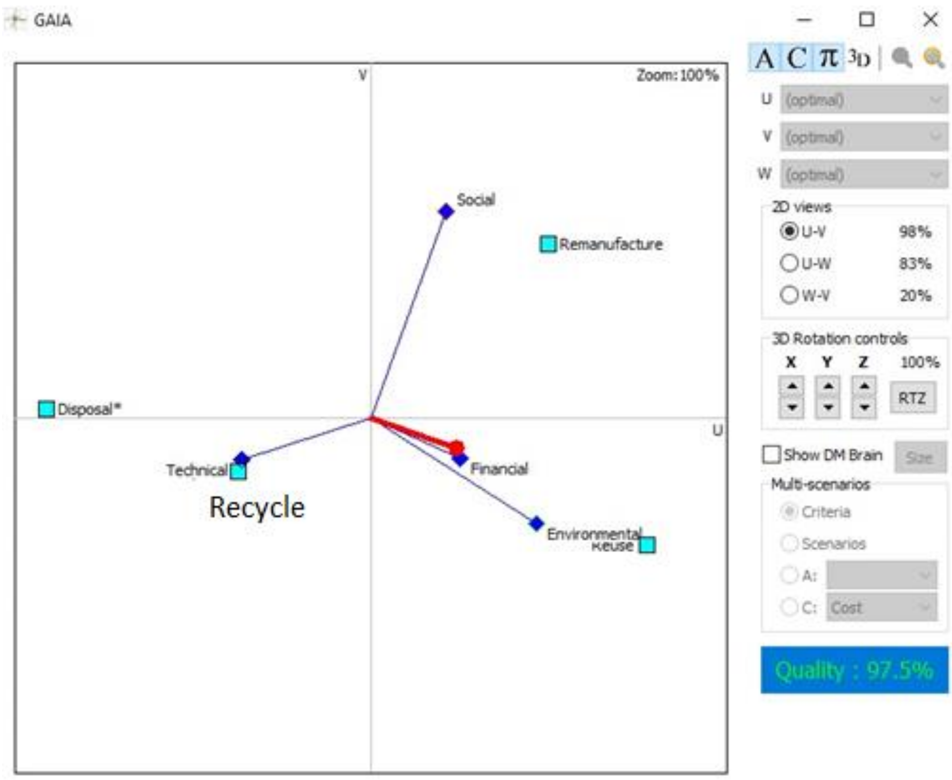


Figure 6.18: GAIA results of the MTDM model

Figure 6.19 illustrates the Promethee rainbow chart in greater detail, which depicts all the actions and their performance in each decision cluster. On the top are clusters where the action was performed positively, while at the bottom are the clusters where the action was performed negatively.

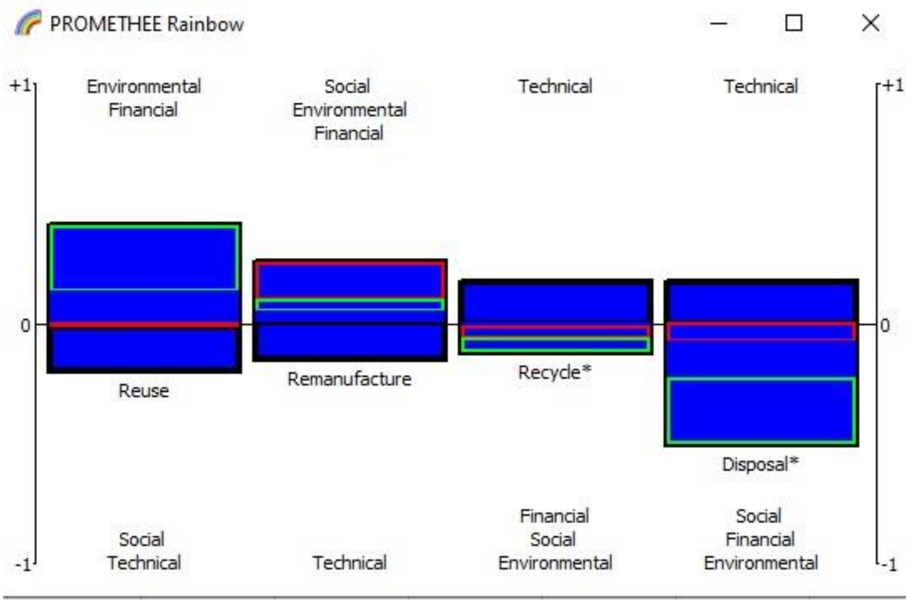
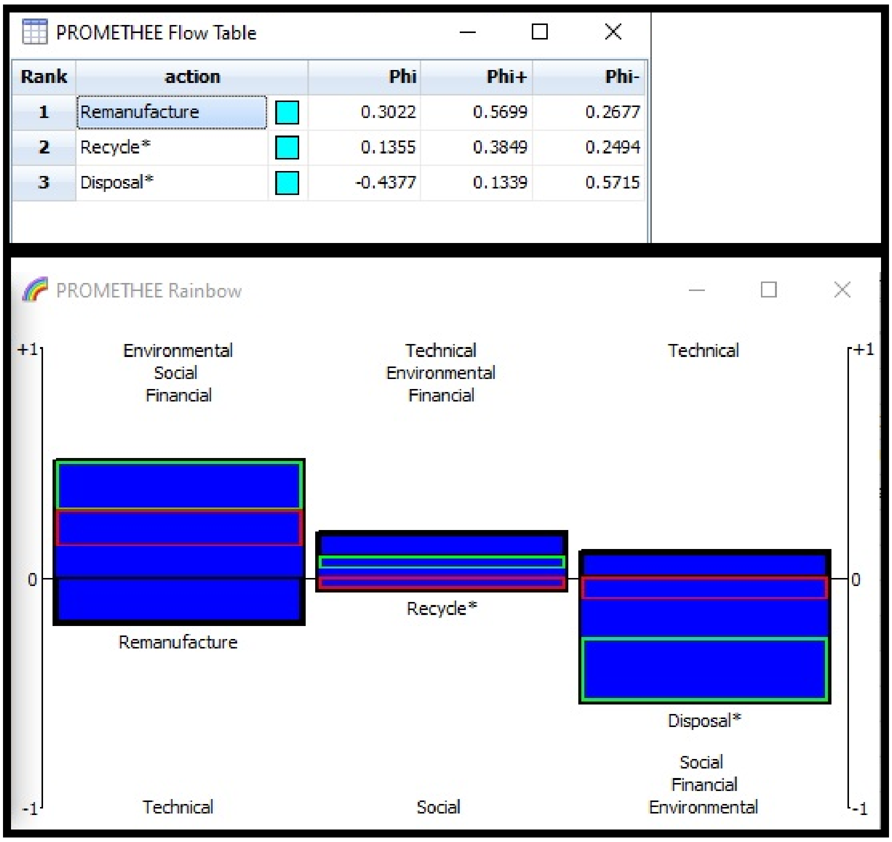


Figure 6.19: Promethee rainbow chart

Since reuse is not a possible EoL scenario, Figure 6.20 comprises the updated rainbow chart and the Promethee flow table. According to Figure 6.20 and the total Phi, *Remanufacture* is the highest-ranked EoL pathway, with *recycling* and *disposal* to follow.



Rank	action		Phi	Phi+	Phi-
1	Remanufacture		0.3022	0.5699	0.2677
2	Recycle*		0.1355	0.3849	0.2494
3	Disposal*		-0.4377	0.1339	0.5715

Figure 6.20: Promethee Flow table and Rainbow chart, No reuse

Based on Figure 6.20, both the *Remanufacture* and *Recycle* options show positive performance in the environmental and financial decision clusters. Additionally, *Remanufacture* positively impacts the social cluster, while *Recycle* scores well in the technical cluster. The positive social impact of *Remanufacture* can be attributed to its role in job creation and other social benefits. On the other hand, *Recycle* involves purchasing a new product and ensuring that the technical criteria are met or even surpassed compared to a reconditioned product. Conversely, the reasons why each of these EoL pathways performs less favourably in the factors above are based on the same underlying principles.

Disposal, as an EoL option, primarily satisfies technical factors, as it too involves replacing the old product with a new one to meet customer needs. As a result, it scores highly in technical factors but does not fare as well in the other decision clusters (social, technical, environmental).

The result of the developed method for the batch of the 100 returned accumulators would be to remanufacture them with the details included in Table 6.17:

Table 6.17: Final result of the method and best-ranked solution

			Batch size	100	
	per accumulator		whole batch		
EoL pathways	**Cost**	**Env. Impact (kgCO2 eq)**	**Cost**	**Env. Impact (kgCO2 eq)**	**Raking sequence**
Remanufacture	$180.27	130.83	$18,027.00	13,083	1st
Recycle	$220.17	274.69	$22,017.00	27,469	2nd
Disposal	$263.60	316.74	$26,360.00	31,674	3rd
Reuse	$72.47	6.19	$7,247.00	619	Not applicable

The results of the application of the method in the described case study will be discussed in the next section, alongside some additional scenarios and different decision weights.

6.6.5 Sensitivity analysis of the results

In this section, the tool named '*Walking weights*' provided by the Visual Promethee software will be used to give insights into how the weights of the decision clusters can impact the proposed solution.

The first scenario in the analysis delves into the sensitivity of decision factors and how they influence the final decision-making process. The objective is to identify the tipping point at which recycling becomes a more favourable EoL pathway than remanufacturing (with the guarantee process applied). The profiles of the EoL pathways, as depicted in the rainbow chart in Figure 6.19, indicate that the technical decision cluster aligns more closely with the recycling option. According to the walking weights tool, it is observed that when the weight assigned to the technical cluster exceeds 39%, recycling emerges as the preferable EoL pathway over remanufacturing. This transition is clearly illustrated in Figure 6.21.

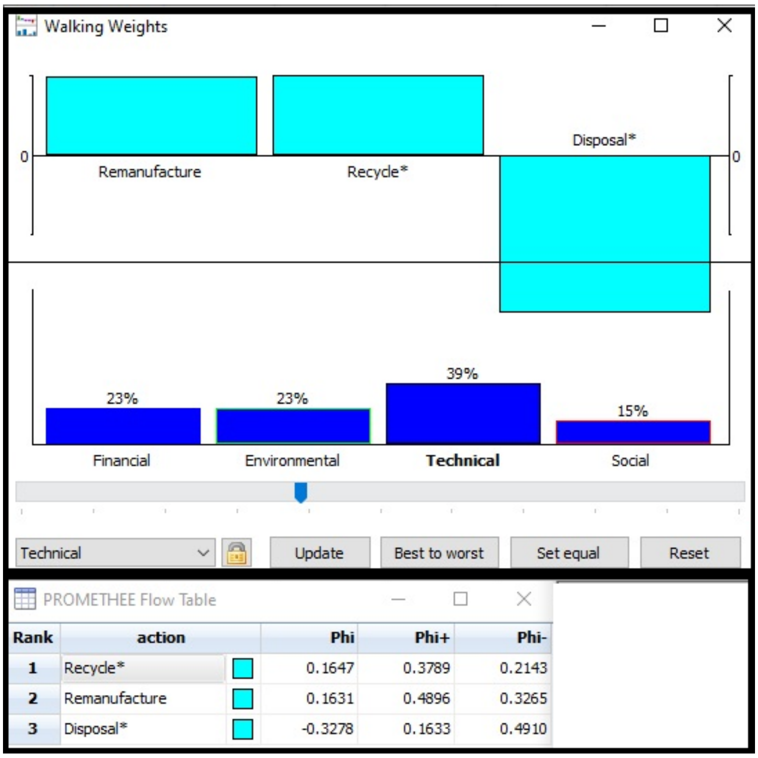


Figure 6.21: Pivotal point when the technical cluster is favoured, with the guarantee process applied

In an alternative analysis scenario, the method's outcomes are explored when the pre-screening process does not necessitate the replacement of two key components as determined by the guarantee and lifespan process. None of the key components require replacement in this hypothetical situation due to their adherence to guarantee and lifespan criteria. As a result, both the cost and environmental impact of remanufacturing will differ from those observed in the original case study. Under this assumption, the recalculated average cost for remanufacturing each accumulator is $135.99, while the environmental impact for the same product is estimated at 89.51 kg CO2 equivalent, as detailed in Table 6.18.

Table 6.18: Pre-screening process with no replacement due to the guarantee

% of products that will need replacement of # components	# of components replaced	cost (avg)	env impact kgCo2
21.4%	0	$72.47	6.19
33.9%	1	$113.53	60.04
23.0%	2	$154.58	113.89
13.6%	3	$195.64	167.74
6.4%	4	$236.69	221.59
1.7%	5	$277.75	275.44
100%	-	**$135.99**	**89.51**

Utilising the profile from the rainbow chart, illustrated in Figure 6.19, it becomes evident that this scenario is even more preferable for remanufacturing since both costs and environmental impact are lower than the case study's application. Thus, similar to the previous scenario, the only way to alter the result would be to change the weight of the decision factors related to the technical factors since recycling performs better there. Figure 6.22 depicts this scenario. When the technical factors' weight impacts amount to 39% and above for the final decision and the rest of the factors lower respectively, recycling is a more suitable EoL pathway. A real-life application of this scenario would apply to products whose obsolescence in design and technology is fast; thus, having an updated product is crucial for the end user.

