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Méthodologie d'aide à la décision pour faciliter la transition vers l'économie circulaire

Methodology of decision-aid for leveraging the transition towards circular economy

Présentée par :

Christian Berenger WANDJI WOUAPI

Direction de thèse :

Andreas RIEL PROFESSEUR DES UNIVERSITES, Grenoble INP - UGA	Directeur de thèse
Helmi BEN REJEB MAITRE DE CONFERENCES, Grenoble INP - UGA	Co-encadrant de thèse

Rapporteurs :

Tomohiko SAKAO
FULL PROFESSOR, Linköpings Universitet
Dominique MILLET
PROFESSEUR DES UNIVERSITES, Université de Toulon

Thèse soutenue publiquement le **1 décembre 2025**, devant le jury composé de :

Pierre DAVID, PROFESSEUR DES UNIVERSITES, Grenoble INP - UGA	Président
Andreas RIEL, PROFESSEUR DES UNIVERSITES, Grenoble INP - UGA	Directeur de thèse
Tomohiko SAKAO, FULL PROFESSOR, Linköpings Universitet	Rapporteur
Dominique MILLET, PROFESSEUR DES UNIVERSITES, Université de Toulon	Rapporteur
François CLUZEL, MAITRE DE CONFERENCES, Université Paris-Saclay	Examinateur
Thècle ALIX, MAITRESSE DE CONFERENCES, ENSAM CER Bordeaux-Talence	Examinatrice

Invités :

Helmi BEN REJEB
MAITRE DE CONFERENCES, Université Grenoble Alpes
Florent PITIS
EUROPE BUSINESS PROCUREMENT MANAGER, Schneider Electric

DEDICATION

I dedicate this thesis to my family, whose constant encouragement, patience, and unconditional support made this work possible, and to all those who believe that research can contribute to a more circular, sustainable and responsible world.

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ABSTRACT

The world is facing a major systemic challenge: climate change. Six out of the nine planetary boundaries have now been exceeded, largely due to human activities. Among these, industry plays a central role, accounting for more than 58% of global emissions, with 34% directly linked to energy. In response, public policies are mobilizing, notably through the European objective of carbon neutrality by 2050 and the deployment of an action plan for the circular economy, one of the pillars of the Green Deal. Both the scientific literature and regulatory frameworks converge on this point: circularity constitutes a key lever for decarbonization.

These initiatives have driven industries, as producers, in the right direction, integrating the environmental dimension into their business strategies. For instance, more than 23,000 companies now disclose their greenhouse gas emissions through platforms such as CDP or EPD. According to an ADEME report, 30% of large European firms have committed to implementing an eco-design approach to achieve carbon neutrality by 2050. Beyond their impact on producers, these policies also influence consumers, notably through the repairability index, with which 47% of French citizens identify (ADEME, 2022).

However, scaling up a circular economy remains hindered by technical, economic, and organizational uncertainties, most of which are internal to companies. Even though 30% of large European firms are committed to carbon neutrality, 70% still struggle to make progress, due to the lack of operational strategies, appropriate skills, or concrete demonstrations of success. Consequently, this scaling-up revolves around three major challenges widely discussed in the literature: first, deciding “when to take back” a product at end of use; second, determining “what to do with it”, i.e., which “R-strategy” to apply reuse, repair, refurbish, remanufacture, or recycle; and finally, “how to organize” to manage the transition while balancing environmental performance and economic viability.

These challenges condition the transition from a linear to a circular model. To address them, this PhD research proposes a methodology of decision-aid for leveraging the transition towards circular economy. This methodology is based on four complementary methods that represent the contributions of the thesis. A fundamental aspect of this approach is that it focuses primarily on existing industrial products (those already designed and in use on the market). This pragmatic orientation aims to demonstrate to industrial stakeholders the operational, environmental, and economic value of circular strategies applied to assets already in service. By revealing this potential within existing systems, the methodology creates the foundation for a major next step: the design of new products optimized for circularity.

The first contribution is a decision-aid method to optimally determine when to take back a product and what to do with it. It combines a decision tree based on the product’s State of Health (SoH), a parametric analysis of environmental impacts, and a parametric analysis of costs for the various “R-strategies.” Since this method depends on the SoH, we developed a generic framework for SoH assessment applicable to diverse product families. This framework, together with a standard definition of SoH in a circular context, forms the second contribution of the thesis. Given the complexity of implementing SoH assessment in industry and the need to improve product design, we introduced a third contribution, which is a user-centered method for evaluating the repairability index. It provides designers with an actionable indicator (available as early as the design phase and sensitive to product use) to facilitate the creation of more repairable products and enhance circularity. To achieve both economic and environmental performance, it is essential to reorganize the industrial ecosystem. Therefore, the fourth contribution consists of a morphological box that facilitates the replicability of circular business models (e.g., subscription, pay-per-use, component-as-a-service).

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These contributions were tested on representative cases with three industrial partners. For the power air circuit breaker (industrial partner 1), the first contribution recommends recovery after 9–10 years and targeted remanufacturing. The results show a 5% reduction in CO_2 emissions (depending on usage), a 1% decrease in total costs, and a 22% increase in profit compared to the linear scenario. The third contribution was applied in academic workshops (domestic circuit breaker, kettle, coffee machine, power converters) and in an industrial context with the industrial partner 2, on a heat-sealing machine. It revealed design and operational levers to extend product lifetime. The fourth contribution, concerning transferability, was tested with the industrial partner 3 to extend a pay-per-use model from the “air” to the “water” department.

