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Economic and ENvironmental Impact Assessment for Sustainability (EENIAS): An innovative method to support design for remanufacturing and remanufacturability evaluation☆

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ABSTRACT

Significant effort has recently been directed towards promoting remanufacturing as a circular and sustainable approach to production. However, current methods for supporting design for remanufacturing and remanufacturability evaluation often lack integration and practical applicability, failing to address the complex trade-offs and interdependencies inherent in remanufacturing processes. To this purpose, this study addresses the need for methods to evaluate the feasibility of product remanufacturing through proposing a novel integrated method named Economic and ENvironmental Impact Assessment for Sustainability (EENIAS), enabling the assessment of remanufacturability for existing products or those in the detail design stage, by analysing diverse remanufacturing scenarios to quantify their economic and environmental impact. The method is demonstrated and validated through two case studies from different industries: an electrical lighting product and an accumulator used in the oil and gas sector, highlighting its applicability. The results quantify how key remanufacturing scenarios are performing economically and environmentally, offering insights into the products' remanufacturability and the design strengths for applying a Circular Business Model (CBM) based on remanufacturing. The luminaire demonstrated strong potential for remanufacturing, with 23 out of 31 remanufacturing scenarios showing significant financial and/or environmental benefits. In the accumulator case, the analysis revealed the dominance of the accumulator's shell as a significant environmental impact driver, though its financial impact was not equally significant. Consequently, the application of EENIAS provided the critical insight that substantial environmental gains could be achieved if the company designs the product in such a way that the shell does not require replacement after the usage stage. The EENIAS approach supports decisions for remanufacturing and sustainable product design practices, such as Design for Remanufacturing, by providing a detailed assessment of the products' remanufacturability and its potential for CBM application.

1. Introduction

In the face of escalating environmental challenges and resource depletion, the global emphasis on sustainability and resource efficiency has intensified. Traditional linear economic models, characterised by the 'take-make-dispose' approach, are increasingly recognised as unsustainable, necessitating a shift towards circular economic practices (Hay, 2015; Ness, 2008). On the contrary, Circular Economy (CE) is characterised by a closed loop material flow within the entire economic system, emphasising the reduction, reuse, and recycling of materials and energy (Kirchherr et al., 2017). Among the various strategies for achieving circularity, remanufacturing has emerged as a transformative solution, offering significant potential for reducing material consumption and mitigating environmental impacts (Singhal et al., 2020).

Remanufacturing involves restoring End-of-Life (EoL) products to a condition comparable to new, thereby extending their life cycles and reducing the reliance on virgin materials (Ijomah et al., 2005). Research indicates that remanufacturing can reduce energy consumption by up to 83 % compared to new manufacturing, significantly cutting CO_2

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Nomenclature

eDiM	the total time needed for disassembly and reassembly
eDiMD	the time needed to for the disassembly
eDiMR	the time needed for the reassembly
i	index representing the component or scenario being considered
N	total number of components in the product.
$n_i = (x_i, y_i)$	tuple representing a point on the EENIAS chart, with cost x_i and environmental impact y_i, and *0* being the reference value referring to the attribute of the new product
$\sum_i^N ()$	summation operator indicating the sum over all components from $i = 1$ to *N* for variable included in the brackets
x_i	cost of remanufacturing scenario *i*
y_i	environmental impact of remanufacturing scenario *i*
Reman.Cost [Component]	the remanufacturing cost per component
Reman.Cost [Product level]	the remanufacturing cost per product

Abbreviations

BOM	Bill of Materials
CBM	circular business models
CE	Circular Economy
DfRem	design for remanufacturing
eDiM	Ease of disassembly Metric
EENIAS	Economic and ENvironmental Impact Assessment for Sustainability
EoL	End-of-Life
EoU	End-of-Usage
HALG	Hierarchical Attributed Liaison Graph
LCC	Life Cycle Costing
LCA	Life Cycle Assessment
MOST	Maynard Operation Sequence Technique
OEM	Original Equipment Manufacturer
OER	Original Equipment Remanufacturer
IR	Independent Remanufacturer

emissions and waste production (Chaudhari, 2023). However, it is essential to acknowledge that not all products are equally suitable for remanufacturing, and large-scale remanufacturing with unsuitable design solutions might deprive it of its energy-saving and emission-reduction benefits (Ke et al., 2023). Additionally, remanufacturing is a resource-intensive process that requires substantial investments in labour, technology, and logistics, necessitating a critical assessment of the feasibility of each step 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 value'*.

Despite the potential of remanufacturing, existing remanufacturability assessment methods often lack integration of multiple criteria and real-world applicability. Assessing remanufacturability is crucial for informed decision-making in product design and the implementation of EoL strategies. Most frameworks focus on isolated factors such as cost savings or material recovery, rather than addressing the complex trade-offs between economic, environmental, and technical feasibility. A comprehensive literature review indicates that over 90 % of existing studies compare remanufacturing to traditional manufacturing but do not provide a holistic framework for assessing remanufacturability throughout a product's lifecycle (Hummen and Wege, 2021).

This study identifies its key objectives as examining current remanufacturing assessment practices, identifying their limitations, and proposing an enhanced and highly applicable in real-world approach to address critical gaps in existing methodologies. The research question of the study is: *How can remanufacturability be assessed efficiently and effectively, integrating economic, environmental and technical perspectives, using a structured technical approach?*

To address this question, this study proposes the novel Economic and ENvironmental Impact Assessment for Sustainability (EENIAS) method. EENIAS integrates economic, environmental, and technical criteria within a structured multi-criteria decision-making process, enhancing the accuracy, utility and applicability of remanufacturability assessments. Unlike conventional models, which are often theoretical, EENIAS provides a practical decision-support tool for industries transitioning towards circular economy models, making it both actionable and scalable across different sectors. It enables the assessment of remanufacturability for both existing products and those in the detail design stage by using established methods such as the Ease of disassembly Metric (eDiM) and Hierarchical Attributed Liaison Graph (HALG) to quantify key technical metrics for the remanufacturing of the products. Following this, it defines various remanufacturing scenarios and quantifies their economic and environmental impacts, presenting the results in a clear, visual, and actionable format. Finally, the applicability and cross-sector adaptability of EENIAS are demonstrated through two real-life industrial case studies from different sectors. By providing a standardised yet adaptable framework, EENIAS has the potential to influence sustainability policies, support circular economy adoption across diverse industries, and contribute to global efforts in reducing industrial waste and carbon footprints.

The next section of the paper presents the literature review, establishing a foundation for understanding the current state of research in remanufacturability assessment. Section 3 outlines the methods and tools used to develop EENIAS, including its application in two distinct industrial case studies. Section 4 presents the results, while Section 5 discusses the proposed method, emphasising its novelty and contributions from both theoretical and managerial perspectives, and highlighting its potential impact on sustainable decision-making processes. Finally, Section 6 concludes the study.

2. Literature review

Remanufacturing has emerged as a cornerstone of the CE, aiming to decouple economic growth from resource depletion (Kirchherr et al., 2017). Its efficient evaluation becomes crucial due to extensive resource requirements and inherent uncertainties (Hatcher et al., 2011). Remanufacturability assessment has emerged as the key process in determining whether a product is worth remanufacturing or not (Hummen and Wege, 2021). As an assessment, it involves evaluating the potential for value retention through remanufacturing processes, which is essential for sustainable product lifecycle management (Ahlstedt and Sundin, 2023).

Remanufacturing assessment or remanufacturability is defined as the degree to which a product's design facilitates cost-effective recovery and reprocessing (Ijomah et al., 2007). In previous studies, remanufacturability is typically assessed using economic, environmental, and/or technical criteria, with some very limited work including social aspects as well (Omwando et al., 2018; Zhang et al., 2021). Although these criteria can be used in single-dimension focused approaches, scholars have highlighted the need for comprehensive evaluation methods for remanufacturing (Zhang et al., 2021). The methods by which these criteria are applied can also be categorised into product-centric, usage-centric, or process-centric approaches, with each approach having unique characteristics and limitations, which are discussed in the following sections.

Assessing the economic evaluation of remanufacturability is essential for industries to determine the feasibility and profitability of remanufacturing initiatives. For economic evaluation, methods such as cost-benefit analysis and activity-based costing (Andarani and Goto, 2012; Parkinson and Cheung, 2024; Psarommatis and May, 2025) are commonly applied to assess the viability of remanufacturing initiatives. These approaches focus on factors like cost savings, profitability, and financial risk but scalability and data acquisition are often cited as challenges (Ding et al., 2018; Ghazalli and Murata, 2011). In a slightly diversified approach, Chen et al. (2024) integrated economic analysis into a decision model, proposing a decision tree-based method for assessing the remanufacturability of used parts, incorporating the Weibull model to estimate the remaining value of components with key shortcomings including the reliance on historical data and the oversimplification of the interdependencies between evaluation criteria, potentially leading to suboptimal decisions.

A recurring critique across these studies is the lack of holistic analysis of long-term sustainability impacts and market dynamics. For example, research highlights the underrepresentation of design-for-disassembly (DfD) principles and the variability of market conditions in profitability assessments (Johnson and Wang, 1998; Moon et al., 2022; Nie et al., 2021). Similarly, empirical data on sector-specific challenges—such as sensor-data quality in gas-insulated switchgear remanufacturing or fluctuating material markets in disassembly operations—remain sparse, limiting the generalisability of findings (Moon et al., 2022). Innovative frameworks like the Remanufacturing Potential Index (RemPI), which evaluates component-level disassemblability and integrity, demonstrate progress but often overlook broader economic implications (Sierra-Fontalvo et al., 2024). Collectively, the literature identifies a critical need for adaptable, empirically validated models to address gaps in real-world application and cross-industry scalability (Psarommatis and May, 2025; Sierra-Fontalvo et al., 2024; Wang et al., 2023a).