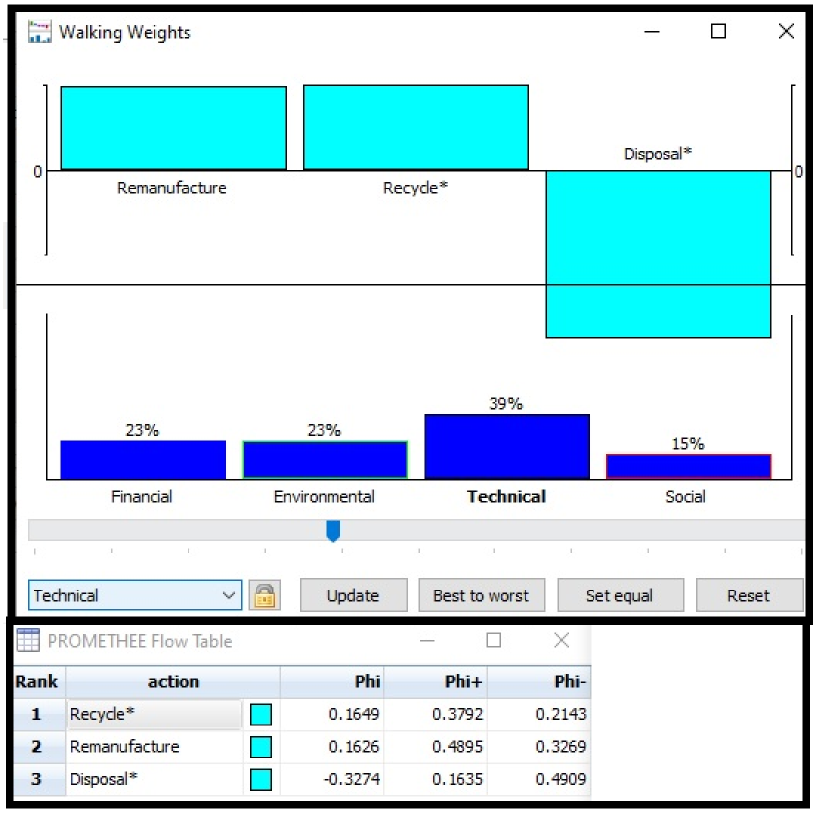
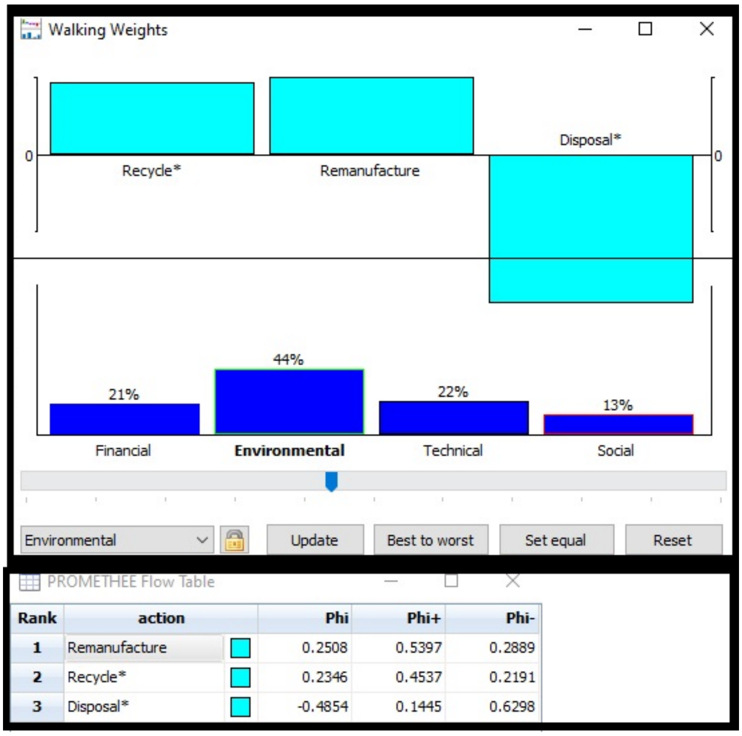


Figure 6.22: Pivotal point when the technical cluster is favoured, with no guarantee process applied

The observation that recycling emerges as the preferable EoL pathway when the weight of the technical decision cluster exceeds 39% holds true in both scenarios discussed earlier. This threshold also applies in situations where direct reuse is a possible option. Therefore, a technical factor weight of 39% represents the critical point where technical considerations become so dominant that they override the advantages of reuse, which is otherwise the best-performing remanufacturing scenario. At this juncture, the model consistently recommends recycling as the most favourable EoL pathway, regardless of the availability of direct reuse.

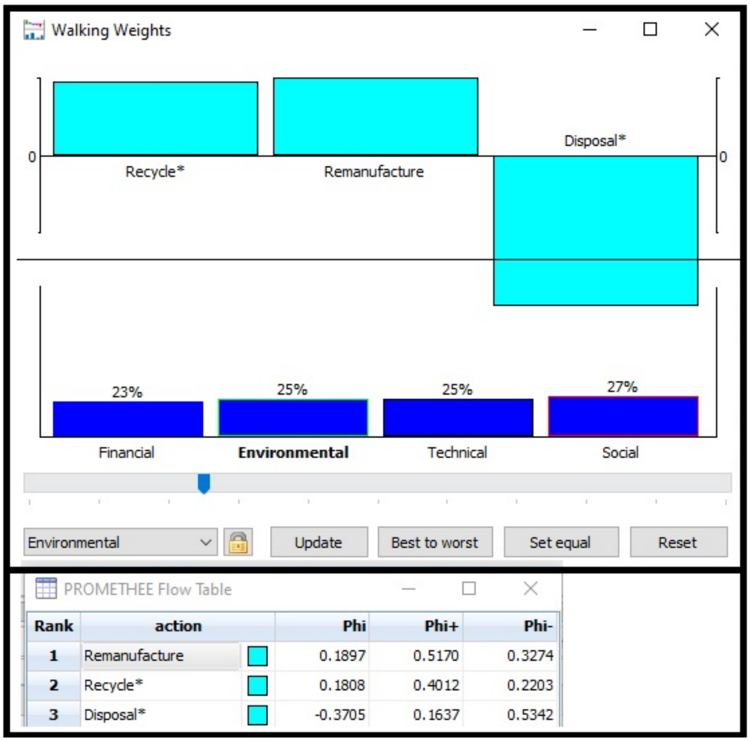
In another scenario, the focus shifts to the pricing policy for used accumulators. The model's analysis reveals a significant threshold value related to profit: 89%. This threshold indicates that when the company sells its remanufactured products at more than 89% of the price of new accumulators, remanufacturing becomes the preferred EoL pathway over recycling. Conversely, pricing the reconditioned products at less than 89% of the full price tends to make recycling more financially advantageous, as it results in lower profits that favour the recycling pathway.

From an environmental and social standpoint, remanufacturing typically outperforms recycling. The analysis, depicted in Figure 6.23, shows that when environmental factors account for more than 43% of the decision-making weight, remanufacturing emerges as the more favourable EoL option, irrespective of profit margins. Similarly, as illustrated in Figure 6.24, when the weight of social factors is set at 27% and environmental factors at 24%, the model again leans towards remanufacturing as the preferred solution, regardless of the profit.



Rank	action	Phi	Phi+	Phi-
1	Remanufacture	0.2508	0.5397	0.2889
2	Recycle*	0.2346	0.4537	0.2191
3	Disposal*	-0.4854	0.1445	0.6298

Figure 6.23: Remanufacture favourable, pricing policy, environmental cluster weights changing



Rank	action	Phi	Phi+	Phi-
1	Remanufacture	0.1897	0.5170	0.3274
2	Recycle*	0.1808	0.4012	0.2203
3	Disposal*	-0.3705	0.1637	0.5342

Figure 6.24: Remanufacture favourable, pricing policy, environmental and social clusters weights changing

6.7 Discussion of results

This section discusses the most essential outcomes of applying the proposed method to this case study. Following the case study description, the developed method has been applied to a returned batch of 100 accumulators. Based on their condition, the practitioner's input, and a thorough analysis of the product's design, decision support was provided through an MCDM method. According to it, the most suitable EoL pathway would be remanufacturing the returned batch. In total, it can be inferred that the proposed method has supported the practitioner at multiple and different stages during the decision-making process.

From a structural representation perspective, applying HALG for the accumulator and its integration with the eDiM tool provided a standardised approach to the times needed for each of the main components to be reached and replaced if necessary. In this case study, the always replaceable components were responsible for setting a minimum time requirement for the reuse scenarios (as defined in this case study). Thus, the differences between times for replacing key components were not as crucial as in the first case study since the operator would have to perform the dis- and re-assembly task no matter the core condition.

Furthermore, during the application of the method, the practitioner gained insight into the product's design suitability for remanufacturing through the CEDA graph. The creation of the four areas, as those depicted in Figure 6.8, provides the practitioner with a quantified answer on how well a product is designed for remanufacturing while the scenarios identification of replacement of key components and their link to the cost and environmental impact visualises the same concept. According to the CEDA graph from Figure 6.8, the accumulator is environmentally dominated by its shell, while financially, there is a clear correlation between the number of components replaced and the total cost. Such a conclusion can be used to optimise the accumulator's design for remanufacturing or a CEBM. Additionally, the grouping of scenarios and plotting their cost and environmental impact supports the practitioner in identifying scenarios that are preferable for remanufacturing and provides the basis for a '*rule of thumb*' approach on which scenarios are accepted for remanufacturing. Finally, on a higher level, the development of the CEDA graph provides the practitioner insights on which of the accumulators' designs have the greater potential for application of a CEBM, providing them with a basis of comparison through the four areas defined.

Another point for discussion arising from the application of the proposed method to the second case study is related to the practitioner's ability to identify remanufacturing scenarios of interest or of high probability of occurrence and estimate their financial and environmental performance. This aspect of the proposed method can be utilised to support tactical and strategic decisions by creating favourable scenarios for remanufacturing, recycling, or implementing other CEBM models, such as direct reuse to secondary markets. Additionally, it can be integrated into a policy of preventive maintenance and mass key component replacements, thus minimising uncertainty based on the quality condition of the cores and achieving homogeneity of the EoL products.

The application of the proposed method in the second case study yielded valuable insights and led to its refinement, further demonstrating the method's modularity. This adaptability across different industries was evident as the method provided tailored solutions specific to each case. The diverse inputs from practitioners played a crucial role in shaping various distinct components of the method. When integrated, these components form a comprehensive and cohesive framework.

This refined method approach facilitates practitioners in acquiring detailed knowledge about assessing returned batches of cores. Such in-depth understanding is instrumental in developing and establishing remanufacturing processes that are both de-risked and efficient. Moreover, it enhances the quality of decision-making, ensuring that it is well-informed and tailored to the specific requirements of the industry and the products in question.

A significant contribution emerging from the case study is the identification of primary decision factors in remanufacturing and the flexibility it offers practitioners to adjust their weights as necessary. This versatility is a key strength of the proposed method, enabling practitioners to modify the weights of these factors to align with their company's tactical or strategic objectives. Importantly, this adaptability does not compromise the method's ability to provide accurate financial data. It ensures that information regarding the costs, profits, and other financial aspects of various EoL pathways for a returned batch of cores is maintained and accurately represented. The method's capacity to balance detailed financial insights with customizable decision-making factors makes it a valuable tool for companies pursuing efficient and goal-aligned remanufacturing strategies.

From the sensitivity analysis, many conclusions can be drawn. A primary finding is the existence of threshold values for each decision cluster. When these threshold values are exceeded, alterations in other decision factors, such as profit, cost, or environmental impact, no longer significantly affect the final decision. This phenomenon arises from the multicriteria nature of the problem being analysed.

A useful tool for understanding how the model responds to changes in the weights of decision clusters is the rainbow PROMETHEE graphs. These graphs visually represent how each action, or potential decision, performs positively or negatively across different clusters. Consequently, they give the practitioner a clearer picture of how each decision cluster influences the final outcome. Additionally, they offer insight into the potential effects of altering the weights within a particular cluster. This understanding is crucial for practitioners aiming to tailor the decision-making process to specific scenarios or objectives.

Based on the insights gained from Figure 6.12 and the practitioner's remarks, it's evident that environmental concerns and evolving legislation will significantly enhance the relevance of the proposed method. As customer awareness and demands regarding CO_2 emissions intensify and legislative frameworks evolve, environmental decision factors will become increasingly critical. As governments potentially implement a mix of incentives, the proposed method can adapt to these changing economic realities. This adaptability of the proposed method and the quantification of EoL pathways, such as remanufacturing, may support companies in meeting both the evolving environmental standards and the financial constraints and opportunities presented by future legislative measures.

6.8 Chapter Summary

This chapter presented the findings from the application of the developed method in an operating context through the case study of an accumulator from the oil and gas industry. This second case study addresses multiple objectives, with the most important being proving the proposed method’s cross-industrial applicability in a completely different sector (oil and gas sector) from the first case study, thus verifying it as sector agnostic.

The modularity of the method provided a canvas for the company of the application to build its bespoke application for the method. Due to its function, The selected product was mature, with aesthetics not being a big part of the decision-making and a focus on operational excellence. Additionally, the always replaceable components have been introduced to the key components, creating the need to redefine direct reuse as a possible EoL pathway. The implementation of the HALG method provided the company with a clear dis- and re-assembly process, and the use of eDiM as a metric of dis- and re-assembly timing offered a standardised way to predict the time for each process based on the type of connectors type, tools used, the size of the product and the handling that it requires.

Interestingly, the importance of the eDiM as a metric in this application was impacted due to the always replaceable components, which created the need for all the remanufactured accumulators to be fully disassembled. A much more predictable cycle time of operation could be achieved due to this event. Based on a detailed LCA and financial analysis of the remanufacturing process, the CEDA analysis assessed the remanufacturability of the existing product design and communicated that result unambiguously to the practitioner. This assessment provided clear, quantifiable insights to the practitioner, especially in understanding the relationship between the accumulator’s shell and other key components from a cost, environmental and remanufacturing aspect.