The scope of these results comes with limitations that open concrete perspectives. These include calibrating thresholds by asset typology and industrializing SoH measurement from the second contribution (via sensors, digital twins, or product passports) to improve the reliability of life-extension decisions. Further research should explore the integration of market acceptance and social life cycle assessment into the first contribution, to better balance perceived circular value between producers and users. Regarding the fourth contribution, future work will focus on the detailed design of value chains for use-oriented and result-oriented business models (subscription, pay-per-use), and on developing integrated decision-support tools capable of simulating the socio-economic and environmental performance of Product-as-a-Service (PaaS) models. Finally, an ambitious perspective lies in integrating all four contributions into a comprehensive decision-aid framework enabling both qualitative and quantitative assessment of the economic, social, and environmental performance of circular business models.

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RESUME

Le monde fait face à un défi systémique majeur : le dérèglement climatique. Six des neuf limites planétaires sont désormais dépassées, en grande partie du fait des activités humaines. Parmi celles-ci, l'industrie occupe une place centrale, représentant plus de 58 % des émissions mondiales, dont 34 % sont directement liées à l'énergie. En réponse, les politiques publiques se mobilisent, avec notamment l'objectif européen de neutralité carbone à l'horizon 2050 et le déploiement d'un plan d'action pour l'économie circulaire, l'un des piliers du Green Deal. La littérature scientifique comme les textes réglementaires convergent : la circularité constitue un levier essentiel de décarbonation.

Ces actions ont drivé les industries, en tant que producteur, dans la bonne direction, celle d'intégrer la composante environnement dans leurs stratégies business. A titre d'exemple, plus de 23 000 entreprises déclarent désormais leurs émissions de gaz à effet de serre via des plateformes telles que CDP ou EPD. Selon un rapport de l'ADEME, 30 % des grandes entreprises européennes se sont engagées à définir une démarche d'écoconception pour atteindre la neutralité carbone d'ici 2050. Au-delà de leur impact sur les producteurs, ces politiques influencent également les consommateurs, notamment grâce à l'indice de réparabilité auquel 47 % des Français déclarent s'identifier (ADEME, 2022).

Toutefois, la mise à l'échelle d'une économie circulaire demeure entravée par des incertitudes techniques, économiques et organisationnelles, pour la plupart internes aux entreprises. Car même si 30 % des grandes entreprises européennes sont engagées pour la neutralité carbone, 70 % peinent encore à progresser, faute de stratégies opérationnelles, de compétences adaptées ou de démonstrations concrètes de réussite. Ainsi, cette mise à l'échelle s'articule autour de trois verrous largement soulignés dans la littérature scientifique : d'abord, décider « quand récupérer » un produit en fin d'usage ; ensuite « quoi en faire », c'est-à-dire quelle stratégie-R appliquer : réutiliser, réparer, reconditionner, remanufacturer ou recycler ; enfin « comment s'organiser » pour piloter la transition et combiner performance environnementale et viabilité économique.

Ces verrous conditionnent le passage d'un modèle linéaire à un modèle circulaire. Pour y répondre, cette thèse propose une méthodologie d'aide à la décision pour faciliter la transition vers l'économie circulaire. Cette méthodologie repose sur quatre principales méthodes complémentaires qui constituent les apports de la thèse. Un point fondamental de l'approche est qu'elle se concentre prioritairement sur les produits existants (déjà conçus et en utilisation sur le marché) des industriels. Cette orientation pragmatique vise à démontrer aux industriels la valeur opérationnelle, environnementale et économique des stratégies circulaires sur les actifs déjà en service. En révélant ce potentiel sur l'existant, cette méthodologie crée les conditions d'une étape majeure : la conception de nouveaux produits optimisés pour la circularité.

Le premier apport est une méthode d'aide à la décision pour déterminer de façon optimale « quand récupérer » un produit, et « quoi en faire ». Elle combine un arbre de décision fondé sur l'état du produit (son SoH), une analyse paramétrique des impacts et une analyse paramétrique des coûts des différentes stratégies « R ». Cette méthode étant dépendante du SoH, nous avons formalisé un cadre générique d'évaluation du SoH pour des familles de produits variées. Ce cadre générique accompagné d'une définition standard du SoH dans le contexte circulaire constitue le deuxième apport de la thèse. Du fait de la complexité d'implémentation du SoH en industrie et dans une démarche d'amélioration de la conception des produits, nous avons introduit un troisième apport, qui est une méthode centrée usagers d'évaluation de l'indice de réparabilité. Elle fournit aux concepteurs un indicateur actionnable dès la conception et sensible à l'usage, facilitant la conception de produits plus aisément réparables pour une meilleure circularité. Pour atteindre une bonne performance économique et environnementale, il est primordial de réorganiser son écosystème. C'est ainsi que nous avons

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proposé, en quatrième apport, une boîte morphologique pour faciliter la réplicabilité de modèles d'affaires circulaires (abonnement, pay-per-use, component-as-a-service).

Ces apports de la thèse ont été testés sur des cas représentatifs avec trois industriels partenaires. Sur le disjoncteur de puissance (partenaire industriel 1), l'apport 1 recommande une reprise après 9–10 ans et un remanufacturing ciblé. Les résultats indiquent −5 % d'émissions de CO_2 selon l'usage, −1 % de coûts totaux et +22 % de profit par rapport au scénario linéaire. L'apport 3 a été appliqué en ateliers académiques (disjoncteur domestique, bouilloire, cafetière, convertisseurs de puissance) et en contexte industriel sur une machine de thermoscellage du partenaire industriel 2. Il met en évidence des leviers de conception et d'exploitation pour allonger la durée de vie. L'apport 4 sur le dispositif de transférabilité a été expérimenté avec le partenaire industriel 3 pour étendre un modèle de paiement à l'usage du département air au département eau.