Environmental evaluation often utilises methods such as Life Cycle Assessment (LCA) to quantify the environmental impact of remanufacturing (Timm et al., 2025). However, the complexity and bespoke nature of LCA remain barriers to its wider adoption within the industry (Wilson et al., 2014). Other approaches—such as the Analytic Hierarchy Process (AHP) and its fuzzy variant—have been adapted by incorporating environmentally related metrics. For example, Shi et al. (2015) combined AHP with LCA to evaluate the remanufacturability of used engines, integrating technological, economic, and environmental dimensions into a comprehensive framework. Similarly, Guo et al. (2015) applied a fuzzy AHP approach to assess electromechanical products, considering factors such as resource conservation, energy efficiency, and economic viability. These studies demonstrate AHP's effectiveness in handling multi-criteria decision-making, particularly when balancing qualitative and quantitative factors. However, its reliance on pairwise comparisons can introduce subjectivity and increases significantly the effort required from decision makers when more than a handful criteria are adopted, while the complexity of fuzzy AHP may hinder practical implementation.

In an alternative approach, Deng et al. (2015) employed the fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to identify key drivers of eco-efficiency in remanufacturing, effectively managing complex, interrelated factors. Nevertheless, the method's dependence on expert judgements and its computational intensity can limit its practicality, particularly for large-scale or data-intensive applications. Yan et al. (2023) addressed these limitations by implementing a multi-source data-driven approach to analyse carbon footprints in remanufacturing systems. Yet, this approach also faces challenges due to its reliance on high-quality, multi-source data. Despite these advancements, scholars continue to highlight a gap in research that integrates environmentally focused methods into remanufacturing assessments. Such integration would assist decision-makers in understanding a product's remanufacturability and using this information to enhance end-of-life decision-making (Akano et al., 2021).

Technical evaluation involves methodologies like decision-making models and engineering feasibility studies to determine the technical feasibility, reliability, and quality of remanufactured products. Scholars have highlighted that evaluating the technical capability of remanufacturing enterprises is crucial to ensure they possess the necessary expertise and resources (Chen et al., 2024) and that production decisions are informed by the technical assessment of the process route and the capabilities of the remanufacturing enterprise (Liu et al., 2019), while others have identified the lack of such technical remanufacturability evaluation studies (Zhang et al., 2021). On the contrary, the focus is on combining the technical aspect with economic and environmental assessments to incorporate these aspects into decision-making processes, allowing practitioners to evaluate remanufacturing initiatives more holistically. Such comprehensive evaluation approaches combine economic, environmental, and technical assessments using multi-criteria decision-making methods to balance trade-offs across different dimensions and provide a holistic understanding of the benefits and limitations of remanufacturing. However, despite the variety of evaluation methods, many cannot be fully integrated into production decision-making models, making them inapplicable to real-world scenarios and providing headroom for improvement due to their complexity (Zhang et al., 2021).

Since remanufacturing evaluation criteria focus on economic, environmental, and technical metrics, most proposed methods integrate more than one of these dimensions. Social aspects, when included, are incorporated into these multi-dimensional assessments as a secondary objective. For instance, Dou and Cao (2020) proposed carbon tax models to incentivize remanufacturing but overlooked regional policy disparities; for instance, the EU's stringent Extended Producer Responsibility (EPR) laws contrast sharply with the U.S.'s voluntary approaches (Atasu et al., 2021). Feng et al. (2021) found that Independent Remanufacturers (IRs) outperform Original Equipment Manufacturers (OEMs) in social performance under subsidies, yet their narrow focus on China's automotive sector limits generalisability.

These methodologies can also be classified according to the perspectives they adopt, and this new classification offers a more holistic understanding of how remanufacturability is addressed within academia.

2.1. Product-centric perspective

The product-centric perspective treats remanufacturability as an inherent design property, with its key elements focusing on modularity, material durability, and ease of disassembly (Goodall et al., 2014). An example of a product-centric approach includes Xerox's modular photocopiers achieving 90 % component reuse through standardised interfaces (Kerr and Ryan, 2001). Methodologies such as Sundin and Bras's (2005) modularity indices quantify design suitability, but these approaches assume ideal conditions (e.g., perfect core availability) and overlook real-world variables like usage patterns (Zhang et al., 2021).

Design for Remanufacturing (DfRem) includes a variety of tools and methods aimed at enhancing the remanufacturability of new products. These tools include a range of metrics like the Product Sustainability Index (ProdSI) developed by Shuaib et al. (2014) or the 9R Circularity Index (Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) proposed by Hosseini and Crawford (2024), both of which emphasise the sustainable aspects of product design. However, while these indexes incorporate multiple R-strategies, they do not provide a detailed consideration of remanufacturing scenarios at the component level.

Other scholars, recognising the importance of a multi-lifecycle approach to remanufactured products, have developed frameworks to maximise product utility and lifespan while minimising environmental impact (Aydin and Badurdeen, 2019; Li et al., 2021). Nonetheless, limitations of these approaches arise due to implementation challenges, particularly in industries with rapidly evolving product technologies and the comprehensive data collection needed for their application.

2.2. Usage-centric perspective

This perspective links remanufacturability to operational wear-and-tear, leveraging Internet of Things (IoT) sensors and predictive analytics to forecast EoL conditions. Key elements include usage intensity, maintenance history, and sensor data. Common methodologies within the field include Predictive Analytics, Machine Learning (ML) and Wear Coefficient Models. For instance, Ke et al. (2016) developed fuzzy logic algorithms to estimate material degradation in automotive parts while other scholars have highlighted the rise in Automated Intelligence (AI) adoption, with over 30 % annual growth since 2014 (Kim et al., 2024). Their findings reinforce the need for better data management and integration of smart technologies to support the CE and highlight the importance of developing dedicated automated tools to improve accessibility and effectiveness in aircraft maintenance (Kim et al., 2024; Stanton et al., 2023). Industrial examples of usage-centric perspective include Rolls-Royce's "Power-by-the-Hour" programme, which uses real-time engine data to schedule remanufacturing, while Komatsu's "Komtrax" system optimises remanufacturing schedules based on construction equipment load cycles. However, reliance on proprietary data and heterogeneity across product populations (e.g., consumer electronics vs. industrial machinery) limit scalability (Fera et al., 2024).

2.3. Process-centric perspective

Process-centric models prioritise process efficiency and optimisation, emphasising supply chain efficiency, disassembly time and sequence, reprocessing costs, and closed-loop logistics. Common methods include the use of algorithms to optimise disassembly sequences. In this respect, Zhan et al. (2023) developed an optimised dual-objective disassembly sequence planning model for EoL vehicle batteries, integrating an improved Northern Goshawk Optimisation (NGO) algorithm to minimize environmental hazards and energy costs. Meanwhile, other scholars tackled energy-aware scheduling in remanufacturing by integrating disassembly, reprocessing, and reassembly stages and employing a hybrid genetic algorithm with variable neighbourhood search for optimisation (Wang et al., 2023b). Both approaches enhance efficiency and sustainability, with their key limitation being the complexity in application and interpretation, which is only amplified by the identified green skills gap in sustainable manufacturing (Weiss et al., 2024). These challenges could be mitigated by developing more user-friendly decision support tools. Such tools would facilitate onboarding and skill development by effectively transferring expert knowledge, thereby improving performance and employee satisfaction (Nikoloski et al., 2024). Additionally, studies on the design and implementation of decision support tools highlight the need for interfaces that reduce friction and streamline the decision-making process, emphasising the importance of user-friendly and intuitive designs (Ahani and Trapp, 2021). An illustrative example of a process-centric approach is the development of metrics like the Ease of disassembly Metric (eDiM), which focuses on standardising and optimising the core disassembly process (Peeters et al., 2018).

2.4. Identified gaps

Despite the existing work on the remanufacturability assessment, both at the detail design stage and for existing products, there is a notable, overarching gap in practical decision-support tools to assist designers or decision-makers in evaluating the remanufacturability of products, with methods that adopt combined economic, environmental and technical criteria in assessing remanufacturability being limited (Zhang et al., 2021). Additionally, the literature identifies a critical need for adaptable, empirically validated models with sector-agnostic scalability to address gaps in real-world application (Psarommatis and May, 2025; Sierra-Fontalvo et al., 2024; Wang et al., 2023a, 2023b).

Moreover, by leveraging visual analytics tools, decision-makers can better understand lifecycle data, assess environmental impacts, and evaluate the feasibility of design changes (Ramanujan et al., 2017). Despite this, the most common methods used in remanufacturing assessment, such as optimisation algorithms and other decision-making methods, lack visual representation—a gap previously identified as a need for a visual aid to support practitioners in EoL decision-making processes (Laurin et al., 2016; Yang et al., 2015b).

Finally, remanufacturing is a highly complex process, a challenge reflected in some of the existing assessment tools. Effective utilisation of these tools requires experienced practitioners, who may be scarce due to an identified green skills shortage (Weiss et al., 2024). Therefore, there is a clear need for an easy-to-use while still comprehensive decision-making tool that can be accessible to a broader audience.

To address these gaps, this paper proposes a novel method named *Economic and ENvironmental Impact Assessment for Sustainability (EENIAS)* to assess the remanufacturability of an existing or a new product during its detailed design stage from an economic, environmental and technical point of view. The proposed method supports *Design for Remanufacturing (DfRem)* and promotes truly sustainable products and product designs. Additionally, through quantifying the product's remanufacturability, the advancement of the CE is achieved since the product's design suitability for implementing a Circular Business Model (CBM) is validated. Finally, the clear visualisation of results enhances decision-making by improving the interpretation of complex problems and provides an effective and easy-to-use tool for practitioners. Table 1 presents in greater detail the contribution of EENIAS against the key gaps identified in the literature.

Table 1
Contributions of EENIAS.

Main evaluation aspects	Existing methods' key shortcomings	Contribution/solution EENIAS
Economic	Limited ability to capture uncertainties in material condition (Andarani and Goto, 2012), specific scenario-only focus (Sabharwal and Garg, 2013), scalability issues (Jiang et al., 2020)	Adoption of multiple remanufacturing scenario approaches that can capture the complexity of remanufacturing. Implementation of industry-agnostic method.
Environmental	Lack of integration of lifecycle benefits (Akano et al., 2021), reliance on limited data (Farrant et al., 2010; Yang et al., 2015a), non-holistic approaches (Liu et al., 2016)	Capturing the environmental impact at a component level, modelling the remanufacturing process, and providing a basis for deeper End-of-Life (EoL) and Circular Economy (CE) environmental impact quantification.
Technical	Assumptions that limit real-world applicability, lack of scalability (Lee and Lee, 2024), difficulty in acquiring data (Liu et al., 2019)	Utilising readily available data, such as Bill of Materials (BOM), and well-established methods, such as the Ease of disassembly Metric (eDiM), to minimize assumptions and uncertainties in remanufacturing
Comprehensive	Absence of holistic models integrating economic, environmental, and social aspects (Zhang et al., 2021)	Development of a comprehensive method integrating economic, environmental and technical aspects that provides a foundation for incorporating additional aspects into the decision-making process.