Additionally, the pre-screening process underwent a minor modification to accurately capture the ratio between visual and performance-based key components, specifically at a ratio of 1 to 4. This adjustment, while specific to this case, did not detract from the core functionality of the pre-screening process module, underscoring its versatility and applicability across various combinations of key components.

The solution constraints played a crucial role in identifying the primary adverse factors that might render one or more EoL pathways unfeasible. Furthermore, the detailed practitioner questionnaire and the weighting process in the Promethee model endowed the practitioner with a comprehensive understanding of the key drivers for remanufacturing a batch. This deepened understanding is vital for effective decision-making in remanufacturing processes.

After capturing all the practitioner’s input through the multiple modules of the proposed method, the results were presented. Firstly, based on the LCA, the accumulator's shell is the main contributor to environmental impact. Moreover, the difference in magnitude in the environmental impact of the accumulator’s shell and the rest of the components resulted in the creation of two groups for the remanufacturing scenarios’ the ones that the shell had to be replaced and the ones that didn’t have to. Interestingly, this trend was not captured through the financial scope since the remanufacturing scenarios generally follow the rule of thumb that the more key components are to be replaced, the greater the average cost, regardless of the components. The CEDA graph and its analysis captured and visualised all this information for the practitioner. Based on the CEDA graph, the accumulator’s product design is very suitable for remanufacturing, especially if the shell can be used multiple times. From the solutions constraints process, it became clear that direct reuse in secondary markets is not feasible due to the product's function and the safety regulations. The direct reuse definition as an EoL pathway, was altered to depict this key difference. The decision factors and their weights provide the Promethee model with the necessary input for ranking the available EoL pathways, with remanufacturing the batch being the most favourable over recycling and disposal.

The sensitivity analysis of the results identified the threshold values for each decision cluster and their weights in the decision-making process. The values that some of the decision clusters impact the final solution were determined through extreme scenarios, such as eliminating any profit from remanufacturing. The same analysis revealed that the pricing policy for reconditioned cores could significantly impact whether remanufacturing or recycling is a more favourable EoL pathway. When selling a reconditioned one, the threshold value for remanufacturing to be ranked higher than recycling was calculated at 89% of the full new product’s price.

The next chapter includes the discussion and conclusions from the development and application of the proposed method against the key aims and objectives as those were set in Chapter 1.

7 Discussion and conclusions

7.1 Introduction to chapter

This chapter presents the discussion and conclusions for the proposed method. Initially, the original research objectives and their achievement are discussed in section 7.2. The research novelty is highlighted in section 7.3, and the reflections on the proposed method are captured in section 7.4. More specifically, the method's boundaries are defined in 7.4.1, followed by the data challenges in 7.4.2. Later, the application and findings are discussed in 7.4.3, where the two case studies are compared, gaining new insights into the proposed method. The advantages and limitations of the proposed method are discussed in 7.5. The contribution to the knowledge is detailed in 7.6 and broken down into its theoretical implications (7.6.1) and implications for the practitioners and industry (7.6.2). The future research recommendations are captured in 7.7, followed by the concluding remarks in 7.8, which also acts as a chapter summary.

7.2 Review of research objectives

The proposed method that was presented in this thesis is the outcome of the research, aiming to answer the following question:

How can the performance of EoL pathways for a core disposition problem be quantitively and qualitatively assessed in a holistic manner?

The research question is answered by developing the proposed method, which is applied in real-life industrial core deposition problems and provides holistic, well-informed EoL decision support to the decision maker while evaluating multiple available EoL pathways. More specifically, the proposed method ranks the available EoL pathways of direct reuse, remanufacturing, recycling and disposal based on the inputs from the decision-maker/ practitioner (i.e. the intended users of the method) by utilising the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) decision-making tool. The method has been described in detail in Chapter 3 and applied in a business context through the two case studies found in Chapters 5 and 6, respectively.

This research successfully achieved its aim by meticulously addressing the key objectives, as those were discussed in Chapter 1. The following paragraphs offer a comprehensive overview of how each objective was met.

Objective 1: *Investigate and analyse the current state-of-the-art decision support methods applied for the EoL product's disposition problem.*

This objective was met through analysis of all the relevant disciplines as described in Chapter 2, which contains the literature review. More specifically, the areas of Sustainability, Circular Economy (CE), EoL Management, a sub-category of Product Lifecycle Management (PLM), and Decision Support (DS), a sub-category of Decision Making (DM) were identified as the most relevant. Figure 2.1 illustrates the application area for the proposed method. First, analysis of the disciplines of Sustainability and PLM led to further narrowing the focus of the literature review on CE and EoL Management, respectively. In the overlapping area of the two previous disciplines, DM was researched, as well as its applications, methods and state-of-the-art. The methods and approaches used for EoL decision support were studied in section 2.4.1 and categorised based on which decision aspects they adopt, their quantitative, qualitative or mixed nature and their application tool. The described literature synthesis revealed several gaps that need to be addressed, as presented in section 2.5. The key literature gaps identified can be expressed as follows:

Gap 1: *There is a need for a holistic approach that simultaneously addresses the economic, environmental, technical and social aspects of EoL decision-making.*

Gap 2: *There is a need for an enhanced End-of-Life (EoL) decision-making approach that specifically addresses the key gap of incorporating practitioner's preferences, an aspect often neglected, especially when navigating solution constraints.*

Gap 3: *There is a need for a method that assesses the remanufacturability of a product's design from an environmental and economic point of view and visualises the results to support informative EoL decision-making.*

Identifying those three literature gaps supported the fulfilment of objective 1; the proposed method was later developed to address each of them.

Objective 2: Understand the key factors and the critical solution constraints impacting the decision to select an EoL pathway to a core disposition problem.

The achievement of this objective commenced with a detailed analysis of existing literature, followed by semi-structured interviews with industry experts and a questionnaire to collect relevant data, as illustrated in Chapter 3, where the methodology of the development of the proposed method was discussed. As a result, insights into the main decision factors in an EoL decision-making problem were identified. Then, these were allocated to the relevant clusters. The key economic, environmental, technical and social clusters were created, and specific decision factors were selected to express them through the literature and industrial feedback. Those factors influence the decision-maker differently; thus, the weights for each cluster and factor were not predetermined but tailored to the practitioners' preferences. Additionally, understanding the decision factors integrated into an EoL decision problem resulted in identifying scenarios where a particular factor might establish a prohibitive, or 'no-go', condition, effectively barring certain EoL routes. This nuanced comprehension aids in pre-emptively addressing constraints that could potentially skew or hinder optimal decision-making pathways.

Understanding the factors influencing the decision to select an EoL pathway to a core disposition problem requires identifying solution constraints applicable to the selected EoL pathway. These solution constraints first emerged during an extensive review of the literature, detailed in Chapter 2, and were subsequently expanded upon through in-depth analysis informed by industry experts' insights. The threshold values for each solution constraint, just like the weights of the decision factors, had to be fully customisable since each decision-maker has different preferences to some extent. Despite this need for customisation, the formulation of the mathematical expressions and main principles applied to each solution constraint were developed based on a '*soft'* and '*hard'* approach, as referred to in section 3.11.2. Using a '*soft'* and '*hard'* approach allows the practitioner to tailor the solution constraints' values to their decision problem, allowing some '*soft'* factors to just to influence the decision problem while other '*hard'* ones to act as conclusive solution constraints.

Objective 3: Design and implement a tool that facilitates the assessment of a product's remanufacturability by linking the product's design's environmental impact and economic performance.

Gap three from the literature analysis identified the need for a method that assesses the remanufacturability of a product's design from an environmental and economic point of view and visualises the results to support informative EoL decision-making. The proposed method addressed this objective by developing a novel tool called Circular Economy Design Analysis

(CEDA), as presented in section 3.7. Firstly, through the literature analysis, knowledge was gained about how remanufacturing evaluation has been conducted in previous studies. Later, a novel approach was adopted through engagement with industry experts, resulting in the CEDA graph. The CEDA graph illustrates a product's design suitability for the application of CEBM by correlating different remanufacturing scenarios' costs with their environmental impact. The values for a new identical (or very similar) product are used for the creation of the four areas of interest, namely, '*Sustainable area (win-win)*', '*Unsustainable area (loss-loss*)', '*Trade-off with economic preference'* and, '*Trade-off with environmental preference'*.

Additionally, the values related to the cost and the environmental impact for each remanufacturing scenario were used as input in the next stage of the proposed method to quantify the environmental and economic aspects of remanufacturing a batch of a specific quality. The integration of the CEDA graph into the proposed method is explained comprehensively in section 3.7, detailing how the CEDA significantly contributes to the method. Moreover, real-world applicability and the practical impact of the CEDA graph are demonstrated through its implementation in two distinct case studies. These instances, which underline the relevance and versatility of the CEDA graph, are discussed in detail in sections 5.5 and 6.5, respectively. Each case study is a testament to the utility of the CEDA graph, showcasing its adaptability and importance in making informed, environmentally conscious, and economically sound decisions in remanufacturing.

Objective 4: Design, implement and evaluate a method that holistically addresses the core disposition problem by quantifying the environmental, economic, social and technical performance aspects while considering the solution constraints input from the decision-maker.

All previous objectives contributed to address this final objective. Thus, after objective three provides a remanufacturing assessment from an economic and environmental aspect, the rest of the method had to be developed to feed this input to a decision support method. The social and technical aspects were captured by integrating the analysis from the decision clusters and factors and their weights, as described in section 3.11.1.

The next step would be developing and applying the pre-screening process, a process aimed at assessing the quality of the cores, as discussed in section 3.11.2. The pre-screening process is thoroughly presented through the real-life industrial case studies in sections 5.6.1.5 and 6.6.1.5. The mathematical expressions for the pre-screening process are based on the product's key components and the condition of a sample from the returned batch.

After completing the pre-screening process, the rest of the technical data related to the technical decision factors are captured. Finally, the practitioner inputs the data related to the social decision factors.

These data are fed to the selected method of analysis, PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) II full ranking method as described in section 3.11.4.1. The PROMETHEE method, which is the final step of applying the proposed method, ranks the performance of the available EoL pathways based on the practitioner's input. Through the application of solution constraints, as described in section 3.11.2, the proposed method ranks only the available EoL pathways and provides a full result on which solution better suits the preferences of the decision maker, what the final environmental and economic impact of that solution would be and a plethora of visualisation tools to convey the results clearer. Social and technical decision factors are also weighted in during the decision model to produce those results.

Additionally, through tools such as the walking weights, the decision maker can dynamically alter decision weights, offering them direct insight into how different priorities impact outcomes. This functionality demystifies the decision-making process and empowers stakeholders, enabling informed, confident choices regarding remanufacturing strategies. This is discussed in 5.6.5 and 6.6.5, respectively, where the proposed method is applied in two real-life industrial cases.

As described in the previous paragraphs, the proposed method was applied to two real-life industrial cases belonging to the *Lighting* and *Oil and Gas* sectors, thus adopting the multiple case studies research approach. The two case studies differ regarding their sector, size, product and level of remanufacturing conducted. More details for each case study can be found in sections 5 and 6, respectively. Applying the proposed method resulted in the numerical findings presented in sections 5.7 and 6.7, while the case studies demonstrated how the practitioner can apply the method step-by-step. The findings were composed of a remanufacturing evaluation of the selected product's design through the selection of key components through the CEDA graph and the developed PROMETHEE decision model that ranked the available EoL pathways for a returned batch of cores and provided a ranking of the available solutions based on the practitioner’s weights for the related decision factors. The proposed method was also tailored to the practitioner’s needs, proving its sector-agnostic and versatile character.

Chapter 4 demonstrated how the proposed method was evaluated against utility, accuracy and applicability criteria. Each of the three critical stages of the evaluation, namely, qualification, verification and validation, was performed based on the continuous expert feedback from the companies that participated in the case studies of this research. Moreover, model qualification was achieved through semi-structured interviews and model verification was accomplished through additional questionnaires and a workshop. Finally, model validation was performed through the workshop and the two case study applications. During each stage, its findings were fed to the model’s development process, thus progressively reinforcing and refining the proposed method. Additionally, through all the stages, especially during the development stage of the proposed method, there was continuous feedback and integration with industry experts. Thus, the objective of evaluating the proposed method was successfully accomplished.

7.3 Research Novelty

The research provides both primary and secondary novelty. The distinction between the two types is based on whether the novelty is linked directly to the aim of this research (primary novelty), or it is linked to the supportive tools used for achieving this aim (secondary novelty).

The novel aspect of this research hinges primarily on the proposed decision support method described in Chapter 3, addressing two vital gaps (out of the three) identified in the literature review (Chapter 2). These gaps highlight the absence of a comprehensive method in EoL decision-making that simultaneously encompasses economic, environmental, technical, and social dimensions and the need for an enhanced EoL decision-making approach that specifically addresses the practitioner's preferences and potential solution constraints.

The proposed method transforms EoL decision-making by facilitating the selection of the optimal EoL pathway for returned products. It quantitatively assesses each pathway's environmental, economic, social, and technical merits. This approach's novelty lies in its holistic consideration of all crucial aspects, a departure from prior methods that didn't integrate these aspects collectively.

Furthermore, the literature underscores another significant gap: the need for an enhanced EoL method that integrates practitioners' preferences, a critical element often overlooked amidst solution constraints. The method adopts a unique, sector-agnostic approach to address this, utilizing a diverse set of decision factors that reflect practitioners' insights and preferences. This customization ensures the method's applicability across various sectors. To the author's best knowledge, this is one of the very few proposed methods that include this often-neglected aspect of EoL decision making.