La portée de ces résultats s'accompagne de limites qui ouvrent des perspectives concrètes. Il s'agit notamment de calibrer les seuils par typologie d'actifs et d'industrialiser la mesure du SoH dans l'apport 2 (capteurs, jumeaux numériques, passeport numérique de produit) afin de fiabiliser les décisions d'allongement de vie. Des perspectives d'évolution portent également sur l'intégration de l'acceptation du marché et de l'analyse du cycle de vie social dans l'apport 1, afin d'équilibrer la valeur de circularité perçue entre producteurs et utilisateurs. Pour l'apport 4, il s'agira d'explorer la conception détaillée de chaînes de valeur pour les modèles orientés usage et résultat (abonnement, pay-per-use), ainsi que le développement d'outils intégrés d'aide à la décision capables de simuler la performance socio-économique et environnementale des modèles PaaS. Enfin, une perspective ambitieuse consiste à intégrer l'ensemble des apports dans un modèle complet d'aide à la décision permettant une évaluation qualitative et quantitative de la performance économique, sociale et environnementale des modèles d'affaires circulaires.

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1. Introduction: General framework

1.1. Environmental challenges

To understand today's environmental challenges, it is important to consider the origins of human motivation. According to Abraham Maslow's hierarchy of needs, human motivations are arranged into five sequential levels. Fulfilling basic requirements such as air, water, food, shelter, and sleep (physiological needs) enables the pursuit of higher-order goals [1]. Once these survival needs are met, individuals seek safety, which is characterized by protection from harm, financial security, and stability. Once safety is assured, individuals pursue a sense of belonging by forming social connections and friendships. This social foundation then supports the development of esteem, encompassing self-respect, confidence, and recognition by others. The apex is self-actualization: the realization of personal potential, creativity, and meaningful achievement. As societies progress up this hierarchy, they demand increasingly sophisticated goods and services, such as smartphones, high-tech buildings, and rapid travel around the world. Meeting this demand within a linear economy (take-make-dispose) leads to overexploitation of resources, higher energy consumption, and greater waste production [2]. These pressures manifest as increased pollutant emissions and the overuse of natural resources, which degrade air, water, and soil quality worldwide.

The planetary boundaries framework identifies nine critical Earth system processes, each defined by a quantitative control variable, that delineate a "safe operating space" for humanity [3]. Exceeding these boundaries risks abrupt or irreversible environmental change. These control variables include atmospheric greenhouse gas concentrations and temperature rise (climate change); genetic diversity and species extinction rates (biosphere integrity); nitrogen and phosphorus fluxes (biogeochemical flows); alteration of terrestrial ecosystems (land system change); consumption of freshwater resources (freshwater change); ocean pH reduction (ocean acidification); ozone layer thinning (stratospheric ozone depletion); particulate matter in the atmosphere (atmosphere aerosol loading); and the accumulation of synthetic chemicals and plastics (novel entities) as illustrated in Fig.1.

By 2009, human activities had already transgressed the boundaries of climate change, biosphere integrity, and biogeochemical flows. By 2015, land system change had also fallen outside its safe limit. As of 2023, six of the nine boundaries had been exceeded, and ocean acidification was approaching its threshold rapidly, as shown in Fig. 1 [3]. Humanity is now operating outside the stable conditions of the Holocene. The primary driver of these transgressions is the emission of greenhouse gases (GHGs), which trap infrared radiation and warm the planet in a process known as the greenhouse effect. Key GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and halocarbons (e.g., hydrofluorocarbons and perfluorocarbons). While essential for habitability, their excess accumulation amplifies global warming.

In 2019, the sectoral distribution of global net anthropogenic GHG emissions was as follows: 34% (20 $GtCO_2$-eq) from energy production; 24% (14 $GtCO_2$-eq) from industry; 22% (13 $GtCO_2$-eq) from agriculture, forestry, and other land use (AFOLU); 15% (8.7 $GtCO_2$-eq) from transport; and 6% (3.3 $GtCO_2$-eq) from buildings [2]. Even if all pre-COP26 nationally determined contributions are fully implemented, projected 2030 emissions make it highly likely that warming will exceed 1.5°C this century, complicating efforts to remain below 2°C without further mitigation [2]. The urgency of these converging crises demands immediate and coordinated action. That is why the United Nations have defined 17 Sustainable Development Goals (SDGs), among them goals to tackle climate change by promoting sustainable thinking in design, production, and consumption. Goals 8, 9, and 11 to 17 are all oriented towards tackling environmental challenges, such as climate change, energy consumption, ozone depletion, resource use, water use, biodiversity loss, and land degradation.

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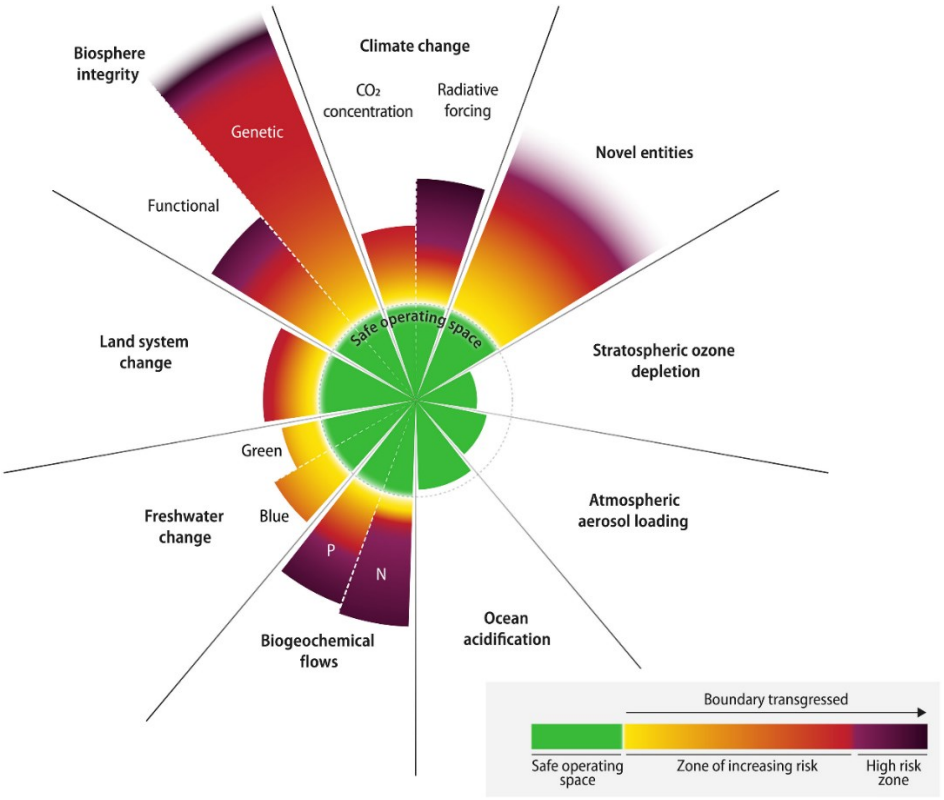