3. Methods

This section outlines the key stages of the EENIAS method. It includes a step-by-step implementation guide in Section 3.1, with detailed information on the selected tools provided in Sections 3.2 to 3.5. The EENIAS method is discussed in Section 3.6, and its applicability is demonstrated through two case studies presented in Section 3.7. Note that the second case study (Section 3.7.2) is not covered in the same detail as the first one due to space limitations.

3.1. Proposed method description

EENIAS development was motivated by the identified literature gaps and feedback from the industry through real-life case studies and discussions with experts in the fields. Fig. 1 describes the flowchart and the steps for the implementation of EENIAS.

At a high level, the method's application begins in Step 1, with *product selection* for implementation of the method. The product can be either an existing product in its End-of-Usage (EoU) stage that an Original Equipment Manufacturer (OEM) or Original Equipment Remanufacturer (OER) are interested in assessing its remanufacturability or a product in its detail design stage where the designer is quantifying the design's suitability for remanufacturing.

Next, in Step 2, the practitioner conducts a *structural analysis*. The input data relating to the product's structure originates from the Bill of Materials (BOM) and information related to the product's connectors. The output of this step is the creation of the Hierarchical Attributed Liaison Graph (HALG), a graph able to display the components' connections and hierarchical levels and an identification of the product's key components.

Step 3 includes the Ease of disassembly Metric (eDiM) analysis, which is used to identify the time needed for dis- and reassembly of each key component at each hierarchal level. The eDiM is utilised to estimate the effort needed and develop the cost modelling for each remanufacturing-related task.

In Step 4, the practitioner uses the key components identified in Step 2 to determine the number of potential remanufacturing scenarios, based on whether the components can be replaced or not. These remanufacturing scenarios are later used to plot the EENIAS chart.

Step 5 includes the product's *environmental assessment*. A simplified LCA is conducted for the product based on the remanufacturing process, resulting in an estimation of the environmental impact for each remanufacturing scenario. Although the outcome is expressed in kg of CO_2 equivalent, all relevant impact categories based on the Life Cycle Impact Assessment (LCIA) ReCiPe Midpoint method are captured and translated into a single impact source, namely climate change.

Step 6 entails the economic assessment of the remanufacturing scenarios. Data such as the remanufacturing process, the cost of component replacement (including labour costs calculated based on the eDiM), and the cost of a new identical product are used as inputs. These data are used to estimate the cost for each remanufacturing scenario, accounting for the replacement of a series of key components.

Finally, in Step 7, for each remanufacturing scenario, its cost and environmental impacts are plotted together on the EENIAS chart, which assesses the remanufacturability of the product's design and can be used to support Design for Remanufacturing, remanufacturability evaluation and enable circular pathways.

3.2. Tools used

This section describes in detail the tools used to develop the innovative EENIAS approach and the case study as well.

3.2.1. Bill of Materials (BOM)

BOM is typically used in manufacturing, outlining all raw materials, components, and assemblies needed for the product, so it is usually readily available. It uses a hierarchical structure, placing the final product at the top to improve communication among manufacturing partners (Lambert and Gupta, 2002; Liu et al., 2014). While BOM is popular for its industry acceptance, ease of use, and clear structure, it falls short by not showing component interconnections, limiting disassembly information. This issue can be addressed by incorporating connection diagrams to reveal these links (Lee et al., 2010) and that is the main reason it has been selected for the proposed method.

3.2.2. Hierarchical Attributed Liaison Graph (HALG)

The proposed methodology leverages the HALG for identifying hierarchical levels in product structures, effectively representing

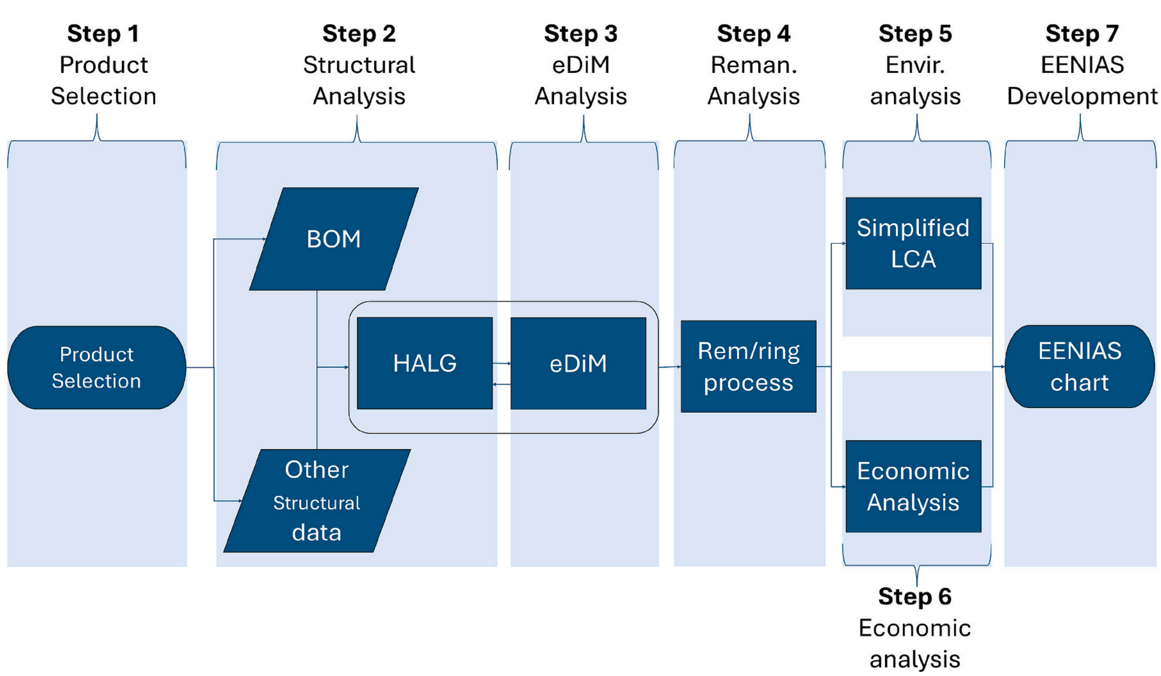


Fig. 1. Steps of the EENIAS chart application.

components' levels and interconnections without needing separate diagrams (Dong et al., 2006). HALG's ability to graphically depict the time required for disassembling and re-assembling connections gives it an edge over traditional methods like BOM or connection diagrams. This feature is crucial for this study as it helps estimate costs and time for component replacement and assess the environmental impact of remanufacturing.

Previous studies have used HALG for EoL decision-making based on economic or environmental criteria. These studies show the effectiveness of a hierarchical approach in EoL decision-making, emphasising the importance of structural representation in evaluating the cost-value relation of the disassembly and reassembly process (Feng et al., 2019; Lee et al., 2010).

Step 2 includes converting a multi-level BOM into a HALG. Starting with a BOM, the practitioner establishes HALG's initial hierarchical levels and then draws interconnections between components to ensure accuracy. Product drawings and practitioner experience validate the final HALG.

3.2.3. Ease of disassembly Metric (eDiM)

Disassembly and reassembly effort metrics are broadly classified into two categories: a) absolute metrics, like time, and b) relative metrics, which cover aspects such as effectiveness (Afrinaldi et al., 2008). eDiM, an absolute metric, is grounded in the Maynard Operation Sequence Technique (MOST) (Zandin, 2002). It provides a standard, comparable index to gauge the ease of replacing components in returned cores. Developed through European Commission funding and the Joint Research Centre, eDiM aims to standardise the measurement of disassembly difficulty levels across remanufacturing sectors.

The eDiM metric utilises a calculation sheet detailing the main actions, sequences, and tools used in disassembling a component. Its validity derives from established literature frameworks and academic publications (Peeters et al., 2018; Vanegas et al., 2018) which affirm its effectiveness across various industrial products, ensuring its reproducibility and reliability. Its industrial validity, data access and academic adoption by similar studies are the main reasons for selecting eDiM over other similar methods. Those are the U-effort technique by Sodhi et al. (2004) where only disconnection time is accounted for, the Kroll's methodology (Boks et al., 1996b; Hanft and Kroll, 2012; Kroll et al., 1996) which can lead to excessive detail, the Philips method (Boks et al., 1996a) which is product specific.

eDiM employs specific equations to quantify the effort and time for component replacement, with the entire metric measured in seconds. eDiMD (Eq. (1)) refers to the time needed to for the disassembly and eDiMR (Eq. (2)) to the time needed for the reassembly. Eq. (3) represents the total eDiM for replacing a component. eDiM categorises disassembly and reassembly tasks into six groups, enabling detailed analysis of resource-intensive tasks and product design. The categories described in these equations are adopted by Vanegas et al. (2018). This categorisation in eDiM is instrumental in pinpointing 'bottlenecks' in the disassembly and reassembly processes, thereby enhancing remanufacturing optimisation. It also aids upper management in understanding operational time allocation, uncovering hidden costs, and improving overall process efficiency. Therefore, such analysis is crucial for supporting Design for Remanufacturing approaches.

Disassembly:

$$eDIMD = tool\ change + identification + manipulation + tool\ positioning + disconnection + removal; \tag{1}$$

Reassembly:

$$eDIMR = addition + tool\ change + identification + manipulation + tool\ positioning + fastening; \tag{2}$$

Total:

$$eDIM = eDIMD + eDIMR \tag{3}$$

3.3. Components replacement scenarios

A critical part of this method is identifying 'key' components critical to the product's functionality as perceived by customers. Components, even those related to aesthetics, may be deemed 'key' based on the customer's perspective. These key components are central to replacement scenarios, forming the basis for all further analysis. Thus, any component valued for its function, appearance, or customer perception can be considered key. Practitioners must determine which components are key for each product application.

In this study, a component is replaced with an identical or similar component with the same economic, 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.