By employing both '*hard*' and '*soft*' criteria (detailed in sections 5.6.2 and 6.6.2), the method's strategy imposes solution constraints tailored to specific disposition challenges, adapting to each practitioner's unique considerations. This adaptability—notably absent in previous scholarly work—distinguishes the developed method, providing a versatile, comprehensive, and user-oriented EoL decision support system. Consequently, the novel approach described in this thesis bridges the identified literature gaps, offering a holistic solution that is adaptable to real-world preferences and constraints and is absent from the exiting relevant literature.

Another primary point of novelty was produced with the creation of the Circular Economy Design Analysis (CEDA) graph. This research is the first to introduce a visualization tool for depicting a product's design suitability for remanufacturing based on both the economic and environmental aspects of multiple specified remanufacturing scenarios. As identified in the critical review in Chapter 2, there was a clear literature gap for such a tool (Gap 3). The CEDA graph can demonstrate to the practitioner the suitability of a product's design for remanufacturing, thus promoting the application of a CEBM based on well-informed decisions. Through adopting the four distinct areas of interest, the practitioner gains rapid insights into the impact of each remanufacturing scenario from an environmental and economic aspect. Scenarios with poor performance can be further investigated for future optimisation of the product's design so it can better apply the '*design for CE'* principles. This novel tool gained the interest of all the collaborating SMEs that supported this research with products for case studies, proving its high potential.

The developed method results from synthesising multiple modules of well-established methods, approaches, and tools, alongside developing new tools and approaches to accomplish the research aim. The mixture of those approaches has produced secondary novelty among different stages of implementation of the proposed method.

A secondary novelty of this research is that the proposed method is the first to introduce the usage of a HALG (Dong et al., 2006) wedded to the eDiM tool. When using the HALG, the product's structural representation was able to visualise the hierarchical stages of dis- and re-assembly and the links between the connected components. Previous studies showed that a hierarchical approach to EoL decision-making is highly beneficial and that effective structural representation is key for identifying the value/ cost relation of the dis- and re-assembly process (Lee et al., 2010). On the other hand, eDiM was developed by a European Commission-funded project and the Joint Research Centre JRC to create a standardised metric to capture the difficulty level of disassembly. Coupling a tool for measuring the dis- and re-assembly times, such as eDiM, with the structural representation through a HALG provides the practitioner with a powerful tool that identifies, separates, and visualises both the hierarchical levels that the product might need to be dis- and re-assembled and also the effort required, expressed in time units. Thus, this novel tool can be used to cost any dis- and re-assembly tasks without physically needing to perform them since the time required for each eDiM-related task is standardised in the tool.

7.4 Reflections

This section presents the reflections on the proposed method's boundaries, the data challenges, the application, and the findings.

7.4.1 Proposed method boundaries

One of the critical decisions in this research was defining the boundaries of the proposed method, mainly due to its multidisciplinary nature and the high potential for adaptation across different types of companies exploring the idea of adopting CEBM. As described in Chapter 1, the aim and objectives of this research provided an answer to this problem by defining the study and narrowing down its scope and field of application.

The first boundary stems from the type of EoL decisions that the proposed method can support. The method focuses on providing EoL decision support at a product level, not a component level. Although parts of the method, such as the LCA, the remanufacturing assessment, and EoL costing, are based on a component-level analysis, as described in Chapter 3, the final decision is provided to a product level by ranking the available EoL pathways based on an average product's performance. Thus, the proposed method does not answer the question of which components should be replaced but based on the analysis of the EoL pathways; it answers the question of which EoL pathway a specific batch of cores should follow based on the practitioner's preferences and ranking of those EoL pathways.

Another boundary stems from the selected EoL pathways the proposed method provides as available solutions. The available EoL pathways selected for the proposed method are thoroughly described in Chapter 3, while an extended list of most EoL pathways met in the literature can be found in section 2.2. The proposed method ranks only the EoL pathways of direct reuse, remanufacturing, recycling, and disposal. It is evident that three of those EoL pathways are circular pathways since they close loops. On the other hand, disposal, although it is included as a possible pathway, is not a circular loop. This research strives to offer measurable evidence on the performance of each available end-of-life (EoL) pathway based on practitioner preferences rather than present solutions that merely appear to be sustainable without an analysis proving them to be objectively so. Thus, by quantifying the disposal's performance, the decision-maker can compare the performance of each of the more sustainable EoL pathways to disposal and better understand what the impact of applying a CEBM for a specific batch of cores really is. Hence, although the proposed method only adopts a limited amount of EoL pathways, it counters the risk of greenwashing or sustainable biased decisions through strict quantification and comparison for each available EoL pathway.

The next boundary of the proposed method occurs from the selected approach on calculating the environmental impact for the product's remanufacturing scenarios. As discussed in section 3.5, this study adopted the simplified LCA with a 'cradle to gate' approach. Thus, the impact during the usage stage is not integrated into the impact calculation of the remanufacturing scenarios. The environmental impact of each component that follows each EoL pathway has been considered for recycling and disposal, partially adopting an '*environmental credits*' solution inspired by ISO14040. Additionally, the method focuses on the environmental impact of the activities directly linked to the remanufacturing of a product. Thus, it excludes any other environmental impact, such as carbon footprint related to the activities of the remanufacturing company itself. Analysis of the carbon emissions for the company in terms of Carbon Foot-printing and then the allocation of those emissions to the remanufactured goods has been excluded from this study because this would create an index highly related to the size of remanufacturing; thus, dependencies that would be uncontrolled from the proposed method would occur. Despite this, such an addition to the proposed method could potentially be a valuable recommendation for future work, especially if a company fully adopts the method since it can replace the usage of averaged data with case specific. To conclude, the level of detail on capturing the environmental impact per EoL pathway and the integration of an LCA to the proposed decision support method has been positively confirmed by the collaborating companies and through the method evaluation process.

Another boundary of the proposed method is that the creation of the four areas of interest in the CEDA graph, as those depicted in Figure 3.5, are defined by the financial and environmental values of a new identical product. Such an approach might make the proposed method subject to volatile pricing. While this aspect might initially seem to be a disadvantage, practitioners from the case studies have identified it as a significant positive attribute. The reasoning is that the method will capture the change in the pricing policies for new products and provide decision support more realistically, with much less bias. Additionally, suppose no identical product can be found. In that case, those four areas of interest will be defined based on the performance of a new product that is the direct competitor of the remanufactured one. Therefore, the proposed method will keep comparing the remanufactured products to similar ones that might be more efficient, and the decision maker will be able to assess the difference between those two.

The final limitation of the proposed method arises from its structural design, which embraces a 'key components' approach for practicality and widespread applicability. Consequently, the analysis delves deeply into only certain essential product components, not every single one. While the environmental impact and cost of all components are acknowledged, the method focuses on generating remanufacturing scenarios from these key components exclusively. This ensures the method's simplicity without overlooking comprehensive considerations.

Each of the assumptions and boundaries discussed above has been consciously selected concerning the aim and objectives of this research. None of them is adequate to jeopardise the proposed method’s efficiency in providing multicriteria, multidimensional product-level EoL decision support tailored to the practitioner’s preferences. They do not compromise the effectiveness of the proposed method in delivering multi-criteria, multi-dimensional, product-level End-of-Life (EoL) decision support customized to practitioner preferences. Instead, these research boundaries present significant opportunities for potential system development, thereby enriching the method with new capabilities and/or domains of application.

Further discussion on the potential enhancements and what future work opportunities have derived from the method’s boundaries is included in section 7.7.

7.4.2 Data challenges

As described in the previous chapters, the research presented in this thesis was driven by an identified need from an academic perspective, through the identified literature gaps, and from an industrial need as well, based on the feedback from industry experts. A method that aims to deliver holistic, multidimensional decision support requires a plethora of data to input. This need has been one of the main challenges during the development of the proposed method, which inevitably led to a much closer collaboration with the companies that provided the case studies and ultimately strengthened the value proposition of the proposed method by enhancing its applicability to the industry in a sector agnostic manner.

One of the primary challenges faced in this research pertained to the development of the HALG using a BOM. Initially, the BOM was utilized to formulate a preliminary version of the HALG. A key difficulty arose when attempting to use only BOM-related data to discern the product's hierarchical levels and component connections. Solely relying on this information was insufficient. Achieving an in-depth understanding of the product's structure proved crucial in the development of the HALG. The draft HALG version was then refined using engineering drawings of the product and feedback from company engineers. This experience underscored the importance of close collaboration, especially during the method's initial implementation, to ensure that the HALG accurately represented the product's structure. Insights gained from the first case study (as detailed in Chapter 5) informed improvements, making the process less resource-intensive in the subsequent case study (Chapter 6). Although this posed a challenge for this research and the method's development, it might be less problematic for companies implementing it. Practitioners equipped with a deep understanding of the product and intra-departmental collaboration can potentially eliminate such data-related challenges. However, validation of the HALG by senior staff could still be essential to ensure the desired accuracy.

An added data challenge occurred from the need for the usage of a standardised tool to assess the effort needed to perform dis- and re-assembly tasks. As discussed in section 3.3, the proposed method uses the eDiM tool based on the MOST (Zandin, 2002). The main challenge was to validate that the time described for each task represented reality and to what extent these times could be adopted. To overcome this challenge, the researcher on-site, dis- and re-assembled one of the products in case study A and timed the process. This process was conducted three times, and average values were used. Considering the researcher's inexperience in this type of work and unfamiliarity with the product’s connectors, both in type and number, the tasks' times differed from those described in the MOST task catalogue. When this was presented to the company engineers, they reviewed the difference and made some minor changes to the times provided by eDiM. Those changes were focused on specific tasks related to the nature of the product, such as unclipping LED lights. The rest of the eDiM were considered representative of reality, thus strengthening the confidence in the selected tool.

Unfortunately, in the second study, due to the COVID-19 restrictions, such practice was not possible. The engineers validated the times through a virtual meeting and based on their experience. Thus, the data challenge of eDiM had to be overcome through closer collaboration with the companies that provided the case studies. While the challenge described is valid in the context of an independent researcher unfamiliar with the product and assembly processes, it might be less pronounced when the method is applied within a company. This is mainly because companies usually possess a deeper understanding of their products, know how their products are manufactured, how they can be disassembled, they have skilled personnel, have access to historical data, and can quickly collaborate and adapt tools to their specific needs. To further strengthen the argument, the company's engineer's feedback is what actually helped the researcher overcome this challenge during this research.

A further challenge encountered in this research was obtaining data on component prices and their environmental impacts. This difficulty arose because one of the companies relied almost entirely on products manufactured by their primary suppliers. While the focal company maintained strong relationships with these first-tier suppliers, its access to information became less reliable at the second tier and deeper levels of the supply chain. In the two case studies conducted, the components identified for potential replacement predominantly came from first-tier suppliers, with only a few exceptions. In instances where exceptions arose, the researcher and the companies collaborated to obtain the necessary data either directly from the second-tier suppliers or from suppliers of similar components when the first option was not available.

Similarly, during the execution of the simplified LCA, there were obstacles in acquiring data about the manufacturing processes and materials for some critical components. As detailed in section 3.5 the lack of detailed data was a primary factor in opting for a simplified LCA over a full LCA. All assumptions made were carefully validated with the collaborating companies to ensure reliability. This data accessibility could also present a hurdle for industry professionals applying this method, particularly if the focal company's reach does not extend to second-tier suppliers and below. Strengthening the lines of communication and building more robust connections with suppliers can help lessen the impact of such challenges.

A potential limitation in applying the proposed method is the lack of detailed descriptions of the remanufacturing process. During the development of the method and its application in the case studies, this issue was addressed by focusing on specific tasks associated with disassembly and reassembly, the tools employed, and any other auxiliary inputs. Attention was particularly given to capturing the energy and resources consumed by these tasks for each key component individually. Thus, in a scenario where the practitioner is unfamiliar with the remanufacturing process, they are advised to familiarise themselves with the process regarding any materials needed, tools, or other consumables before financially modelling it. Using eDiM helps greatly in mitigating this challenge since the standardisation of the time spent per task results in a confident cost estimation of the labour related to the task. Therefore, if practitioners are well-acquainted with the remanufacturing process, this challenge is unlikely to present a significant obstacle when the proposed method is applied in a company setting.

Finally, key parts of the developed method include the solution constraints and decision factors, which posed challenges in terms of correctly selecting the appropriate elements as solution constraints and decision factors. To address this challenge, this research capitalized on a literature review from Chapter 2, expert feedback, and established research methodologies, such as workshops, semi-structured interviews, and questionnaires, to collect relevant data. For companies implementing the proposed method, these challenges may be less pronounced. The method offers a sector-agnostic foundation, enabling companies to adapt and enhance it with specific features as necessary.

7.4.3 Application and findings

An interesting analysis of the findings occurs when comparing the two CEDA graphs from the two case studies. Of course, since the two products are entirely different and belong to different categories, there cannot be any direct comparison of their designs. However, analysing the outcomes of applying the developed method to these products and discussing their CEDAs, presents an opportunity to examine the implementation of the method to a higher level.