Fig. 1. Current status of control variables for all nine planetary boundaries from [3]

1.2. Actions made to reduce the environmental impacts

To address these planetary risks in contributing to the SDGs, policymakers have introduced a combination of regulatory constraints and market incentives at the international, European, and national levels. The Paris Agreement (2015) commits Parties to limiting global warming to well below 2°C and pursuing efforts towards 1.5°C. The IPCC indicates that reaching the 1.5°C target needs reducing global CO_2 emissions by approximately 45% relative to 2010 levels by 2030, and reaching net-zero emissions around 2050 (IPCC, 2018). Article 6 of the Paris agreement establishes international carbon markets, enabling parties and private entities to trade carbon credits, each of which represents the reduction or removal of one ton of CO_2-equivalent emissions. The rules for transparency and environmental integrity were finalized at COP29 in December 2024 [4].

Alongside this, the Greenhouse Gas Protocol, developed by the World Resources Institute and the World Business Council for Sustainable Development, provides standardized methods for quantifying, reporting, and verifying emissions across three categories (direct operations, purchased energy, and value chain activities) [5]. The ISO 14064 series specifies organizational requirements for greenhouse gas (GHG) inventory design, reporting, and independent verification [6].

Within the European Union, Regulation (EU) 2024/1781, the Ecodesign for Sustainable Products Regulation (ESPR) [7], came into force on 18 July 2024. It requires products to meet minimum durability, reparability, recyclability, and Digital Product Passport (DPP) integration requirements by 2030, thereby facilitating transparency throughout product lifecycles. This regulation is a cornerstone of the European Circular Economy Action Plan (CEAP) [8], which outlines measures related to design, production, and consumption with the goal of keeping materials in use and minimizing waste. The CEAP is one of the main building blocks of the European Green Deal [9], as the 2021 adoption of the EU Climate Law commits to reducing GHG emissions by 55% by 2030 compared to 1990, and achieving

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climate neutrality by 2050. This commitment is reinforced through expansions to the EU Emissions Trading Scheme and the inclusion of transport and buildings. Building on the CEAP under the European Green Deal, the 8th Environment Action Programme (EAP) aims to accelerate the green transition through a regenerative circular economy (CE), which is one of the eight objectives targeted by the EU [10]. Further sector-specific rules, such as the Industrial Emissions Directive IED) [11] and the EU batteries regulations [12], enforce the adoption of the best available techniques and lifecycle assessments to reduce emissions and make material flows more circular. ISO standards 59010, 59020, and 59040 guide systemic business model transitions, performance measurement, and product data transparency to promote CE [13–15].

At the national level, France's Anti-Waste and Circular Economy Law AGEC [16] prohibits the destruction of unsold goods, mandates ecodesign scoring for products, introduces new Extended Producer Responsibility (EPR) schemes to new product categories, and penalizes planned obsolescence, thereby reinforcing circular practices within the household appliance industry. Together, these standards, directives, and regulations create a comprehensive policy ecosystem that constrains unsustainable practices and incentivizes circular business models.

These multi-level actions directly reduce emissions by lowering production demand, improving resource efficiency, and extending product lifespans. By aligning incentives and obligations across the value chain, they aim to encourage governments and companies to adopt sustainable, circular economic models. Despite these efforts, many companies are struggling to transition their activities and business models to sustainable, circular ones due to various barriers.

1.3. Impacts of these actions

The actions taken to address environmental challenges primarily target producers, including both private and public enterprises, as well as consumers, encompassing other businesses and individuals. These actions have started to impact these two actors.

Consumer engagement has evolved through awareness campaigns and an increasing understanding of environmental issues. This is evident, for instance, in the AGEC law on reparability, where a survey conducted by ADEME reveals that 47% of French people in 2022 (compared to 38% in 2021) claim to fully understand what the reparability index means [17]. The AGEC law mandates that OEMs (Original Equipment Manufacturers) of certain products (such as corded and cordless vacuum cleaners, front- and top-loading washing machines, lawnmowers, laptops, smartphones, and televisions) must display their reparability index. This legal requirement, which indirectly raises consumer awareness, has impacted the consumption habits of the French population. Eight out of ten consumers now report considering this index when choosing which products to purchase [18]. This suggests that regulatory frameworks are effective tools for raising awareness and driving consumer mentality change.