3.4. Product's environmental assessment

To ensure transparency in environmental analysis, the method adopts a carbon footprint measure, conducting an LCA in line with ISO 14040:2006 standards (Finkbeiner et al., 2006). More specifically, it adopts the simplified LCA as described by Christiansen et al. (1997). The adopted approach provides a detailed environmental impact assessment for each EoL pathway to prevent 'greenwashing' and provide definitive results. The selection of the simplified LCA stems from the challenges of data collection from second and higher-tier suppliers and the focus on carbon emissions equivalents as a singular metric to describe environmental impact. Additionally, the speed and flexibility of a simplified LCA align perfectly with the method's goal of enabling quick and reliable results without compromising their validity.

3.5. Cost analysis of the end-of-life pathways

For each EoL pathway, the cost functions have been defined based on their main cost-related tasks. The direct reuse costs (Eq. (4)) 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 reassembly tasks. Thus:

$$Direct\ reuse\ cost = Cleaning\ cost + Inspection\ cost \tag{4}$$

The cost of each remanufacturing scenario is analysed at the 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 reassembly of a specific component. The remanufacturing cost at the product level aims to calculate the final cost of remanufacturing the product as a whole by summing the costs of remanufacturing each key component and adding the final product's inspection cost. Eq. (5) expresses the Remanufacturing cost at the components level and Eq. (6) the Remanufacturing cost at the product level when N is the number of key components:

$$Reman.Cost\ [Component] = Cleaning\ cost + Comp.replacem.Cost + Disassembly\ cost + Reassembly\ Cost + Comp.recycle\ cost + Comp.Disposal\ cost \quad (5)$$

$$Reman.Cost\ [product\ level] = Inspection\ cost\ [product] + \sum_{i}^{N} Reman.Cost\ [Component] \quad (6)$$

For this study, 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 Recycle Cost at the component level is described below in Eq. (7) and the Recycle cost at the product level in Eq. (8):

$$Recycle\ Cost\ [Component] = (-Component\ weight{*}Material\ price\ for\ recycling) + Disposal\ cost\ of\ component \quad (7)$$

$$Recycle\ Cost\ [product] = \sum_{i}^{N} Recycle\ Cost\ [Component] \quad (8)$$

The components' disposal cost is estimated based on the disposal cost rate for that material and the weight of the components as expressed in Eq. (9):

$$Disposal\ cost\ of\ component = Component\ weight{*}Disposal\ rate \quad (9)$$

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 representing income, when recycling rates are paid to the company from the recycling centers for the returned materials.

Based on the previous paragraph, the disposal cost (Eq. (10)) is the sum of the disposal of each component and is linked to the disposal rate for each material. Thus:

$$Disposal\ cost\ of\ product = \sum_{i}^{N} Disposal\ cost\ of\ component \quad (10)$$

The aforementioned cost functions have been used to identify the cost related to each of the remanufacturing key component replacement scenarios used in the EENIAS method.

3.6. Economic and ENvironmental Impact Assessment for Sustainability (EENIAS)

The EENIAS chart combines the outcomes from the economic and environmental analysis for each of the remanufacturing scenarios. The calculation of the remanufacturing scenarios is crucial for developing the EENIAS chart since each of those scenarios is a point on the graph expressed through Eq. (11), where n_i represents the point of the remanufacturing i-scenario, x_i its cost and y_i its environmental impact.

$$n_i = (x_i, y_i) \quad (11)$$

The cost of the remanufacturing scenario i (x_i) is based on the economic model, and the environmental performance (y_i) is calculated through the conducted simplified LCA. The environmental impact 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.

After estimating each remanufacturing scenario's environmental and economic impact, the points are plotted on the EENIAS. The LCA provides y_0, an estimation of the environmental impact of a new product expressed in kg of carbon emissions equivalent (kgCO_2 eq). Then, the cost of a new equivalent product to the company provides the x_0 value.

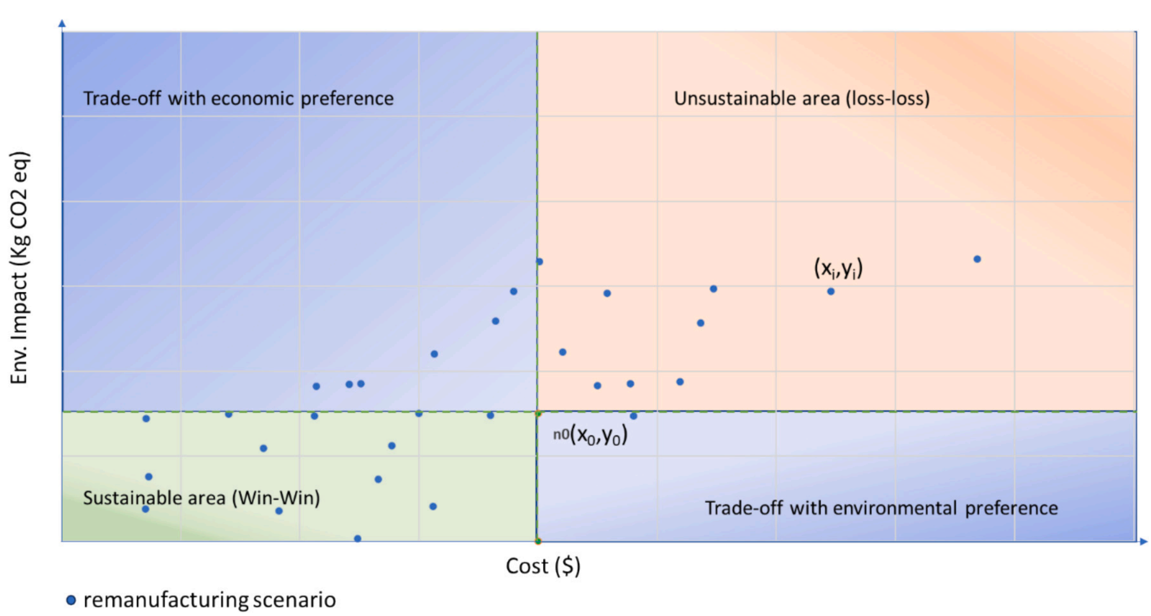


Fig. 2. Economic and ENvironmental Impact Assessment for Sustainability (EENIAS) chart with examples of remanufacturing scenarios.

Thus, the benchmark set n_0 (x_0, y_0) has been defined. This set of values represents the boundaries defining the four areas of analysis that will provide the practitioner with the visual aid for a better understanding of the suitability of the product for remanufacturing. The four areas of interest are: 'Sustainable area (win-win)', 'Unsustainable area (loss-loss)', 'Trade-off with economic preference' and '*Trade-off with environmental preference*' (see Fig. 2).

In the sustainable area (win-win), remanufacturing scenarios are identified with less environmental impact and cost than 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 with higher costs and more environmental impact than buying a new identical product (n_0). When a product's EENIAS 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 CBM since it doesn't provide the necessary value to be competitive against purchasing a new product.

The other two areas that constitute the EENIAS chart are the trade-off areas. The first is the trade-off area with *economic preference*, where remanufacturing a product is cost-effective 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 more significant 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 with a higher cost than buying a new product, but the environmental impact will be lower. Companies with strong environmental values and strict goals may still consider remanufacturing such products when the loss is not too significant to achieve their sustainability targets, such as carbon neutrality or net-zero emissions.

The EENIAS chart 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 EENIAS charts for other similar products, they can compare them to identify the best-suited product for applying a CBM. The allocation of the remanufacturing scenarios across the four areas of interest provides the practitioner with a rough risk estimation of acquiring returned products without 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 EENIAS chart can provide detailed cost and environmental impact for each remanufacturing scenario. Quantifying those dimensions gives the practitioner an idea of how remanufacturing is compared to buying a new product. Finally, the EENIAS chart provides guidance on remanufacturing scenarios that are particularly interesting 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 financially; thus, decision-making is supported at a much more preliminary stage. EENIAS will be further demonstrated through a real-life application in two case studies over the following sections.

3.7. *Case studies*

To demonstrate the applicability of EENIAS, two case studies from different industries have been conducted. The first case study focuses on the lighting sector and will be presented in detail to clearly outline the implementation steps of the proposed method, facilitating a comprehensive understanding of the methodology. The second case study is from the oil and gas sector, specifically involving an accumulator, a much more complex product with multiple assemblies and sub-assemblies. Despite their differences, both products have a great degree of modularity in their designs. Due to space limitations, only the outcome (EENIAS chart) will be provided for this case, while all relevant details can be found in the supplementary material. Both selected products are real-life examples, with data provided by collaborating companies that incorporate remanufacturing into their business models to some extent.

3.7.1. *Luminaire*

To implement EENIAS, step 1 requires the selection of a specific product. For this case study, the selected product is the 'Strathclyde' luminaire from the lighting catalogue, which is a widely used type of luminaire and an ideal replacement for linear fluorescent luminaires in educational environments. Therefore, this existing luminaire is the ideal candidate for remanufacturing assessment, as mass remanufacturing is a feasible EoL pathway. The following paragraphs describe the implementation of each step of developing the EENIAS chart for the selected product.

3.7.1.1. Hierarchical Attributed Liaison Graph (HALG). Step 2 involves a structural analysis of the selected product. Based on the BOM and other basic structural information, the luminaire's HALG is developed by the practitioner as seen in Fig. 3. The key components identified in this product are the diffuser [1], the bookplate [14], the end caps [2], the LED strips [12] and the Driver [7], with the numbers depicting those components in the HALG. 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.