Initially, the CEDA graphs illustrated in Figures 5.13 and 6.8 show a completely different picture. The CEDA graph of the accumulator reveals that multiple scenarios belong to the Unsustainable area (loss-loss) and that the accumulator shell dominated the environmental impact of the remanufacturing scenarios. Moreover, the CEDA for the luminaire illustrates that no scenarios belong to the loss-loss area. On the contrary, the luminaire's CEDA reveals a linear correlation between the number of replaced components and the financial and environmental performance of the product. Table 7.1 contains the average values for all 32 remanufacturing scenarios for both products and a comparison to a new product's values:

Table 7.1: Average values for the 32 Remanufacturing scenarios

	Remanufacturing cost	Env. Impact (kgCO2 eq)
	Average values- Luminaire	
	Remanufacturing cost	Env. Impact (kgCO2 eq)
	$ 19.25	17.15
Reduction (from new)	23%	59%
	Average values- Accumulator	
	Remanufacturing cost	Env. Impact (kgCO2 eq)
	$ 178.42	145.16
Reduction (from new)	31%	54%

Based on Table 7.1, the accumulator seems to be more profitable if remanufactured on average but with a slightly higher environmental impact. Interestingly enough, drawing conclusions strictly based on the average values of the table might be misleading since the table does not convey the same information CEDA does. Specifically, average values do not account for the varying quality of returned cores. This variability is visually represented in Figure 7.1, which depicts the range of costs - minimum, average, and maximum - associated with replacing a certain number of components in a remanufacturing scenario, compared to the cost of buying a new product. Each of the 32 remanufacturing scenarios is equally likely, which means the analysis could be skewed if outliers in cost or emissions heavily influence the results, potentially misleading decision-makers. Significant variations can arise depending on the specific components that need replacement, highlighting that the impact is not merely a function of the quantity of components replaced, as illustrated in Figure 7.1.

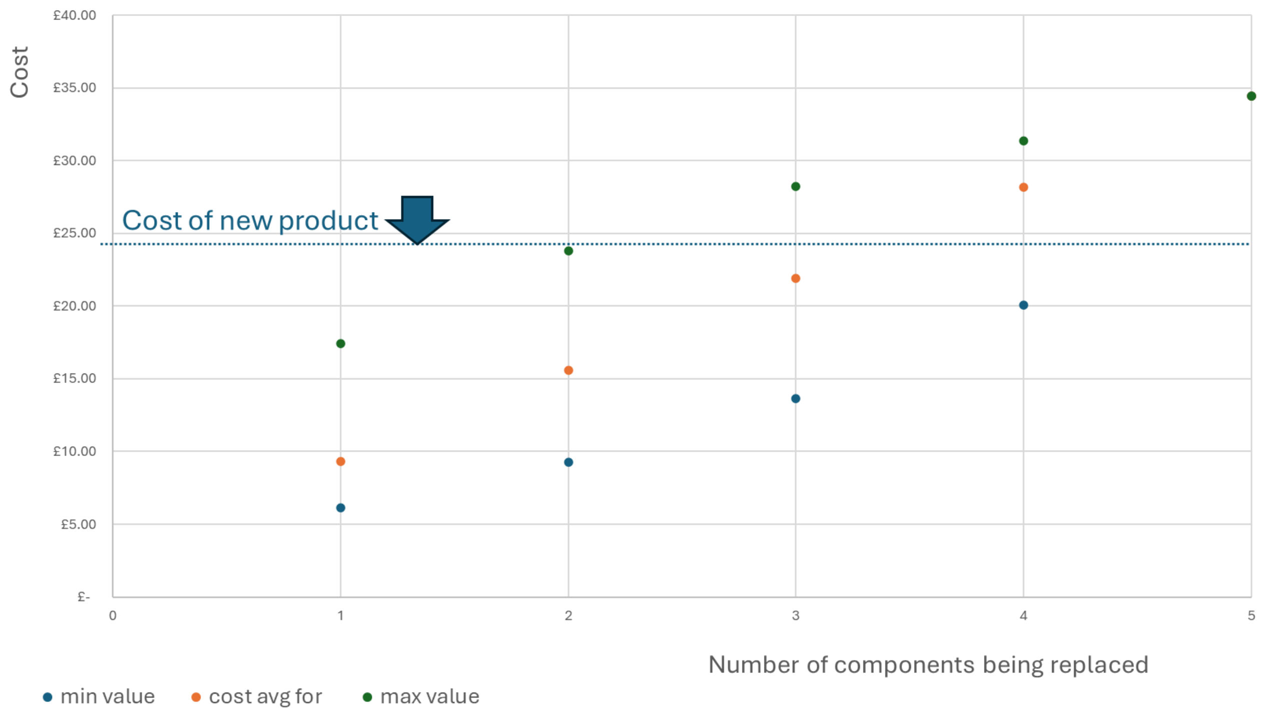


Figure 7.1: Range of costs - minimum, average, and maximum - associated with replacing a certain number of components

Thus, the importance of the intermediate step of the CEDA development during the method application is once again highlighted since the decision maker can gain a much clearer understanding of the remanufacturability of a product. This would be achieved by visualising all the remanufacturing scenarios across the four key areas and highlighting the ones with the most interest for the decision maker.

This investigation provides the practitioner with critical information regarding their cost elements and what type of solutions might be needed to improve the margins of remanufacturing profits. Figure 7.2 compares the number of remanufacturing scenarios for the two distinct case studies: the accumulator and the luminaire. The cost of the remanufacturing scenarios is stratified by their cost relative to obtaining a new product.

From this analysis, it becomes clear that the highest number of remanufacturing scenarios for the accumulator belong to the cost range between 70-80% of a new product's cost, thus leading to a 20-30% reduction in costs. Conversely, the luminaire's remanufacturing scenarios predominantly align with or exceed the full cost of a brand-new luminaire. This distinction underscores why, on average, remanufacturing the luminaire appears less economically advantageous than the accumulator. The reason for such difference lies in the nature of the products. The luminaire is a relatively low-cost product with parts usually imported from countries that mass produce them with low labour costs. On the contrary, the UK-based labour cost is significantly higher than the countries of origin of the components, thus making remanufacturing non-profitable over many remanufacturing scenarios. The accumulator is a product with high-value components and potentially less labour-intensive to remanufacture. The high value of some of the components creates an opportunity for remanufacturing since the cost of a new product is significantly higher than the cost of the remanufacturing process, including UK-based labour.

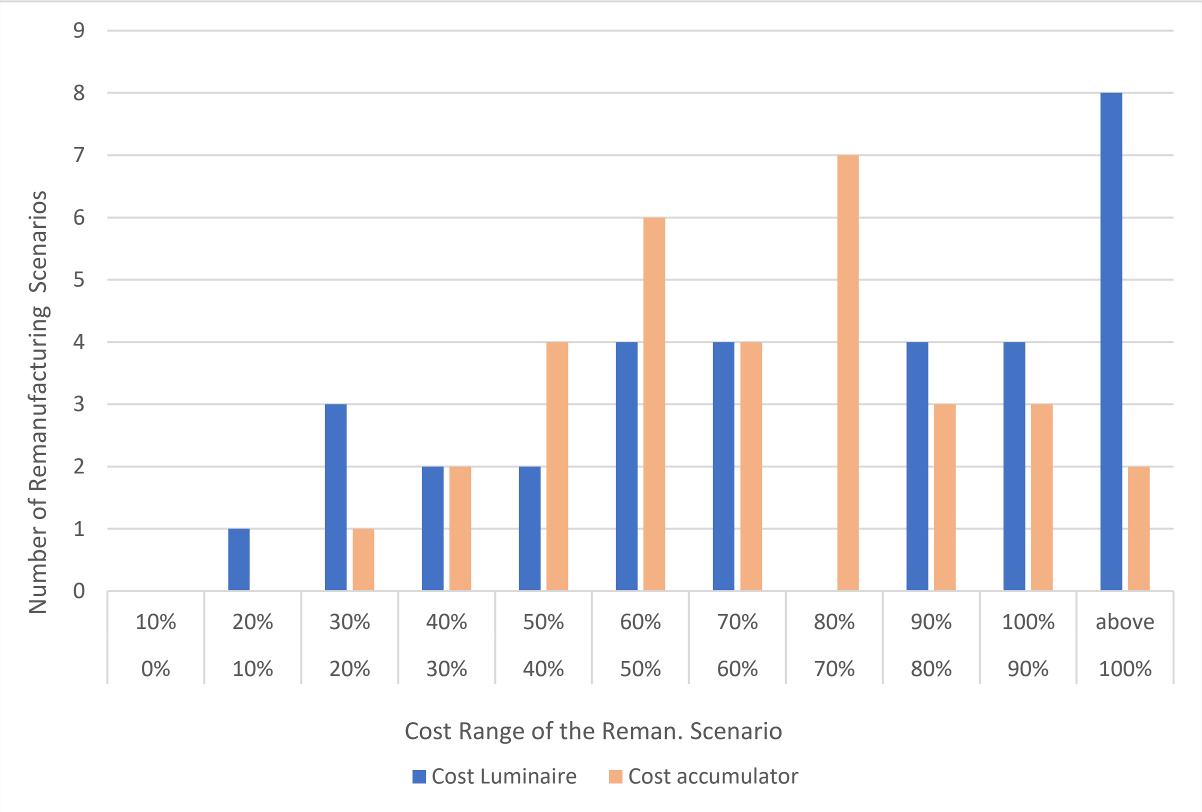


Figure 7.2: Number of Remanufacturing Scenarios Comparison between the case studies

Figure 7.3 provides a comparative environmental impact analysis of remanufacturing scenarios for the accumulator and the luminaire, parallel to the earlier cost analysis. In this case, the difference between the profiles of the two products is again dominated by the accumulator's shell impact. If the accumulator's shell has to be replaced, the environmental impact of those remanufacturing scenarios is 80-90% of that involved in producing a new unit. In contrast, if the shell remains intact and does not necessitate replacement, the environmental impact dramatically decreases, corresponding to 0-10% for the same number of scenarios (16 total).

Thus, for the accumulator, only two peaks describe the environmental impact of remanufacturing the product.

On the other hand, the luminaire's environmental impact during remanufacturing presents a more uniform distribution across different scenarios, with the most substantial impact being in the 80-90% range relative to a new product. This suggests a less variable environmental benefit from remanufacturing luminaires, as opposed to the more distinct outcomes observable with the accumulator, dependent on the specific condition of the shell component. This data is crucial for practitioners in strategizing environmentally responsible remanufacturing practices, especially in considering replacing significant components like the accumulator's shell.

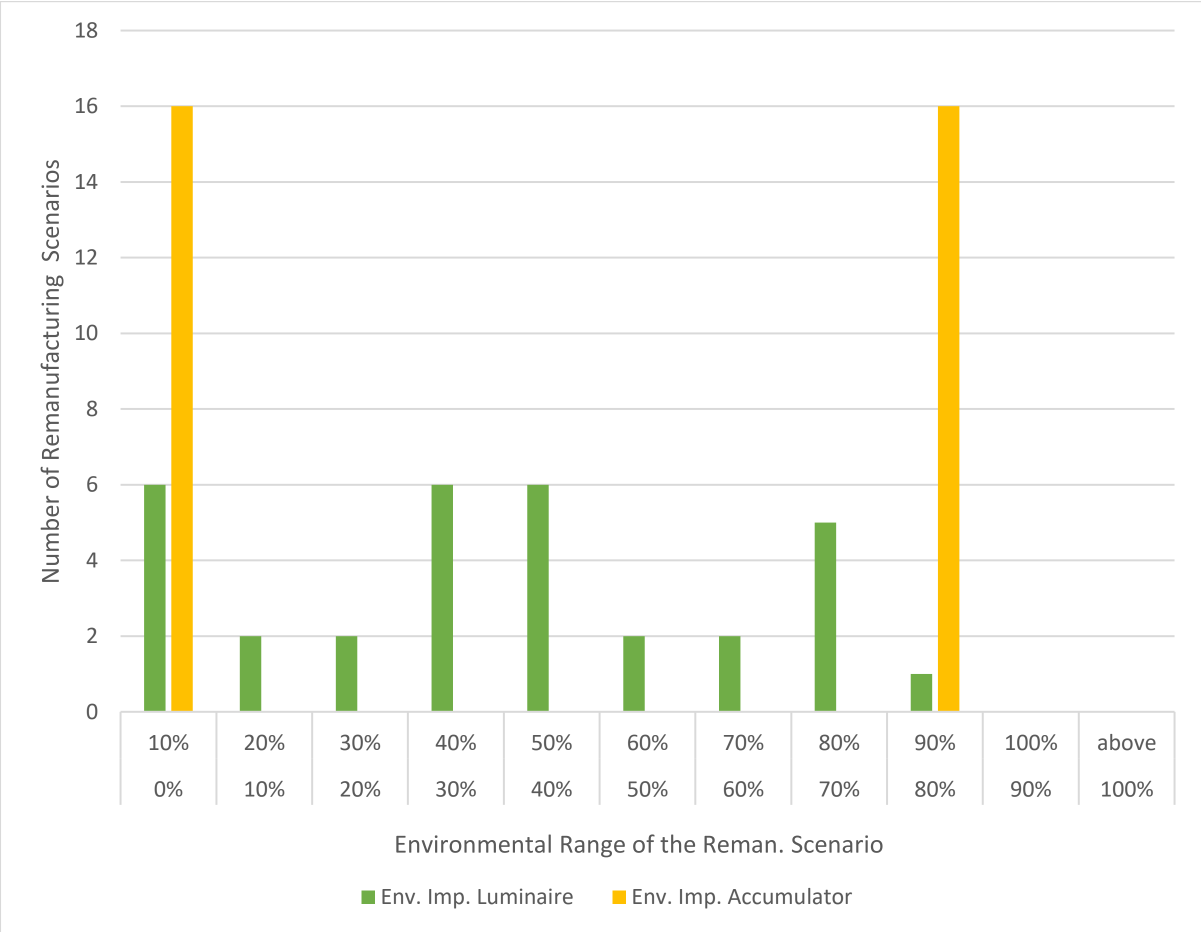


Figure 7.3: Number of Remanufacturing Scenarios Comparison between the case studies

Another difference between the two case studies emerged through applying the pre-screening processes. The pre-screening process, which for each case study has been discussed in 5.6.1.5 and 6.6.1.5 respectively, differed between the two case studies due to the number of components that belonged to each of the two groups: visual and performance-assessed components. For the luminaire, three of the five key components belonged to the visually reviewed group of components. For the accumulator, only one key component, the shell, belonged to this category. For each case study, the remaining ones were allocated to the performance-related group of components. This change resulted in a small change to how the probabilities that described the quality condition of the returned batch were calculated for each of the two products. The fact that the developed pre-screening process was able, with few changes, to be successfully applied to both of those significantly different case studies validated the proposed tool's applicability.