In parallel, the commitment of companies to policy-makers' actions has become increasingly evident. The United Nations Global Compact reports that over 20,000 companies have already committed to its sustainability principles [19]. Additionally, more than 23,000 companies now report their greenhouse gas emissions through platforms like CDP or EPD [20,21]. In 2022, according to a KPMG report [22], 96% of the world's 250 largest companies now publish sustainability or ESG reports. This suggests that most large companies are committed, while many small listed companies are not yet. In Europe, according to ADEME's report [23], 30% of large European companies have committed to defining an ecodesign approach for achieving carbon neutrality by 2050, as part of the climate law. Furthermore, according to the PwC survey report in 2022 [24], over two-thirds of the 300 European companies surveyed have already allocated capital to sustainable projects such as decarbonization and

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the circular economy. 70% of organizations have explored ways to refurbish or reuse products with a limited lifespan or predictable obsolescence, signaling their intention to take action. In summary, the share of the global economy covered by scientific and verified climate commitments of companies has risen sharply in recent years. Companies have implemented the polices makers' actions by using the Life Cycle Assessment (LCA) method to assess their emissions, the concept of Circular Economy (CE) as an ecodesign approach to reduce their emissions and make their business sustainable.

The concept of CE is defined by the Ellen MacArthur Foundation [25] as "*a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. The circular economy tackles climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources*". The CE concept, based on design principles aimed at eliminating waste and pollution, circulating products and materials at their maximum value, and regenerating nature, is illustrated in Fig. 2. According to Konietzko et al. [26], the CE transition may be achieved from a business perspective through the narrow, slow, close, regenerative, and informed business strategies. Narrowing the loop refers to using fewer resources during the product lifecycle [27]. Slowing the loop refers to using resources longer [27]. Closing the loop refers to reusing materials or post-consumer recycling [27]. Regenerating the loop refers to focusing on leaving the environment (and society) in a better state than before [27]. Informing refers to using information technology as a support strategy to enhance CE [26].

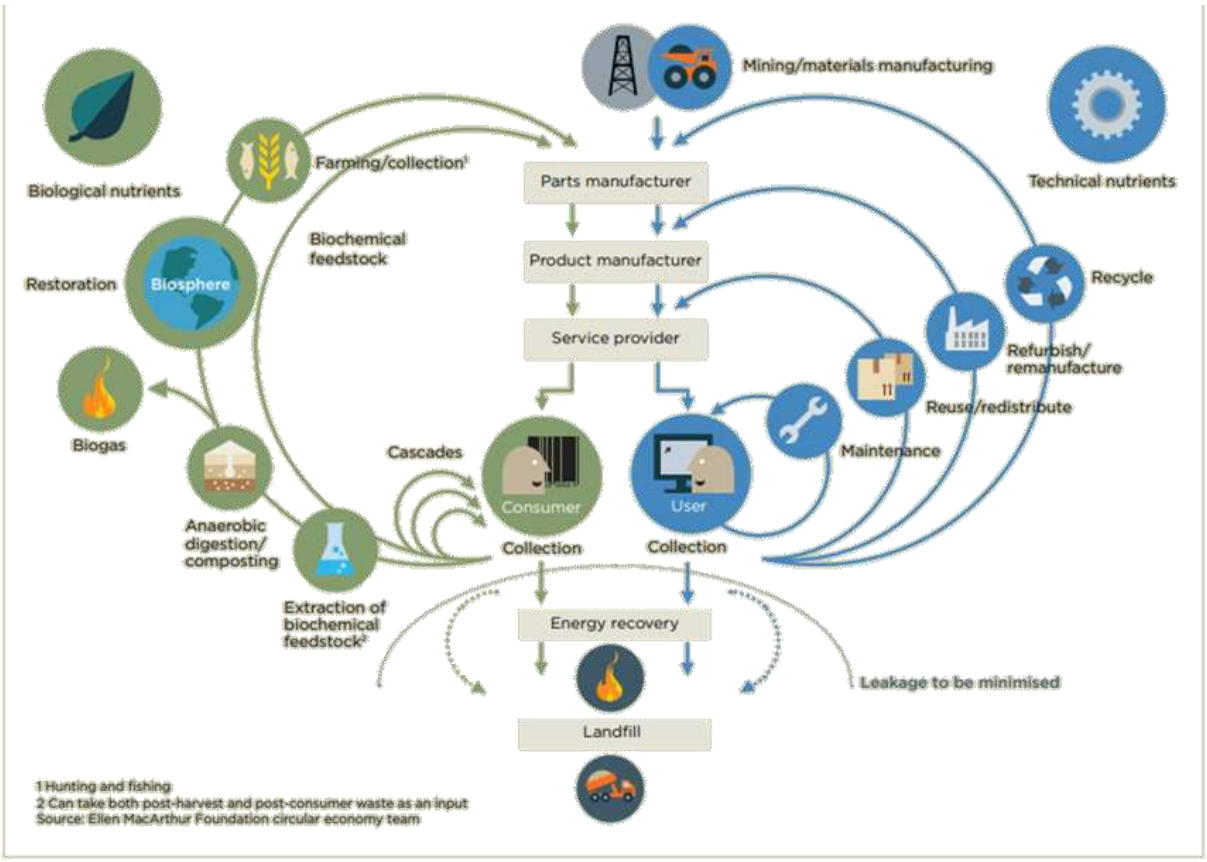

Fig. 2. The Circular Economy concept by Ellen MacArthur Foundation [25]

This progress in the companies' commitments and consumer engagement is a good sign for our planet, but it is still not enough because many companies have not yet taken their commitment, and certain consumers are still not aware. The European Environment Agency's (EEA) latest report on the progress

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towards the 8th EAP objectives - 2024 edition reveals that the regenerative circular economy objectives are likely not on track to meet the targets of significantly decreasing the raw material consumption and the total amount of generated waste indicators by 2030 [28]. This proves that there is a gap between existing legislation on ecodesign and the circular economy, and its implementation and adoption by businesses. This is even confirmed by the 2022 PwC survey report, which mentioned that 60% of organizations admitted to having difficulties on the understanding and implementation of some recommendations from the Green Deal regulations [24]. According to the ADEME report [23], 30% of large European companies have committed to an ecodesign approach to achieve carbon neutrality by 2050. The remaining 70%, including SMEs (small and medium-sized enterprises) and mid-sized companies, have not yet made this commitment.
In conclusion, despite the growing number of commitments, many companies still struggle to integrate sustainability into their core strategies. This can be attributed to the various challenges companies face in transitioning and aligning their business with actions enacted by policy-makers (legislations).