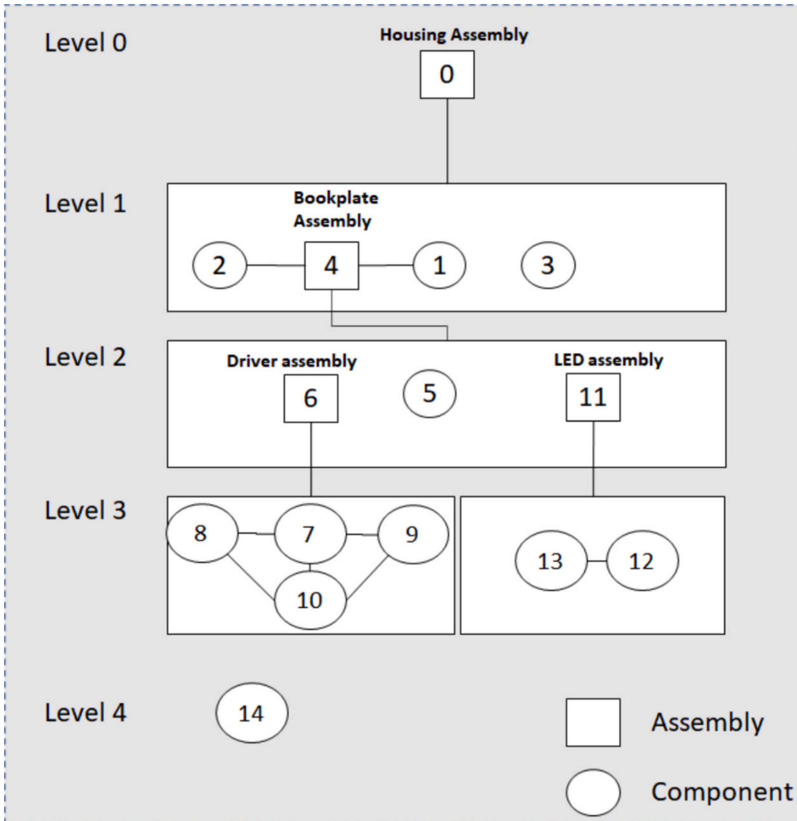
At this point, the practitioner has gained knowledge of the product's structure and the connections between its components.

3.7.1.2. Ease of disassembly Metric (eDiM). Step 3 includes the eDiM calculation for the product's disassembly and reassembly. This is calculated based on the type of connectors and the standardised time needed for each task. Table S2 (found in the supplementary material) contains the eDiM analysis for the disassembly, and Table S3 (found in the supplementary material) contains the reassembly analysis and the total eDiM index for the complete dis- and reassembly of the Strathclyde luminaire. In both tables, all the values use seconds (s) as the time measurement unit.

Based on data from Table S2, a pie graph was composed of the main disassembly tasks and their percentage of time for the Strathclyde luminaire, as depicted in Fig. 4. Such categorisation allows the identification of the 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 %).

Table S3 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 reassembly 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.

Fig. 5 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



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

Fig. 3. Strathclyde luminaire HALG and table of components.

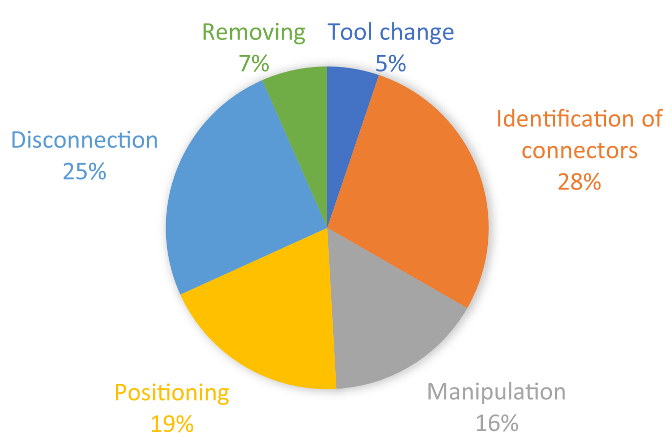


Fig. 4. Percentage of the duration of disassembly tasks.

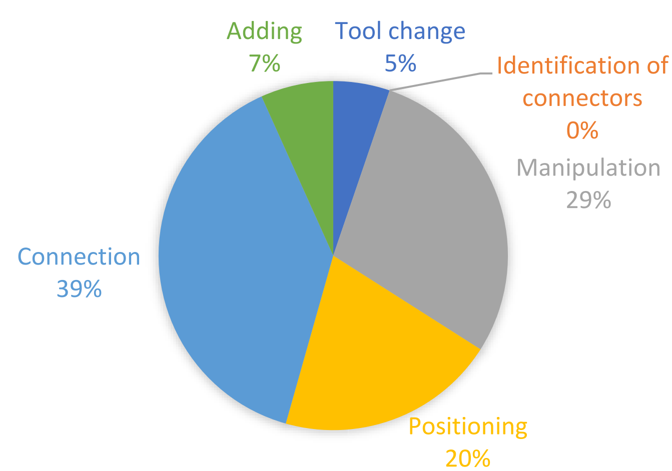


Fig. 5. Percentage of the duration of reassembly tasks.

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. From this analysis, practitioners can realise that 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. Additionally, the more eDiM is adopted by a company, the more accurate its predictions of effort needed per task will be since it can be updated with more real-life data.

3.7.1.3. Components replacement scenarios. Step 4 includes the definition of the remanufacturing scenarios, which is the potential replacement of one or more of the key components. Thus, in the case study of the luminaire with five key components, the total number of scenarios is 32 and presented in Table S4 (found in the supplementary material),

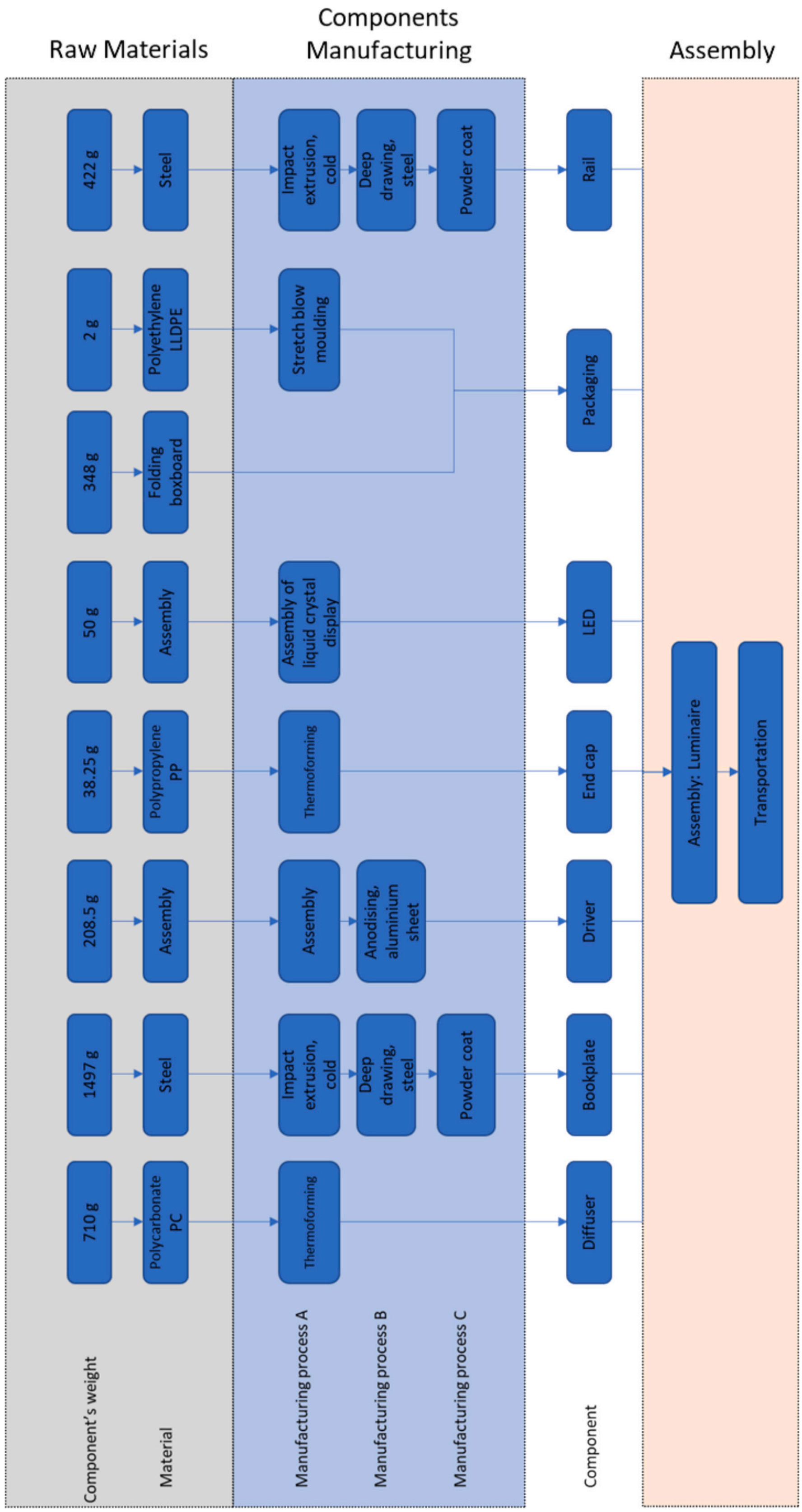


Fig. 6. Luminaire manufacturing process tree.

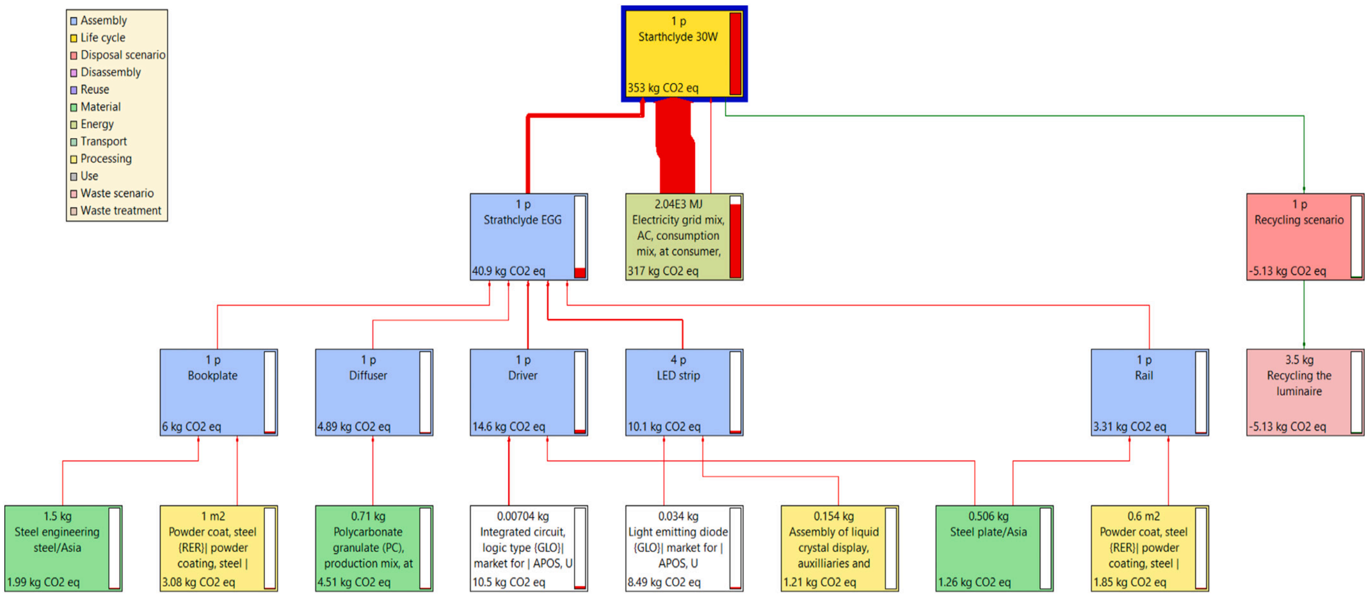


Fig. 7. Life Cycle Assessment network of 30 W luminaire.

where the value “0” equals the component not being replaced and “1” being replaced. In Table S4, 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.