Regarding the constraints of the solution, the main difference in application occurred through the guarantee process. For the luminaire, ensuring effective operation is managed via established industry guidelines, such as the minimal accepted Lamp Luminous Flux Maintenance Factor or LLMF. As described in section 5.6.1, the proposed method applied those guidelines and developed a tailored tool for performing a guarantee check of good future operation for the luminaire. The results of this process were used as intended from the proposed method, and restriction checks for the available EoL pathways were performed.

In the accumulator case study, no specific information on how the industry calculates and defines the good operation of an accumulator was provided. Consequently, a more rudimentary version of the guarantee process was implemented. The process is described in section 6.6.1.1, and the key difference with the one described in the luminaire is the initial information usage between the two case studies and the LED performance checker tool. This divergent application of the guarantee process across two distinct products underlines the method's adaptability and industry-wide relevance. It suggests that while the core process remains consistent, it can be customized effectively to account for various products' unique requirements and characteristics, thus affirming the method's flexibility and capacity for broader sector application.

In each of the two case studies, a sensitivity analysis was conducted to study the results further. The analysis in both case studies underscored the remanufacturing process as the optimal EoL pathway when considering a balance of technical, environmental, social, and financial factors. A notable observation is that across both studies, the various EoL pathways, particularly those involving the purchase of new products, such as Recycle and Disposal, tended to score higher in technical factors. Remanufacturing yielded positive outcomes in environmental, social, and financial decision clusters, but it was less favourable in the technical one.

The proposed method's critical contribution is that through quantifying those performances per available EoL, a balance can be achieved based on the practitioners' inputs among the positive and negative performances of the EoL pathways. For instance, in the luminaire case study, a pivotal threshold of 46% was discovered in the importance of technical decision factors. Should practitioners assign a weight equal to or greater than this threshold, they may lean towards recycling and purchasing new luminaires rather than remanufacturing. In contrast, for the accumulator, the corresponding threshold was determined to be 39%. These findings illustrate the responsiveness and flexibility of the MCDA PROMETHEE model developed for this research, which adapts to the unique inputs and preferences of the practitioner, thus confirming the method's efficacy in providing customized EoL pathway recommendations based on specific decision-making criteria.

One of the interesting analysis points for the two case studies is that direct reuse had to be defined differently for each of them. Specifically, in the first case study with the luminaire, direct reuse meant that the product would be sold to a secondary market where the correlation of its limited efficiency and reduced cost would create an attractive alternative to buying a new one. Despite what was described in Chapter 5, such a scenario could not be applied due to legislative restrictions. On the other hand, the accumulator's case (Chapter 6) necessitated a more involved approach to direct reuse, demanding the replacement of all components deemed *always replaceable* to adhere to stringent safety standards; thus, direct reuse required a significant amount of work for the returned core. The reasoning behind this is that the accumulator is considered a safety-related product, and standards of good operation must always be implemented independently of the type of market, secondary or primary.

The variations in the definition of direct reuse across these studies reveal a broader industry challenge: EoL pathways cannot be universally applied but must be tailored to respect product-specific and industry-specific requirements and regulations. The method introduced in this research addresses this challenge by classifying a direct reuse scenario. It's marked as the first scenario from the list of remanufacturing scenarios. This first scenario requires none of the key components to be replaced. As a reminder to the reader, a component that must be replaced due to safety legislation independently of its condition cannot be defined as a key component but as an always replaceable component. The approach followed by the proposed method has successfully solved the issue of difference in the definition of direct reuse scenario and managed to capture it in the CEDA graph as well, providing the practitioner with an overview of the impact of this scenario in comparison with the rest of the remanufacturing scenarios and of course, in comparison with a new product.

7.5 Advantages and limitations of the proposed method

The proposed method from this research was meticulously developed to bridge the three specific literature gaps highlighted in Chapter 2. A critical strength of this approach has been the active involvement of industry partners from the early phases of the research, which infused the developed method with practical insights. Besides being theoretically robust, this collaborative approach has ensured that the resulting method is grounded in real-world needs.

However, like any other academic research, the proposed method has advantages and limitations, which will be described in the subsequent sections. Acknowledging those is essential for a balanced view of the method's applicability and for guiding future research to build upon this foundational work.

7.5.1 Advantages

The proposed method can be used to provide EoL decision support across in core disposition problems as well as to provide insights on the product's design remanufacturability. A significant advantage of the method is its applicability to established products already in the market and products still in the design phase. Moreover, the sector-agnostic nature of the method broadens its potential impact, making it a valuable resource for a diverse range of industries. This universality enables many businesses to adapt the method to their specific EoL decision-making challenges, facilitating better-informed EoL decision-making across different sectors.

When the presented method is applied to a product that is already on the market, its emphasis shifts toward operational decisions that affect the handling of products at the end of their life cycle. This operational focus aims to provide regular, batch-level EoL decision-making support. By doing so, the method helps decision-makers determine the most suitable EoL pathway that aligns with their specific preferences and the prevailing conditions at any given time. Additionally, the initial application of the method to an existing product offers comprehensive insights. It not only assists in choosing the right EoL option but also reveals in-depth information about the product's potential for remanufacturing, its structural composition, and the environmental implications of its lifecycle. This level of understanding is critical in shaping more informed and sustainable EoL strategies.

When applied during the design phase of a product, the proposed method shifts focus from day-to-day operational support to providing more long-term tactical and strategic decision support. This is because the proposed method offers a critical advantage at the design stage: it allows designers to evaluate and enhance the product's potential for remanufacturing. By identifying and addressing design aspects that impact remanufacturability early on, designers can align the product more closely with the principles of a CEBM. An excellent example of this stems from the second case study in this thesis, where the accumulator's shell is responsible for almost 90% of the product's total environmental impact. If designers prioritize reusability and remanufacturability of the shell throughout multiple life cycles, it could lead to a significantly more environmentally friendly product. Such design optimization can result in considerable savings for the company and a reduced environmental footprint.

Another advantage of the proposed method is its ease of use and simplicity, particularly after the initial implementation. As detailed in section 3.1, the method becomes streamlined upon subsequent applications; it only necessitates the quality assessment of returned products through the pre-screening process. The method can readily output new results unless there are changes in the decision-maker's preferences. This advantage is key for wider acceptance and implementation of the method from SMEs since, after the initial customization, the method can be applied quickly and repeatedly to assist in decision-making without further significant adjustments.

In addition to the straightforward application process, the resource requirements for the method are minimal, which contributes to its user-friendliness. Specifically, in terms of this research, the method is completely built in Microsoft Excel sheets, a tool that is widely accessible and does not demand extensive computational resources. As an example, all the calculations for the case studies run on a Windows 10 (64-bit operating system, x64-based processor), 11th Gen Intel(R) Core (TM) i7-1165G7 @ 2.80GHz (1.69 GHz) laptop, and there was no incident of the computational power not being adequate to deliver the results. This low barrier to entry in terms of technology reinforces the method's appeal to organizations with limited IT capabilities, facilitating broader adoption and application in various business settings.

Moreover, another benefit is highlighted through the recurring application of the method: it allows a company to accurately measure and assign the emissions saved with each batch of its products, thereby establishing a robust, trackable, and transparent environmental performance record. Such data, which the industry usually lacks, can generate a greener value proposition, promote ethical contracts, minimise carbon footprint, and attract green investors and new clients. This advantage has been highlighted during the evaluation stage by the collaborating companies and the workshop participants since, as they stated, there is a clear need for SMEs '*doing things differently than big companies*', as one participant noted. The quote refers to the need for SMEs to be able to move the agenda of value proposition towards areas where they can directly compete with larger companies since the economy of scale applied by large companies leads to prices that an SME cannot usually compete.

The proposed method stands out for its remarkable flexibility and modularity, enabling it to be finely tuned according to the specific requirements and preferences of the practitioner. For instance, as illustrated from the two case studies discussed in Chapters 5 and 6, there can be significant differences in how the pre-screening process is applied to capture the returned cores' quality condition. Moreover, the method's design allows for the customization of decision-making factors, such as adjusting the weights assigned to different decision clusters, which reflect the importance of various criteria based on the unique context of each case. Practitioners can also selectively apply different modules of the method, ensuring that the solutions are precisely tailored to their specific scenarios. Additionally, the method accommodates a range of solution constraints that practitioners can define either as *'soft criteria'*, which are incorporated into the decision-making process as weighted factors, or as *'hard criteria'*, which serve as definitive rules that can automatically exclude specific EoL pathways from consideration. This advantage of the high degree of adaptability not only enhances the method's practicality but also makes it particularly attractive to SMEs engaged in remanufacturing and EoL decision-making. Such enterprises often need tailored solutions that can flexibly conform to their dynamic operating environments, and the proposed method's ability to adjust to these needs paves the way for its broader adoption.

Finally, the CEDA, a key element of the proposed method, can be used independently to provide an index for the design's suitability for remanufacturing for a series of company products. Adopting CEDA on a broad range of products within a company can unearth common remanufacturing scenarios, streamlining various strategic decisions. These, among others, can include optimizing inventory levels for key components, refining production schedules, and improving the planning of core remanufacturing operations. Such data-driven insights can lead to more efficient resource allocation and operational workflows, ultimately bolstering the company's remanufacturing strategy.

The universal adoption of CEDA within a company's remanufacturing efforts can catalyse improved product lifecycle management, ensuring that design decisions are consistently aligned with remanufacturability. Such alignment is crucial for businesses aiming to transition to more sustainable and circular practices, as it enhances the economic viability of remanufacturing and contributes positively to environmental sustainability goals.

7.5.2 Limitations

The proposed method, while robust, encounters its primary limitation in the complexity of its initial application. This challenge was notably underscored during the workshop presented to industry experts by one of the participants, as discussed in Chapter 4. The multi-step and multi-tool nature of the method, outlined in Chapter 3, means that the first-time implementation is not straightforward and typically requires the assistance of someone with previous experience. This initial complexity arises from the intricate nature of EoL decision-making. New users must not only grasp the individual components of the method but also understand how they interconnect and the full scope of the method's capabilities. While subsequent applications for batches of the same product become significantly simpler (a matter of minutes for any practitioner), the steep learning curve of the initial application can be a barrier. Moreover, individuals who have received guidance or have been trained during the first application of the method can extend its application to other products. Consequently, they can facilitate operational decision-making for other practitioners, broadening the method’s reach within an organization.

Another limitation of the method is the fact that the proposed method does not provide decision support at a component level. This limitation is acknowledged as a derivative of the method's design boundaries and its targeted decision-support objectives. Although the method could be potentially updated with this feature, this is something that was out of scope in terms of this PhD research due to limitations on time and resources. In the case that a component is complex enough, the proposed method can be applied directly to it, and information regarding which EoL is more suitable for implementation could be gained. Nevertheless, such an approach has not been practically tested through a case study, and its level of success might be too dependent on the practitioner’s knowledge and familiarity with the proposed method.

Another associated limitation is the user interface (UI) of the method. Although the proposed method has the objective of implementing the method in a real-life application through the case studies, developing a user-friendly UI was beyond the scope of this research. The UI of the proposed method is heavily based on multiple Microsoft EXCEL sheets. Consequently, the design of the method's UI does not inherently emphasize user-friendliness, potentially making it less approachable for individuals not well-versed in such technological or decision-support tools. This can present an additional hurdle to its adoption, particularly in settings with less capacity for specialized training or rapid upskilling is not feasible. A future recommendation would be to create software to compile all the information together and guide the practitioner through its application step-by-step.

Despite the limitations above, the overall design of the proposed method adheres well to its defined boundaries and successfully meets its research aims and objectives.

7.6 Knowledge contribution

This section discusses the research's contributions to both academia and industry. It focuses on the areas most influenced by these contributions, specifically the theoretical implications and practical applications for practitioners and the industry.

7.6.1 Theoretical implications

The main contribution of the work presented in this thesis is the development of a method that supports the decision-maker in an EoL core disposition problem through an assessment of the EoL pathways from an economic, environmental, social and technical point of view. The research in the field of EoL decision-making has mostly focused on providing decision-making based on financial (Stewart & Ijomah, 2011), technical (Murayama & Shu, 2002), environmental (Li et al., 2016) or social criteria individually or some combination. This work provides a holistic method for EoL decision-making that simultaneously compiles all four types of criteria while developing a practically oriented method.

The developed method contributes to knowledge by addressing the research gap for a method that holistically addresses the decisions of multiple activities that compose the remanufacturing function (Sitcharangsie et al., 2019). The proposed method expands the body of literature in the area of EoL decision-making, addressing the need identified by the academia to provide well-informed EoL decision-making to companies concerned about adopting any CEBM (Bocken et al., 2016).

Moreover, this work provides evidence of the detailed application of the method into an operating context through two case studies, as seen in the relevant chapters. This demonstrates its suitability to achieve a holistic approach in EoL decision-making, driven by the practitioner’s preferences. Finally, through the application of the method into different industrial sectors and its evaluation through the case studies and the industrial workshops, this work addresses the lack of methods that can be applied sector agnostically and provide EoL decision-making, further supporting the shift towards more integrated and sector-agnostic approaches (Fountzoula & Aravossis, 2022).