1.4. Barriers to the implementation of the actions enacted by policymakers

The transition to sustainable business through circularity is underway, driven by supportive regulations that encourage and incentivize producers and consumers alike. A circular business model (CBM) describes how a company creates, captures, and delivers value by slowing, closing, narrowing, or regenerating resource loops [29]. While many companies are integrating circular principles into their strategies, others still face considerable challenges. A study by OPEO (operations and organisations consultasing company) and INEC (Institute National de l'Economie Circulaire) found that, although 85% of OEMs view the circular economy as an economic opportunity, only 36% have incorporated it into their strategy [30]. This discrepancy highlights the presence of significant barriers. The CE is not merely an environmental strategy; it represents a paradigm shift in how economic and social systems function. It requires continuous, collaborative relationships between producers and consumers, as well as a rethinking of product design and reconfiguration of value chains. Given the uncertainty inherent in these new configurations, building strong collaborations across the value chain is essential to enabling circularity. This contrasts sharply with the linear economy model, which isolates actors and contributes to organizational inertia.

Numerous European institutions, including CEPS (Centre for European Policy Studies), OPEO, INEC, and Circle Economy, have conducted empirical studies across firms of all sizes to identify the primary barriers to CE adoption. Despite differences in sector or scale, a set of common barriers emerges [30]: fragmented regulation, rigid supply chains, internal organizational limitations, low consumer awareness, inadequate technical capabilities, insufficient financial resources, and profitability doubts. These findings are supported by academic literature, particularly the systematic review by Assmann et al. [31]. This review categorizes 54 key determinants into eight macro areas: culture, regulation, market, strategy, business case, collaboration, operations, and knowledge. These determinants may arise internally, externally, or through their intersection.

External barriers lie beyond the direct control of companies. The political landscape is the most important of these. Although CE-related legislation has evolved, its implementation remains inconsistent. CEPS (2021) case studies highlight the operational challenges resulting from the inconsistent enforcement of directives such as WEEE across EU member states [32]. Similarly, the Extended Producer Responsibility (EPR) schemes vary widely in flexibility and structure, often leading to uncertainty and an additional administrative burden. In some cases, regulations on waste classification or chemical substances conflict with circularity goals, hindering material reuse and component recovery. Market factors also pose challenges. Consumer resistance to change, a lack of

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trust in circular solutions, and a limited understanding of circular value propositions weaken demand. These issues are exacerbated by broader economic constraints, such as low purchasing power and volatile market conditions, which make investing in CE strategies seem riskier. These external barriers are out of the thesis' scope as well as the following intermediate barriers.

Intermediate barriers arise from interactions between companies and their broader ecosystems. Financial uncertainty is a major concern. Many businesses struggle to access funding or justify investments without clear evidence of profitability. Reverse logistics systems, which are essential for take-back or reuse schemes, incur significant costs and may disrupt existing linear revenue streams. This can lead to fears of cannibalization.

A company's organizational culture can further impede CE adoption. Resistance to innovation, prioritization of short-term performance metrics, and a lack of leadership commitment can all weaken internal momentum. Both Assmann et al. and Rizos et al. emphasize that having internal champions and aligning values with sustainability objectives are essential for change [31,33]. Barriers related to managerial dimensions are also outside the scope of this thesis.

Internal barriers stem from a company's strategy, knowledge base, and infrastructure. Many firms lack a coherent CE strategy and the internal competencies needed to develop one. Skills in product lifecycle thinking, circular design, and systems integration are often lacking, particularly among OEMs and consultancies that are new to the CE field. Operationally, adopting CE requires collaboration with external stakeholders, such as suppliers, recyclers, and logistics providers, who may have different capabilities and expectations. A lack of shared standards and data systems worsens this complexity, limiting traceability and material recovery. Transparency remains a significant issue; many companies lack visibility into product usage and end-of-life scenarios, which hinders circular planning. As noticed by researchers and within the CEPS report of their investigations, there is an urgent need for traceability solutions accessible to small and medium-sized enterprises [34–36]. Technology is another bottleneck. Scalable solutions for tracking materials, modular product design, and efficient reverse logistics infrastructure are either unavailable or underdeveloped, especially for SMEs.

A further challenge lies in recognizing that circular processes are not impact-free [37]. Activities such as collection, disassembly, and remanufacturing consume energy and resources, sometimes generating emissions comparable to or greater than linear processes if poorly designed [38]. The rebound effect compounds this problem: efficiency gains or extended product lifetimes may encourage higher consumption, offsetting the expected benefits of circular strategies [39]. As a result, companies face uncertainty not only about how to implement circular models but also about whether these models truly deliver net environmental gains.

Despite these obstacles, barriers can be transformed into enablers with targeted interventions. Regulation illustrates this dual role. As the Circularity Gap Report 2025 highlights, a robust policy environment built on science-based material use targets, regulatory coherence, and strong governmental leadership, is essential [40]. Tools such as enhanced EPR schemes and ecodesign mandates can accelerate innovation and encourage the integration of circularity principles upstream.

Within this frame, the thesis addresses three internal barriers where transformation is both feasible and impactful from an engineering perspective:

- **Operational strategy**: Developing structured, process-driven approaches for circular implementation.
- **Knowledge and competencies**: Closing internal skill gaps through capacity building and training.