3.7.1.4. Simplified Life Cycle Assessment (LCA). Fig. 6 illustrates the manufacturing process tree used in the simplified LCA conducted for the selected luminaire, which is the Step 5 of the implementation process. The datasets used were extracted from the Ecoinvent 3.6 and Industry 2.0 databases and the LCIA method of choice was the ReCiPe Midpoint 2016 (H) V1.04/World (2010), which expresses Climate change in kilograms of Carbon emissions equivalent (kgCO_2 eq).

The approach of this simplified LCA is cradle to grave; thus, all the stages from raw material extraction to EoL recycling scenario are analysed. Fig. 7 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. 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 17,850 h in total (7 years) with a power consumption of 31.7 watts. Although the nominal power value of the product is 30 watts, measurements from the technicians revealed that its actual power is 31.7 watts; hence, that was selected as a more realistic value.

Additionally, as illustrated in Fig. 7, 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 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. All the results from this simplified LCA have been used to quantify the environmental impact for each remanufacturing scenario in EENIAS.

Step 6 includes the application of the financial model to estimate the cost for each of the 32 remanufacturing scenarios. The financial model described in Section 3.5 is applied.

Fig. 8. Similar bladder accumulator.

3.7.2. Accumulator

This section introduces the accumulator case study. Steps 1 to 6 for the accumulator case study are included in the supplementary material and have been omitted from the main body of the article due to space constraints. The product selected is a generic 20-litre bladder accumulator commonly used in the Oil and Gas industry, as shown in Fig. 8.

Similarly to the previous case study, five key components have been identified (namely: Gas Valve Assembly, Fluid Port, Locking Ring, Gas Valve Stem, and Accumulator’s Shell), resulting in 32 remanufacturing scenarios. Steps 2–6 are included through graphs and tables in the

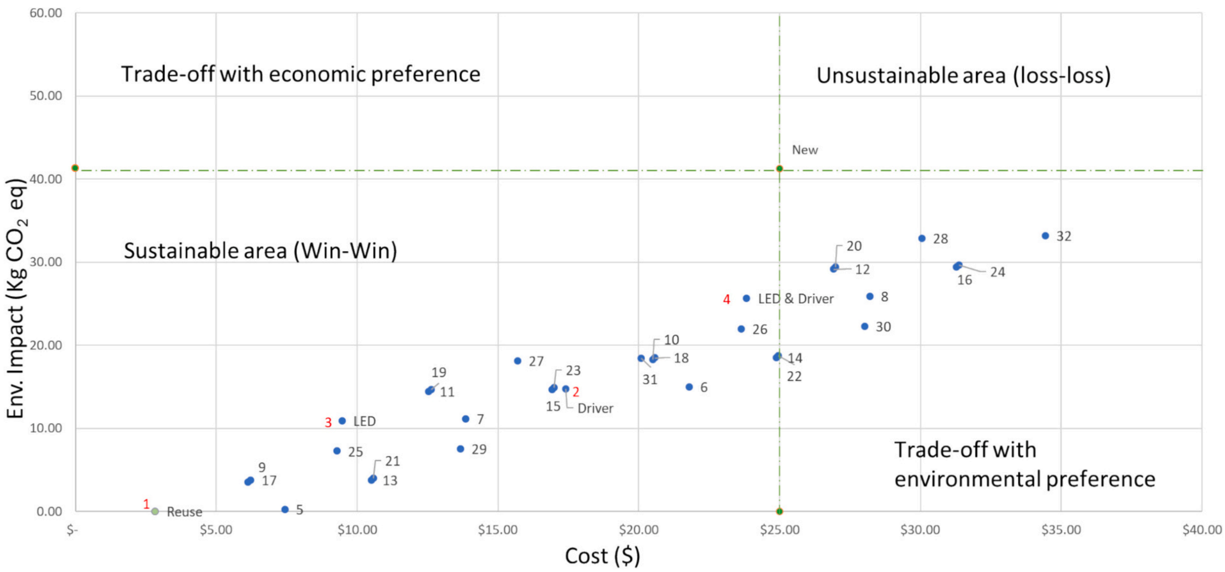


Fig. 9. EENIAS for the Strathclyde luminaire.

supplementary material.

The accumulator's components are categorised into three main types: key components, always-replaceable components, and consumables. Key components are crucial for financial and environmental analysis, as their functionality or cost significantly affects the decision on the most suitable end-of-life pathway. Always-replaceable components are replaced during remanufacturing or direct reuse because of their rapid wear, safety, or critical functionality. Their replacement cost and environmental impact are included in all remanufacturing and reuse scenarios. Consumables are components with minimal cost, function, or complexity, and replacing them has no significant impact on cost or environmental analysis. Despite being termed "consumables," these components can often be reused multiple times without signs of wear.

4. Results

This section presents the results of the luminaire case study, which has been detailed extensively, as well as the results of the accumulator case study.

4.1. Luminaire

The EENIAS chart for the 32 remanufacturing scenarios of the Strathclyde luminaire is illustrated in Fig. 9, with every dot representing a different remanufacturing scenario (Step 7 of the implementation process).

Analysis of Fig. 9 yields several key insights, the foremost being that the luminaire design is favourable to remanufacturing, as most potential scenarios fall within the sustainable (win-win) area. Scenario 1, which involves no component replacement and is thus categorised 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 financial and environmental benefits at the same time. On average, remanufacturing costs $19.25, representing a 23 % reduction from the price of a new product. Excluding financially infeasible 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 prioritising environmental objectives. The company has identified several remanufacturing scenarios of particular interest, which are further analysed in the subsequent paragraphs.

4.1.1. Special interest remanufacturing scenarios

Direct reuse environmental impact is 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 a feasible option. 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.

Remanufacturing scenario 2 includes the replacement of solely the driver, which 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 driver replacement is a widespread remanufacturing practice.

Another scenario of particular interest for the company is the exclusive replacement of the LEDs with newer ones after the EoU stage (Scenario 3). This remanufacturing scenario results in reductions of 62.15 % to the cost and 73.53 % to carbon emissions. This scenario reveals the massive potential for environmental and economic 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 more efficient.

The final scenario that is of special interest to the company requires the replacement of both the LED and the driver (Scenario 4). 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 almost negligible. 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 are assumed to 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 delivering the product's 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 (Ijomah et al., 2005). This scenario is also considered one of the worst-case scenarios since it assumes that both critical components have failed and need replacement. Ultimately, remanufacturing the product has a slight financial benefit for the company and a significant environmental benefit, and it 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.

4.2. Accumulator

The EENIAS chart for the accumulator is illustrated in Fig. 10, where many conclusions can be drawn, 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 underlying reason behind the apparent grouping of scenarios is the magnitude of the difference between the shell and every other component expressed in the environmental impact aspect. The dominance of this part in the EENIAS chart reveals that significant environmental gains can be achieved if the company designs the product so that the shell does not need replacement after the usage stage.

Additionally, the EENIAS chart could support decision-making for core acquisition by creating a rule of thumb based on the shell's condition. Although the shell is clearly the dominant component from an environmental point of view, this is not the case financially. Fig. 11 includes remanufacturing scenarios (axis x), their cost (axis y- left), and the number of components being replaced (axis y- right). Based on Fig. 11 the cost of replacing different components is greater when more key components are replaced. The same information is also captured from EENIAS since the cost is growing towards the *x*-axis named cost and expressed in USD ($), leading to the same conclusion.

Based on the EENIAS chart, in greater detail, 93.75 % of the remanufacturing scenarios belong to the 'win-win' area. 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 almost 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.

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 components are identical to the ones used originally. This assumption simplifies the model and allows a sector-agnostic 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 by capturing the new impacts of these technologies and updating the four quadrants of the EENIAS chart. Thus, technological progress can potentially mitigate those components' environmental impact and cost, moving the EENIAS chart scenarios towards the sustainable area (win-win) and rendering remanufacturing an even more attractive solution.

4.2.1. Special interest remanufacturing scenarios

A scenario of particular interest to the company is Scenario 1, which

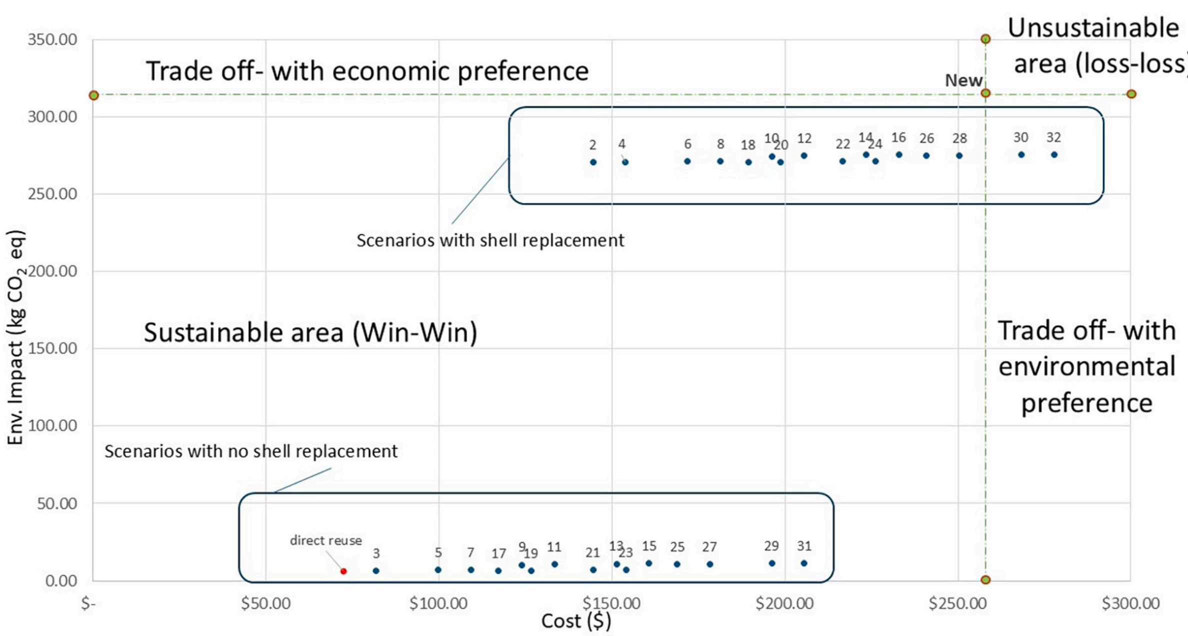


Fig. 10. EENIAS for the accumulator.