The work presented in this thesis builds on the call by scholars (Zhang et al., 2021) to develop ‘*a method that assesses the remanufacturability of a product’s design from an environmental and economic point of view and visualises the results to support informative EoL decision-making’*. Additionally, Goodall et al. (2014) considers remanufacturability as a product characteristic. The proposed method expands the body of knowledge in the field of decision-making for remanufacturing and remanufacturability assessment. Adopting a novel approach based on remanufacturing scenarios and quantification of the environmental and financial impact for each of them, the proposed method, through the CEDA graph, furthers contributes to the body of knowledge, leading the way for effective remanufacturability assessment of a product’s design. The identification of remanufacturing scenarios and the analysis provided by the CEDA graph further support the challenge of the high variability of EoL products (Liu et al., 2016), thus contributing to the literature on the subject. Moreover, it provides the product designer with a powerful tool, the CEDA graph, for assessing the product’s remanufacturability, further supporting the idea that remanufacturability can be a product characteristic that should be assessed.

Another area that the proposed method further contributes to knowledge is the area of Operations Management and Industrial Engineering. More specifically, the proposed method uses the HALG, a method for modelling complex systems or products by detailing the relationships between different components and the eDiM, which is based on the MOST, and it’s a measurement methodology used for setting the standard times for work activities. The combination of those two methods results in a novel tool introduced to the area of Operations Management. The new tool depicts the product’s structure in a hierarchical manner while revealing the effort needed for each of the connections between its components, leading the way for an effective depiction of the hierarchy of the disassembly operations and the effort associated with them.

Another contribution to knowledge through the proposed method is the analysis of the decision factors related to an EoL core disposition decision problem. Past research on the subject has identified key decision factors related to the aspects adopted by the method. Since the proposed method has adopted environmental, financial, social, and technical aspects, it has identified and listed many relevant decision factors for each of those aspects. Such a comprehensive approach expands the knowledge on the area of decision-making by supporting less considered aspects of the EoL decision-making problem, such as social trends and legislative aspects, as identified by the literature (Alamerew & Brissaud, 2019).

Additionally, even in cases where a more holistic approach that considers multiple aspects has been adopted, scholars have underscored the importance of incorporating solution constraints pertaining to EoL pathways (Meng et al., 2016). The proposed method answers this call by incorporating into its methodology the usage of solution constraints acting both as '*soft*' and '*hard'* criteria. Ultimately, the proposed method has a high degree of direct applicability to accommodate the preferences and input of practitioners on a case-by-case basis, resulting in high adaptability. Thus, the proposed method further contributes to knowledge by supporting prior efforts in this domain, as other scholars identified (Sitcharangsie et al., 2019).

7.6.2 Implication for practitioners and the industry

This section delves into the proposed method's significant contribution to practitioners and the industry. A user of the proposed method could be a decision-maker in an SME or larger company or a product designer. The contributions are divided into primary and secondary contributions based on each contribution's significance, originality, and impact.

The primary contribution of the proposed method to practitioners is its support for EoL decision-making problems. It offers a transformative approach to EoL decision-making, enabling practitioners to navigate challenges with unprecedented clarity and precision. By facilitating well-informed, data-driven, and transparent decision-making processes, the method ensures that practitioners can tailor solutions to their specific needs and preferences. This level of support is crucial for making decisions that are effective and align with the practitioner's unique product considerations, thereby enhancing the quality and relevance of EoL strategies.

Another primary contribution of the method stems from its adaptability and future-proofing capabilities. Based on its sector-agnostic approach, it allows for the application across various products and designs, providing insights into the most effective strategies for CEBM while allowing wider industrial adoption. This adaptability is crucial as it ensures the method remains relevant even as corporate priorities shift, or as new competitive products emerge. Moreover, the ease with which the method can be updated is a significant advantage for industrial practitioners. With the ability to swiftly incorporate the latest data on environmental impacts and product costs, the method supports a rapid response to changing information landscapes, ensuring that decision-making is always grounded in the most current data.

An additional primary implication is that the industries can utilise the developed method to support different types of EoL decisions. The developed method can support operational decisions such as identifying the most suitable EoL pathway for a specific batch and more tactical and even strategic decisions. A tactical decision the method may support, would focus on which of the available product’s designs would be more suitable for remanufacturing. A strategic decision would be for the proposed method to be used to assess the potential for an SME to apply a CEBM. Through decision support in all three types of decisions, the impact of this research on the industry is great, especially when considering that the proposed method is sector-agnostic. Additionally, through the wider application of the method, the application of CEBM is promoted since the process, benefits and disadvantages can be quantified and demystified in advance before an SME commits significant resources to it. Moreover, for companies that test the idea of offering a CEBM through remanufacturing, the proposed method can identify the key parameters and the most suitable products and set the basis for bigger, more systemic changes that promote the application of CEBM in that industry.

The CEDA graph has a significant and primary contribution by assessing the product’s design remanufacturability in a coherent, transparent, and informative manner. The graph provides quantitative support to the design decisions and can be integrated into a Design for ‘X’ methodology, resulting in a more efficient product. The practitioner can also quickly and accurately assess the remanufacturability of existing product designs and support decisions regarding the application of CEBM or identification of the most promising products for those CEBM. Thus, it limits the subjectivity and uncertainty introduced by decision makers that, based on judgements of experts, attempt to identify how to implement CEBM in their company best. Finally, the CEDA graph can provide the practitioner with a comparison between the remanufacturability of different products and support better decision-making at a supply chain level since it can quantitatively assess their remanufacturability.

An excellent example of using the CEDA graph to optimise EoL decisions from the product designer stems from the second case study in this thesis. In that case, the accumulator’s shell is responsible for almost 90% of the product's total environmental impact. If designers prioritize reusability and remanufacturability of the shell throughout multiple life cycles, it could lead to a significantly more environmentally friendly product. Such design optimization can result in considerable savings for the company and a reduced environmental footprint. Moreover, the environmental benefits of such a design approach can be an integral part of the company's value proposition. It could allow the company to offer products that help customers decrease their Scope 3 Greenhouse Gas emissions, encompassing indirect emissions in the value chain outlined in the Greenhouse Gas Protocol. This strategic move enhances the company's sustainability profile and can be a compelling selling point in a market increasingly attentive to environmental responsibility, while its reasoning was originally derived from the application of the proposed method and the CEDA graph.

A secondary implication for the practitioners stems from the structure of the proposed method, and it allows them a deeper understanding of the product's remanufacturability. By adopting the key components approach and deriving the remanufacturing scenarios from them, the product designer practitioner gains insights into how the selection for each component affects the product’s remanufacturability. Such a feature of the proposed method is a crucial contribution to practice since those insights can further strengthen a better-aligned product design with sustainable principles such as remanufacturability, repairability and longevity. This contribution of the method further supports the product designs to be efficient and environmentally responsible, contributing significantly to sustainable practices in product development.

On a similar note, by implementing the solution constraints in the proposed method, the product designer can access information regarding decision factors that may adversely impact the application of CEBM due to their product’s design limitations. A good example of such would be the insights into the *obsolescence and market predictions* solution constraint, where the product designer can assess how the selection of the product’s components can impact the rate of its obsolescence. This is another secondary contribution to practice since it supports the *front-loading* of the product’s design decisions, a key requirement for successful product design (Maropoulos & Ceglarek, 2010).

A secondary contribution of the proposed method to the practitioners derives from synthesising the eDiM and HALG. From the practitioner's perspective, synthesising the HALG with the eDiM provides a novel and less time-consuming manner to depict the hierarchical levels of the product’s structure. The combination of those tools finds potential application across all the remanufactured products of a company, providing an immediate understanding of the product's structure and the effort needed to dis- and re-assembly it. A primary application of this method is in training new employees, helping them grasp the product structure and inter-component relationships more effectively. Unlike existing tools, the eDiM-HALG synthesis offers directness and simplicity in conveying complex information. Additionally, it serves as a versatile tool for designers evaluating alternative connector designs. Using eDiM and HALG, product designers can assess the impact of these designs on the disassembly and reassembly time at each hierarchical level, enhancing decision-making in design alterations or new developments.

A prime example of the significant impact of this research is its influence on one of the two companies involved in a case study, specifically the company that provided the luminaire for analysis. As part of this case study, the application of the developed method to their product led to a pivotal realization. The company recognized the necessity for broader, systemic change within the lighting industry, particularly in setting standards for good practice in lighting remanufacturing. Following extensive efforts, which are beyond the scope of this thesis to detail, the company collaborated with the researcher and various other stakeholders to achieve a noteworthy milestone. Together, they contributed to developing a new British Standards Institution (BSI) standard tailored explicitly to the remanufacturing of the lighting sector. This standard is part of the series BS 8887-221:2010 and is provisionally titled *'BS 8887-XXX: Design for Manufacture, Assembly, Disassembly, and End-of-Life Processing (MADE) – Part XXX: Code of Practice for the Remanufacture of Luminaire*'. The committee has not yet confirmed some information, such as the part number of the standards. This contribution is significant since the research conducted and described in this thesis, the proposed method and its application were able, even at a preliminary stage, to further support the application of CE for the lighting sector in the UK by supporting a BSI standard exclusively focused on remanufacturing in the sector. Thus, through the contribution to a standard, the proposed method has managed to have an extended contribution to the industry.

7.7 Future research recommendations

The research presented in this thesis has a rich landscape for future exploration, which can significantly enhance the field of EoL decision-making. The following paragraphs will describe each of them in greater detail.

Future research could be done to develop an automated way to create a HALG from a BOM directly, with the only additional information required being the connections between the components. Such a feature of the proposed method could significantly reduce the effort needed for the initial application.

Another approach in the same direction would be using Computer-Aided Design (CAD) software and CAD files to create the HALG. This is a fascinating prospect since it supports the digitisation of the proposed method and the improvement of its UI. Additionally, by feeding the eDiM standardised time for each task, the dis- and re-assembly effort can be captured automatically, thereby reducing the application time for the method. The ultimate goal is completely digitising the proposed method into a software tool that provides a seamless, user-friendly experience. A' plug-and-play' solution could be created by merging and optimizing data and workflows by integrating CAD software, the proposed method, and the PROMETHEE. This solution would enable EoL decision-making on a large scale for small and medium-sized enterprises SMEs while minimizing costs and resource requirements.

Another future recommendation for research is the development of a similar method to the proposed one but at a component level. Such an approach would also include and assess EoL pathways such as parts harvesting, component repair and component upgrade. Those EoL pathways have been omitted from the proposed method due to the boundaries applied in this research. Nonetheless, as identified in the literature, there is a need for holistic EoL decision support at a component level as well. There is also the ability for the proposed method to be altered to some extent to provide decision support to a component level as well, but this was out of the scope of this research. Investigating this approach holds considerable potential and interest for future research, and its contribution would support the broader implementation of CEBM through transparent and science-based decision-making.

A future research recommendation the conducted study has identified is the need for a standardized and sector-agnostic remanufacturing index of a product’s design. While this research has taken steps toward meeting this need with the creation of the CEDA, the fact that this is one of the first attempts to visualise and study a product’s design suitability for remanufacturing proves that there is ample room for additional research. More specifically, CEDA provides an indication through the four identified areas but is not a quantitative index that can be used as a standalone remanufacturability index. The growing interest in this sector underscores the importance of further developing such indices that could provide a future direction for further research.

The support for decision-making was derived from specific decision factors grouped into decision clusters. Each factor within these clusters was assigned a weight based on the input from practitioners. A promising direction for future research would be the development of standard decision profiles. These profiles would come with preset weights for each factor, reflecting the tendencies of different decision-makers. Such a decision profile creation would benefit the industry through a quicker application of the method and accelerated adoption.

Moreover, another emerging research area is the transparent quantification of the environmental impact of remanufacturing within an LCA framework. As remanufacturing grows, more data related to the environmental impact will be available. This data must be made accessible to LCA practitioners to enhance the precision of product environmental modelling. Methods such as those proposed in this research further support the transparency of data related to the ecological impact of remanufacturing processes and support the better development of LCA models. Critical parts of the LCA, such as the functional unit, functional flow and EoL pathway, will be impacted by the research of integrating remanufacturing environmental data to a product's original LCA and achieving higher accuracy in the LCA calculations.

Finally, incorporating the carbon footprint generated by the economic activities of the companies that conduct remanufacturing and will use the proposed method could also provide a much more detailed environmental assessment of the product’s remanufacturing process. Such a direction for future research could further support a more detailed caption of the environmental impact per remanufacturing scenario, thus providing higher accuracy and confidence in the environmental data from the proposed method.

7.8 Concluding remarks

As the global interest in overcoming environmental challenges is rising, the application of CEBM is considered essential. Circular EoL pathways, including direct reuse, remanufacturing, and recycling, are crucial for mitigating the environmental impacts of manufacturing. These practices close material loops and extend the operational life of products and materials. This increase in interest has led many SMEs and large companies to apply or test the idea of implementing a CEBM, such as ‘product as service’, remanufacturing of products and others. While large companies often have the resources to experiment with these business models, SMEs typically face financial constraints.

Consequently, there's a growing need for methods that can provide effective EoL decision support. These methods should be capable of demystifying and quantifying the benefits of circular EoL pathways, offering a direct comparison with traditional disposal or recycling methods and linear economy business models. Thus, the need for EoL decision support methods that holistically evaluate all the available EoL pathways and support the decision-maker on a complex core disposition problem has been identified from the literature (Chapter 2) and the industry.