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- **Business case**: Demonstrating the technical and financial viability of circular initiatives.

These internal barriers were prioritized because they concern the production system of companies, a field in which the G-SCOP laboratory possesses both background knowledge and proven research expertise. The thesis' objective is to provide companies with methods to design and implement circular strategies within CBMs. The strategic ambition is to equip decision-makers with evidence that circularity can be environmentally beneficial, technically viable, and economically profitable when optimized. The underlying hypothesis is that CBMs generate value primarily through extended product use. Demonstrating the technical feasibility of these models is therefore essential to establishing their financial and environmental performance. This triad of feasibility (technical, socio-economic, and environmental) forms the cornerstone of a successful transition toward sustainable business through circularity.

1.5. Structure of the manuscript

The manuscript begins with this introductory chapter that outlines the environmental challenges humanity faces today, reviews the actions enacted by policymakers to address these challenges, and examines the obstacles companies encounter when trying to implement or consider these actions. The chapter places special emphasis on the primary barrier addressed by this thesis.

The second chapter presents the background and challenges in the circular economy context.

The third chapter situates the thesis's core problem within the broader scientific literature and surveys the solutions that businesses have already adopted.

Chapter four highlights the key gaps related to this core problem and clearly articulates the resulting research questions.

In chapters five, the hypotheses taken are presented as well as the research methodologies adopted to answer the research questions.

Chapter six synthesizes the main contributions of the thesis, drawing together the insights generated through the research.

Chapters seven and eight present respectively the scientific articles in revue and conference articles, with their link to the contributions.

Chapter nine synthesizes the complete methodological framework, showing how the contributions interlock to form a coherent whole. It also critically examines methodological limitations in academic and industrial settings and outlines alternative approaches and targeted improvements as avenues for future work.

Chapter ten presents the general conclusion.

Finally, chapter eleven presents the extended summary in French.

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2. Background and challenges of the circular economy

The concept of ecodesign has evolved over the course of several decades. It began in the 1990s with a focus on reducing pollution during product development [41]. Initially, the goal was to make products more energy efficient and less harmful to the environment. Over time, however, the focus shifted from minimizing impacts at the end of a product's life to improving its entire life cycle [42]. Researchers and policymakers began including ideas such as durability, reparability, and reuse. These changes led to broader goals, such as designing products that can remain in use for longer periods of time and generate less waste [43,44]. In the European Union, this shift is reflected in the new Ecodesign for Sustainable Products Regulation (ESPR), which promotes the goals of the circular economy [45]. Today, ecodesign encompasses more than just products; it is part of a larger effort to create circular systems that reduce resource use and emissions while minimizing waste.

The CE is defined by Kirchherr et al. [46] as: "a regenerative economic system which necessitates a paradigm shift to replace the 'end of life' concept with reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain, with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is enabled by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities."

2.1. Product life cycle in the circular economy

The CE, when combined with life cycle thinking, requires that the entire product life cycle to be considered from the earliest design stages. This approach necessitates a change in mindset: products must be designed not only for functionality and aesthetics, but also for durability, repairability, upgradeability, and end-of-life recovery [7]. Designing for circularity also involves anticipating how the product will be manufactured and used, how the used product will be taken back, which circular process should be used to give a product a second life, and which circular business model, such as product-as-a-service (PaaS) or product-service-system (PSS), will best support prolonged value retention [8,26,32,47]. A central objective of the circular economy is to ensure that products are used and managed effectively and responsibly at their end-of-use (EOU) and end-of-life (EOL) stages [40]. In this study, we choose to separate the EOU phase from the EOL phase to make a clear distinction between processes that aim to retain the value of a product as long as possible from those that destroy that value through recycling, energy recovery, or waste treatment [46,48].

The product life cycle (PLC) encompasses a series of interconnected stages as shown in Fig. 4, each with distinct environmental, economic, and social implications. According to the Product Environmental Footprint (PEF) methodology [49], which the European Commission recommends for Life Cycle Assessment (LCA), the PLC is typically structured as follows:

- **Raw material acquisition stage:** Extraction of resources from nature, including their pre-processing and transportation to production facilities.
- **Manufacturing stage:** Production of components, assembly of the final product, and transportation of intermediate and final goods.
- **Distribution stage:** Delivery of finished goods from the production site to warehouses or retailers for storage and eventual transport to consumers.
- **Use stage:** This involves the installation (if applicable), operation, maintenance (repair), and potential upgrading of the product during its useful life.
- **End-of-use (EOU) stage:** Encompasses circular R-strategies such as reuse, refurbishment, remanufacturing, and repurposing, with the aim of extending the product's value retention.

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- **End-of-life (EOL) stage:** Covers recycling to get recycled raw material and final waste treatment processes, including landfilling, incineration, and potential energy recovery when no further reuse or recycling is viable.

Like linear processes, circular economy processes have advantages and challenges.

2.2. Advantages of Circular Economy

The circular economy can offer businesses a more sustainable way to conduct their activities [30,46,50]. Fig. 3 summarizes some advantages.

- From an environmental perspective, it can reduce the use of virgin raw materials, decreases energy consumption, and minimizes waste and emissions if optimized and well deployed.
- Socially, it creates new employment opportunities, encourages cooperation, promotes the collaborative economy, and strengthens the sense of belonging to a community.
- Economically, it reduces costs related to raw materials, energy, environmental regulations, taxes, and insurance. Additionally, it opens up new markets and attracts potential investors.