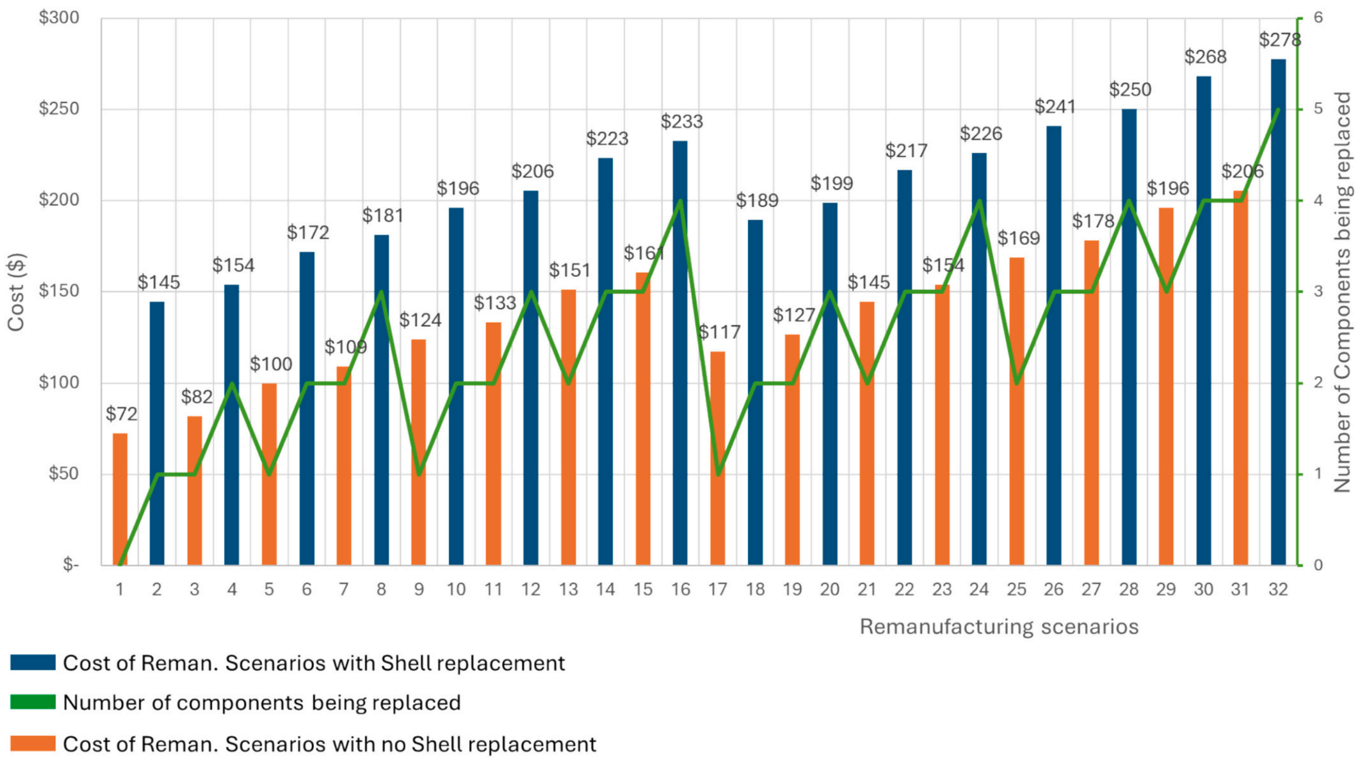


Fig. 11. Cost per Reman. scenario and number of components being replaced.

involves replacing only the always-replaceable components while reusing all key components. This approach corresponds to the reuse of the accumulator and results in the lowest cost and environmental impact. Based on the company's data, Scenario 1 has been identified as the most common and serves as a cornerstone for supporting the implementation of CBMs, such as the service-based model considered by the company.

Scenario 2, one of the remanufacturing scenarios, is also of special interest to the company. In this scenario, only the accumulator's shell, a key component, requires replacement. However, this scenario is nearly double the cost of the reuse scenario and has 43 times the environmental impact. The quantification of Scenario 2 was described as an 'eye-opener' by one of the company's engineers, as it highlighted the critical need for accumulator shells designed for multiple usage stages with minimal wear.

5. Discussion

EENIAS was applied to two distinct products: an accumulator and a luminaire. These case studies aimed to illustrate the proposed method's applicability in two distinct real life industrial cases. From a structural representation perspective, both case studies benefited from the application of HALG and the eDiM tool, which facilitated systematic estimations of disassembly and reassembly times. In the accumulator case study, the presence of always replaceable components established a minimum time requirement for reuse scenarios. This meant that differences in the time needed to replace key components were less impactful, as disassembly and reassembly tasks had to be performed regardless of the core condition. The standardised approach ensured consistency in evaluating the time requirements across various scenarios.

In contrast, the luminaire case study showcased a product with a clear sequence of tasks required to access each component, making it easier to allocate key components hierarchically. The time distribution measured by the eDiM tool highlighted potential areas for design optimization. For instance, it was found that the use of 'snap-fit' connectors that required no tooling could significantly expedite disassembly and reassembly processes. This insight underscored an opportunity to further align the luminaire's design with Design for Remanufacturing principles, potentially reducing labour costs and enhancing efficiency.

The EENIAS chart was instrumental in both case studies, providing practitioners with quantified assessments of the products' suitability for remanufacturing and a visualisation of the different remanufacturing scenarios' performance, responding to the need for more visual tools identified in the literature (Laurin et al., 2016; Yang et al., 2015b). In the accumulator case study, the EENIAS chart revealed that the environmental impact was dominated by the potential replacement of the shell, while the total cost correlated with the number of components replaced. This correlation indicated that focusing on reducing the environmental impact of the shell, through extension of its lifespan, could significantly improve both environmental and economic outcomes. The grouping of scenarios by means of their cost and environmental impact helped identify the preferable remanufacturing options, offering a basis for a *'rule of thumb'* approach in core acceptance strategies offering practical and actionable outcomes for remanufacturing, a gap highlighted multiple times in previous works (Psarommatis and May, 2025; Sierra-Fontalvo et al., 2024; Wang et al., 2023a; Zhang et al., 2021).

Similarly, in the luminaire case study, the EENIAS chart showed that none of the scenarios fell into the unsustainable area (loss-loss) or trade-off area with economic preference. This absence suggested that, based on the model's assumptions and development, remanufacturing the luminaire would always yield at least an environmental benefit. The luminaire proved highly suitable for remanufacturing, with 74.2 % of scenarios in the sustainable area and the remaining 25.8 % in the trade-off with environmental preference area. This outcome aligns with Hummen & Wege's findings (2021), which emphasise that remanufacturing energy-using products is most beneficial for mature products due to limited technological advancements. One key assumption in this case study is that the LEDs and drivers, two critical components of the luminaire, will be replaced with similar or improved parts, ensuring they remain equally efficient during use. The environmental impact and cost of those parts can be captured in the EENIAS graph, thus validating its high adaptability. Finally, this quantitative assessment affirmed the luminaire's design compatibility the company's business model of a high-volume remanufacturing service (The Ellen MacArthur Foundation, 2013).

While a direct comparison between the EENIAS method and other established approaches is challenging due to its distinctive nature, certain aspects can be compared to similar methods to highlight its contributions. Lee et al. (2010) and Yang et al. (2015b) support EoL decision-making by leveraging the HALG approach to identify disassembly hierarchies and associated costs, which validates their relevance to EENIAS's development. However, these methods do not provide scenario-specific environmental assessments or in-depth insights into a product's overall remanufacturing suitability. Their primary focus is on maximizing profitability while complying with environmental regulations, leaving a gap in understanding the environmental impacts associated with remanufacturing. This limitation, noted by scholars in the field (Akano et al., 2021; Hummen and Wege, 2021), is directly addressed by the EENIAS method.

More specifically, Yang et al. (2015b) evaluated the remanufacturability of an alternator and a hedge trimmer at the component level using environmental and economic indexes, reaching a conclusion aligned to the findings of the EENIAS method and its two case studies: while remanufacturing can yield significant environmental and economic gains, it is not universally beneficial. However, Yang et al. (2015b) lack the scenario-based analysis and visual representation offered by EENIAS, which are essential for identifying design improvements and guiding strategies at the product level. This distinction underscores EENIAS's broader focus on remanufacturing cost scenarios and product design evaluation. Similarly, Omwando et al. (2018) proposed a comprehensive EoL decision system to assess remanufacturability while it considered the steps in the entire remanufacturing process and variations as single or multiple tire recovery. The EENIAS method could enhance such approaches by addressing their limitation of overlooking remanufacturing scenario-specific cost evaluations and design-focused remanufacturability assessments, achieving a higher degree of customisation of the tools used.

Additionally, EENIAS analyses a product's remanufacturability during the detailed design phase by combining LCA data with environmental and economic impact assessments, addressing the need for more efficient integration of LCA data identified by other scholars Ramanujan et al. (2017). This integration enables designers to systematically trace how specific design decisions affect sustainability outcomes across a product's lifecycle.