This thesis introduces a novel method to support EoL decision-making, considering environmental, economic, social, and technical factors at the product level. It uniquely incorporates weighted decision factors and solution constraints, all based on practitioner input. This method successfully bridges the three critical gaps identified in the literature, as outlined in Chapter 2, and fulfils each objective set for this study. Specifically, it analysed the current decision support methods for EoL product disposition while identifying key factors and critical constraints affecting EoL pathway selection. Moreover, it developed a tool to assess product remanufacturability, integrating environmental and economic impacts. Finally, it created and evaluated a comprehensive method for EoL decision-making, incorporating environmental, economic, social, and technical performance metrics alongside decision-maker constraints.

The robustness of the proposed method was rigorously evaluated, as described in Chapter 5. The evaluation process included semi-structured interviews, questionnaires, continuous expert feedback, and a workshop with industry participants, ensuring its qualification, verification, and validation. The method's practical applicability and benefits were further demonstrated through its implementation in two distinct case studies. These studies, representing different industries, products, and decision profiles, underscore the method's versatility and effectiveness. The details of these case studies are presented in Chapters 5 and 6, with additional insights into the application findings discussed in Section 7.4.3

The research presented in this thesis has the potential to alter the way the industry approaches EoL decision-making by providing a transparent, versatile, comprehensive way to assess the available EoL pathways and, ultimately, support decision-making. In the design phase, the proposed method can be used to design products that better align with the Design for "X" guidelines, especially for remanufacturing. In the later stages of the product's Lifecycle, the proposed method can identify which existing products are more suitable for remanufacturing and application of a CEBM, ensuring and de-risking its application. Finally, the proposed method delivers EoL decision support by providing the decision maker with the most aligned EoL pathway for a returned batch that is aligned to their preferences. Each of those contributions of the proposed method can support the industry in the more successful implementation of CEBM through better-informed decisions and adopting more sustainable practices. Thus, the entire industry, especially the remanufacturing sector, stands to gain deeper insights into decision-making processes and opportunities for growth.

Additionally, the research provided numerous outputs, such as two journal publications (one under review) and a white paper with an industrial focus, and it provided support to create and develop a BSI standard for remanufacturing in the lighting sector. The following list includes additional information on the publications:

1. Verification and Validation: A novel product lifecycle management-based approach, Karkasinas, A. & Rentizelas, A., 1 Mar 2020, *International Journal of Product Lifecycle Management (IJPLM), Vol. 12, No. 2, 2019, pages 149-183, doi.org/10.1504/IJPLM.2019.107007*.
2. Justification for remanufacture in the lighting industry, Tom Ruddell & Karkasinas, Aineias, 2021.
3. BS 8887-XXX: Design for Manufacture, Assembly, Disassembly, and End-of-Life Processing (MADE) – Part XXX: Code of Practice for the Remanufacture of Luminaire.
4. Economic and Environmental Impact Assessment for Sustainability (EENIAS): An innovative method to support Design for Remanufacturing and Remanufacturability Evaluation, *Journal of Cleaner Production,* Manuscript number: JCLEPRO-D-24-06849, *under review status*

The first publication discussed verification and validation across the product's Lifecycle and was used to identify the need for a comprehensive EoL decision-making method that, among others, would expand those two terms to the EoL. Following the narrowing of the scope of this research and through the application of the proposed method at its primal stage, the white paper titled '*Justification for remanufacture in the lighting industry*' was produced with the aim of the research to gain more traction within the lighting sector. Following the success of the previous white paper, the research was a key contributor to the related BSI standard, which derived from those efforts. Finally, the second publication that is under review at the time of the submission of this thesis includes a detailed description of the development and application of the CEDA graph in the two case studies described in the related chapters.

In conclusion, this research has introduced a groundbreaking EoL decision support method. This development represents a significant contribution to academia, the industry, and practitioners, offering a transparent, insightful, and comprehensive approach to EoL decision-making. The method's innovative design and practical applicability ensure it stands as a valuable tool for guiding informed, sustainable decisions in various contexts.

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Appendix A

This Appendix contains the questionnaire used for identification of the main decision factors in EoL. The purpose of this questionnaire was to capture the industry feedback on the selected decision factors that have originally identified on the literature.

EoL Decision-Making factors - A Questionnaire

Description

Project aim: The aim of the project is to provide decision support for implementation of Circular Economy solutions for End of Life (EoL) products by analysing the financial and environmental impact of each of the EoL pathways and taking into consideration decision factors and constraints defined by the decision maker.

Questionnaire aim: As part of the project, we have developed a set of decision factors that will be taken into consideration when a remanufacturer examines the viability of remanufacturing a specific product. As a remanufacturing practitioner, we are requesting your help to validate these factors and provide us with feedback on their importance. You can also add or delete factors based on your experience or views.

Description of the factors selected

The factors identified in this research have been selected based on various literature sources, discussion with remanufacturers and feedback from the academia.

Q1. Respondent's characteristics

Please answer the following general questions to have an overall characterisation of the sample.

Table 7.2: Generic Information of the practitioner/ company

Questions	Answer options

1.1	Type of remanufacturer	1	OEM/ OER (Original Equipment Remanufacturer- OER)
		2	Contracted Remanufacturer (CR)
		3	Independent Remanufacturer (IR)
1.2	Company name		
1.3	Sector/industry		
1.4	Product		
1.5	Company Size (Annual turnover)		
1.6	Size of remanufacturing operations (Annual turnover)		
1.7	Name of practitioner		
1.8	Position in Company		

Q2. Environmental factors

In this study, the environmental factors are directly linked to the End of Life (EoL) pathways and related to manufacturing and processing the returned products (cores). The study's aim is to capture the environmental impact for each of the EoL pathways.

Table 2 includes a set of factors that we believe are relevant to the environmental impacts. We ask you to rate how important you believe each of these factors are in a scale of 1 to 9, where 1 is not important at all and 9 is extremely important.

Table 2: Environmental factors

Environmental factor	Importance		
	Not important	Important but not critical	Critical

	1	2	3	4	5	6	7	8	9
2.1 **Carbon Emissions** *Calculation of the carbon emissions of the proposed EoL pathway*									
2.2 Add other factor(s) of interest to your company									
Landfill/scrap avoidance for customers									

2.3 If you have any further comments, please use the blank space below.

Q3. Financial factors

The financial factors are directly linked to each of the End of Life (EoL) pathways and related to costs and profits associated with the selected EoL pathway. The aim is to capture the financial impact for each of the EoL pathways.

Table 3 includes a set of financial factors that we believe are relevant to remanufacturing decision making. We ask you to rate how important you believe each of these factors are in a scale of 1 to 9, where 1 is not important at all and 9 is extremely important.

Table 3: Financial factors

Financial factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
3.1 **Cost** *The predicted cost for each applied EoL scenario*									
3.2 **Residual Value** *The value of the product in the EoL*									
3.3 **Profit** *The difference between the market price and the net cost of an applied EoL scenario*									
3.4 **Market demand** *The prediction of demand and it's growth*									
3.5 Add other factor(s) of interest to your company									

3.6 If you have any further comments, please use the blank space below.

Q4. Technical factors

Technical factors are related to the feasibility of each of the EoL pathways. They are used as a metric to understand the remanufacturability of a specific product and its potential and burdens.

Table 4 includes a set of technical factors that we believe are relevant to the feasibility of the Circular economy pathways, such as Reuse or Remanufacture. We ask you to rate how important you believe each of these factors are in a scale of 1 to 9, where 1 is not important at all and 9 is extremely important.

Table 4: Technical factors

Technical factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
4.1 **Batch Quality** *Refers to the condition of the returned products of a batch*									
4.2 **Design Durability**									

Technical factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
Aims to capture the durability of the design and it's flaws									
4.3 **Ease of disassembly (eDiM)** Refers to the time needed to disassembly key components of the product									
4.4 **Market obsolescence** *Aims to identify how obsolete the product's design is and uses three subfactors as decision pillars*									
4.4.1 Use of classic or minimal aesthetic *Refers to how classic the product's design*									
4.4.2 Broadness of the applicable market *Refers to how specific the product design is and if it*									

Technical factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
can be used in other applications									
4.4.3 Susceptibility to changes in market demand *Refers to how susceptible the product is to changes to the market demand*									
4.4.4. Add other sub-factor(s) of interest to your company									
4.5 **Remanufacturing capability** *Aims to identify the capability for remanufacturing a specific type of core and uses three subfactors as decision pillars*									
4.5.1 Training									

Technical factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
Aims to identify if the personnel training is adequate to handle this product									
4.5.2 Equipment *Aims to identify if the available equipment is adequate to handle this product*									
4.5.3 Experience in this product/process and confidence *Aims to capture the confidence and experience in remanufacturing this product*									
4.5.4 Add other factor(s) of interest to your company									

Technical factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
4.6 **Remanufacturability**									
4.6.1 Easiness of inspection/ Testing *It captures the difficulty in testing or inspection the product*									
4.6.2 Standardization of components *Aims to identify the level of standardisation of components in the design*									
4.6.3 Easiness in repair/ maintenance *It captures the easiness in repair or maintenance*									

Technical factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
4.6.4 Fasteners standardisation index *Aims to identify to what extent the product uses standardised fasteners*									
4.6.5 Materials index *Aims to identify to what extent the materials are mixed*									
4.6.6 Electrical connections index *Aims to identify the electrical replacement, rewiretability and replaceability condition of the product*									
4.6.7 Add other factor(s) of interest to your company									

Technical factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
4.7 **Component Upgradability (Technical obsolescence)** *Captures the easiness to upgrade a specific component and the efficiency of the product's design for components upgrading*									
4.8 **Availability of components** *Aims to identify how easy is to secure components for the product*									
4.9 Add other factor(s) of interest to your company									
Add other factor(s) of interest to your company									

Technical factors	Importance								
	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
Add other factor(s) of interest to your company									

4.8 If you have any further comments, please use the blank space below.

Q5. Social factors

In this study, the social factors have a direct impact on the End of Life (EoL) pathways and are not related to the product design or its condition. The aim is to capture the social impact for each of the EoL pathways.

Table 5 includes a set of social factors that we believe are relevant to the selection of the most appropriate EoL pathway. We ask you to rate how important you believe each of these factors are in a scale of 1 to 9, where 1 is not important at all and 9 is extremely important.

Table 5: Social factors

Social factors	Importance

	Not important			Important but not critical			Critical		
	1	2	3	4	5	6	7	8	9
5.1 **Jobs Creation** *Relative to employment, either through net job creation, up-skilling, pay or working condition*									
5.2 **Harmonisation with the local society needs** *Focused on if the EoL pathway is in alignment with the local community's interests*									
5.3 **Customer accessibility to high quality products** *Focused on impact of the EoL pathway to the customer's accessibility to high quality products*									
5.4 Add other factor(s) of interest to your company									

5.5 If you have any further comments, please use the blank space below.

Q6. Overall factors

The following part contains all the decision factors that have been identified until this point and a classification if they are operational, tactical, or tactical/ Strategic decisions.

Strategic-level decisions are made from the top management, are long term (2 to 5 years) and are responsible for the determination and alternation of organizations' objectives. The main categories for such decisions are engagement in remanufacturing, product design, supply chain coordination, network design, marketing management and, collection strategy.

Tactical decisions are made from mid-level managers, are medium-term (6-24 months) and their aim is to provide support to strategic level decisions by effective and efficient use of resources and material flow. In remanufacturing, tactical decisions are also responsible for issues related to the recovering options and products, such as End of Life (EoL) pathways, used product acquisition, production planning and inventory management. In this research, they are mostly focused on the product's design.

Operational-level decisions are made by production/ line managers, are everyday operations decisions, within a timeframe of a day to some months, and focus on serving both the strategic and tactical level decisions by efficiently executing everyday activities with respect to goals and restrictions. Such decisions are related to disassembly planning, logistics, scheduling and process planning. They are usually focused on a specific returned batch's properties such as its quality condition.

The practitioners are asked to **draw an "X"** for each of the decision factors to the category that believe this specific factor belongs to. If the practitioners have added any factors, they could add them as well. Additionally, for each factor, the practitioners are asked **to input a weight** of what the importance is for that specific factor with respect to the rest of the factors of the same hierarchical level. The factor's weight scale expands from 0 to 10, with 0 meaning that *"this specific factor has zero impact on our remanufacturing decisions"* and, 10 meaning that *"this factor has the maximum impact on remanufacturing decisions"*. The areas for input are highlighted with a light shade of green colour for easier identification.

Table 6 contains the identified overall factors:

Table 7.3: Overall factors

Code	Weights (0-10)	Decision making Categorisation Factors\ Factor's focus	Operational Batch focused	Tactical Product design focused	Tactical/Strategic Strategy focused
		Social			
S1		Jobs creation			
S2		Harmonisation with the local society needs			
S3		Customer accessibility to high quality products			
Added factor (s)					
		Environmental			
E1		Environmental Impact in kgCO2 eq			
Added factor (s)					
		Financial (Market)			
F1		Cost			
F2		Residual value			
F3		Profit			
F4		Market demand			
Added factor (s)					
		Technical			
T1		Quality of the batch			
T2		eDiM			
T3		Availability of components			
T4		Component Upgradability (Technical obsolescence)			
T5		Market obsolescence			
TS5-1		Use of classic or minimal aesthetic			
TS5-2		Broadness of the applicable market			
TS5-3		Susceptibility to changes in market demand			
T5		Remanufacturing capability			
TS6-1		Training			
TS6-2		Equipment			
TS6-3		Experience in this product/process and confidence			
T7		Product's Remanufacturability			
TS7-1		Easiness of inspection/ Testing			
TS7-2		Standardization of components			
TS7-3		Easiness in repair/ maintenance			

TS7-4		Fasteners standardisation index			
TS7-5		Materials index			
TS7-6		Electrical connections index			
Added factor (s)					

6.6 If you have any further comments, please use the blank space below.

Thank you for participating in this research

END of Questionnaire

End of Thesis