Furthermore, EENIAS illustrates the complex environmental and economic trade-offs, empowering practitioners to interpret remanufacturability effectively. This is an aspect commonly missing from similar works, which often is hard to obtained due to the 'black box' algorithmic approach they follow. Specifically, the degree of customisation in the EENIAS method allows for rapid updates to reflect real-world changes. For example, if a luminaire is sold with discounts the EENIAS method can incorporate these changes and adjust its assessment of the product's suitability for remanufacturing accordingly. Fig. 12 demonstrates this with the luminaire example. It shows that a 30 % price reduction on the new luminaire leads to 15 out of 31 (48.4 %) remanufacturing scenarios falling within the sustainable range, while the remainder moves to the trade-off zone favouring environmental considerations.

This dynamic aspect of the EENIAS enables practitioners to continuously update a product's remanufacturability based on changing market conditions instead of static product criteria, thus making remanufacturability a dynamic product characteristic.

5.1. Theoretical implications

This work contributes to theory and academic knowledge in the fields of product design and remanufacturing primarily by proposing a new method (EENIAS) to quantify remanufacturability, which, according to Goodall et al. (2014), is considered to be a product characteristic. EENIAS' novelty lies in the comprehensive assessment of remanufacturability based on identifying and allocating the products' remanufacturing scenarios across the four areas of interest of the EENIAS chart. Researchers in the fields of product design and remanufacturing can build on this method further to better link product design with the remanufacturing process.

The proposed method further contributes to knowledge in the area of remanufacturing by integrating established approaches to system modelling and time measurement in a novel tool that offers an

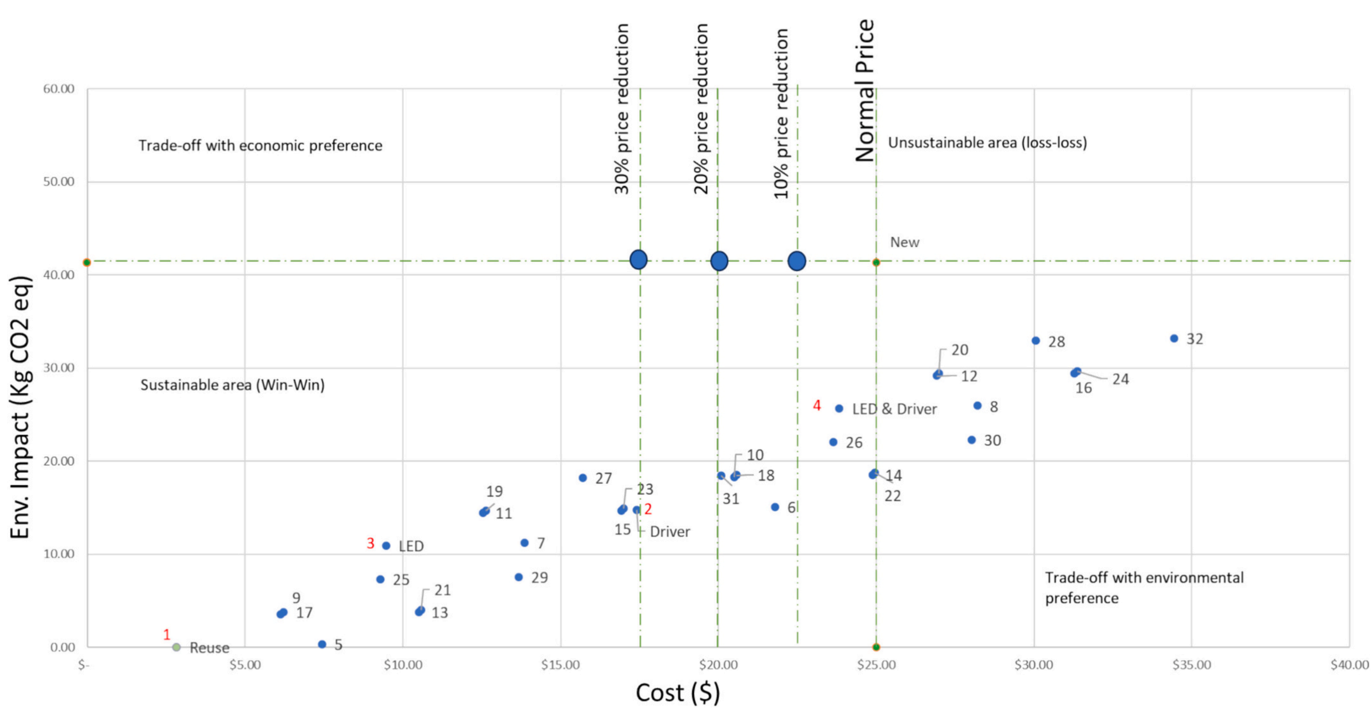


Fig. 12. Cost reduction for new luminaire and EENIAS update.

integrated depiction of the hierarchy of the disassembly operations and the effort associated with them. Specifically, it combines the HALG, a method for modelling complex systems or products by detailing the relationships between different components, with the eDiM, which is based on MOST and is a measurement methodology used for setting the standard times for work activities. This integrated approach may inspire researchers to develop more holistic approaches on remanufacturability assessment.

5.2. Managerial implications

Firstly, the proposed method was purposely implemented as simplified, visual tools to facilitate their applicability in industrial practice. The focus on data inputs that are typically available in industrial environments combined with the visual outputs of the method allow practitioners to apply the method easily and quickly and receive information on environmental – economic trade-offs of multiple remanufacturing scenarios simultaneously. This can support the formulation of core acceptance strategies in remanufacturing operations. The fact that the method is sector-agnostic further enhances its real-life applicability potential.

Additionally, the proposed method allows informed decisions to be made at the product design stage too. By adopting the key components approach and deriving the remanufacturing scenarios from them, the product designer can gain insights into how the selection for each component may affect the product's remanufacturability early on in the design process. It can also support designers in evaluating the impact of alternative connector designs on the disassembly and reassembly time at each hierarchical level, enhancing decision-making in design alterations or new developments. Ultimately, the EENIAS method provides quantitative support to design decisions and can be integrated into a Design for 'X' methodology, resulting in products that are more suitable for remanufacturing and CE.

Another contribution of the proposed method to industrial practice is its potential to support training of employees, to speed up and improve efficiency of remanufacturing operations. Due to the synthesis of the HALG with the eDiM, the method provides a novel and less time-consuming approach to depict the hierarchical levels of the product's structure, thus providing an immediate understanding of the product's structure and the effort needed to dis- and reassemble it. This can support the training of new employees (or existing employees in new dis- and reassembly processes), helping them grasp the product structure and inter-component relationships more effectively.

Another notable aspect of this method is its ease of updating, allowing practitioners to stay up to date with evolving market or other conditions while quickly incorporating the latest inputs like environmental impacts, product and core specifications changes and product costs. The direct comparison with a new product's cost and environmental impact - that can potentially change over time - keeps the product's design remanufacturability assessment updated and dynamic rather than static. This feature is particularly beneficial for industrial practitioners, as it enables them to adapt their remanufacturing and product design strategies as new information becomes available.

Finally, focusing at the strategic and tactical levels, the EENIAS can support practitioners in selecting the most promising products/product families to embark on circular business models application based on a comprehensive approach that includes economic, environmental and technical criteria. Thus, it reduces the subjectivity and uncertainty introduced by decision makers who, based on the judgements of experts, attempt to identify how to implement CBM in their company.

5.3. Limitations

However, the proposed method has certain limitations. One key limitation is the assumption of identical component replacement, which may not hold in industries experiencing rapid technological advancements. Additionally, while the use of a simplified LCA requires less data than a comprehensive LCA, it also limits the depth of environmental analysis. Another challenge arises from the acquisition, management, and accuracy of data required to properly assess remanufacturability—an issue well-documented in remanufacturing research (Wagner et al., 2024). Inaccurate data could lead the EENIAS graph to misrepresent a product's remanufacturability. Finally, the method primarily adopts a product-centric approach, which, while effective for visualising remanufacturability, may oversimplify the complexities of the remanufacturing process.

Each of these limitations has been considered and addressed to some extent in the development of the proposed method. Despite the constraints of a simplified LCA, it remains sufficient for this study's scope, as it captures essential aspects of an LCA for each component and presents environmental impacts in a clear and traceable manner. To mitigate data access challenges, the method reduces the need for extensive new data collection by leveraging well-established tools such as eDiM and LCA, which already contain relevant data within their databases.

Moreover, the primary purpose of this method is to assess remanufacturability and support decision-makers, rather than to prescribe optimal decisions. As a result, it does not require a broader usage- or process-centric approach. However, to enhance its effectiveness and reduce potential oversimplifications, future developments could integrate additional decision-making criteria and factors. This evolution would transform the method from a decision-support tool into a more comprehensive decision-making method.

6. Conclusions

The EENIAS method represents an innovative approach to support remanufacturability evaluation by integrating environmental and cost metrics through a technically based key component analysis, while aiming for a simplified application process and visual outputs to facilitate real-life applicability. Its application to the luminaire and accumulator case studies has demonstrated both its practicality, versatility, and applicability across different industries. By dynamically analysing remanufacturing scenarios derived from combinations of key product components, the method offers valuable insights to support informed decision-making. In the luminaire study, a substantial majority of scenarios exhibited noteworthy financial and environmental benefits, prompting further investigation to align design and business strategies with a remanufacturing-focused approach. In contrast, the accumulator study revealed that the shell is a critical environmental impact driver, suggesting that designing a more durable shell capable of enduring multiple usage cycles could significantly enhance both environmental and financial outcomes. These findings underline the importance of durable component design and provide actionable recommendations for stakeholders transitioning towards circular business models. Future research should aim to integrate the EENIAS method with advanced decision-making models, supported by automation and digitization, to enable widespread adoption in the industry. By providing a versatile, detailed, and actionable framework for assessing remanufacturability, EENIAS positions itself as a transformative tool for advancing circular economy adoption and promoting sustainable, cost-effective manufacturing practices.

CRediT authorship contribution statement

Aineias Karkasinas: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Athanasios Rentizelas:** Writing – review & editing, Validation, Supervision, Conceptualization. **Jonathan Corney:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

Declaration of generative AI and AI-assisted Technologies in the writing process: During the preparation of this work, the author(s) used Grammarly Ai and ChatGPT to check grammar and syntax errors. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the publication's content.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2025.03.019.

Data availability

Additional data can be provided upon request.

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