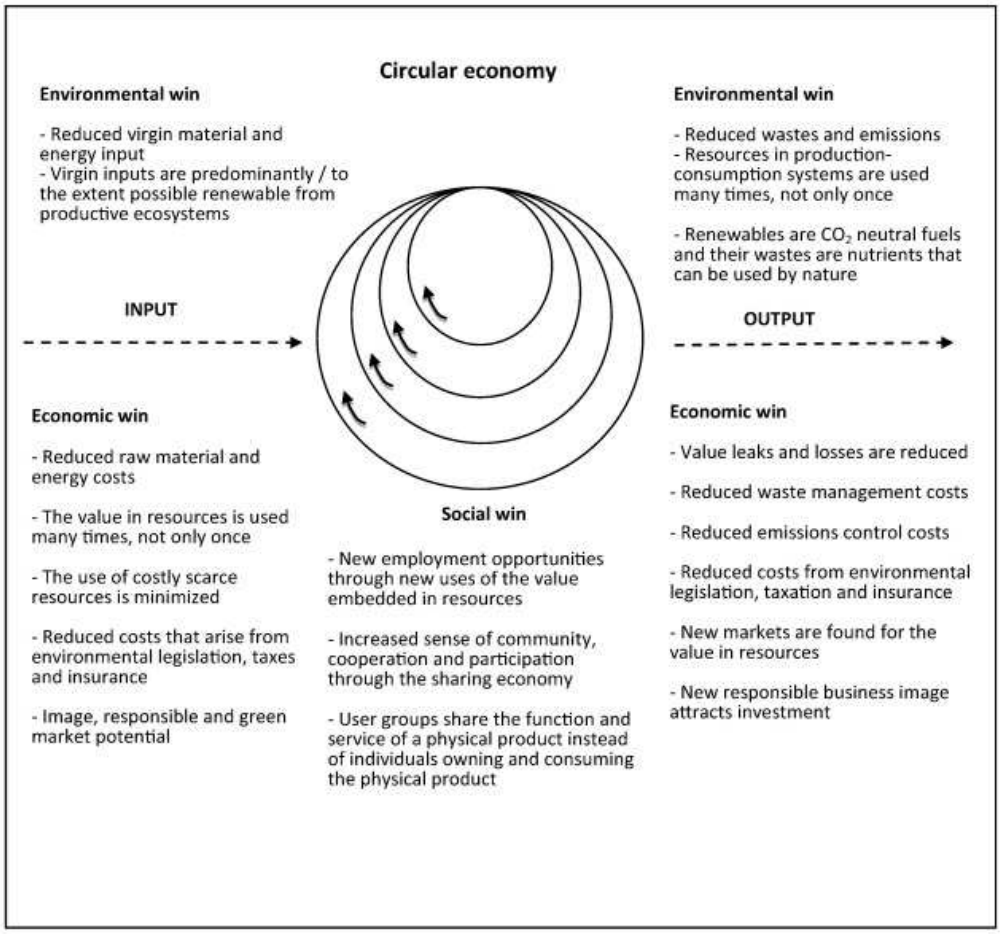

Fig. 3. Summary of circular economy advantages from [50].

2.3. Challenges of Circular Economy

The EOU stage of the PLC is tightly linked to product utilization and has a profound impact on residual value. Researchers emphasize that understanding usage patterns should inform ecodesign team from the beginning, as these early decisions significantly shape subsequent circular performance [51].

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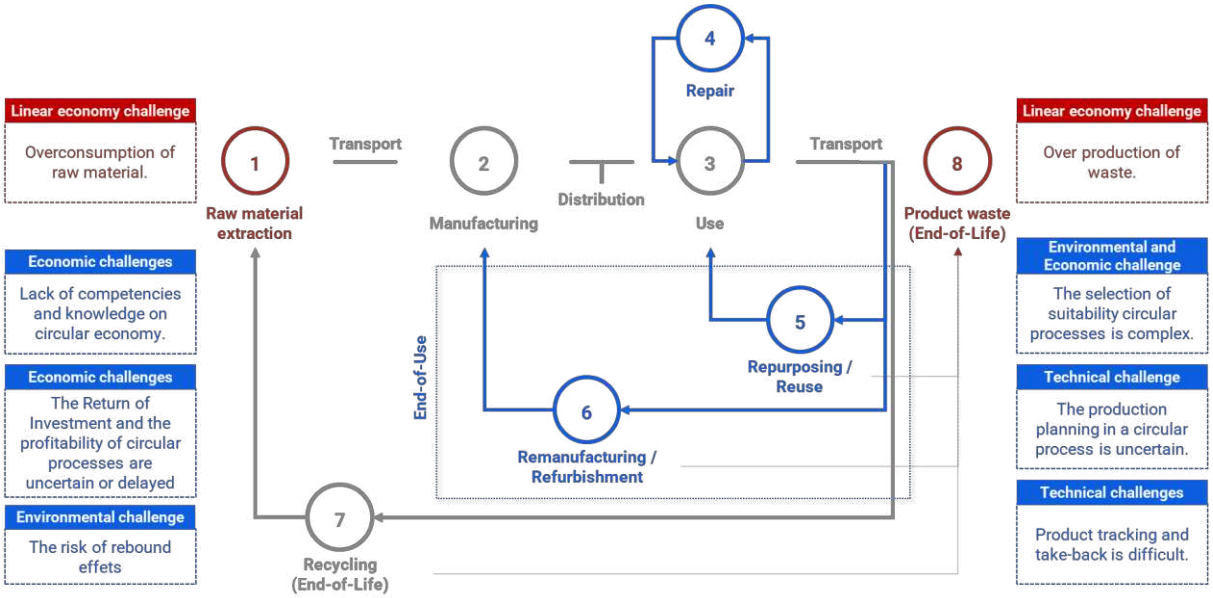

Fig. 4. PLC with technical and economic challenges associated with linear (red) and circular (blue) processes.

This design foresight is even more critical for products already on the market. Many established firms manage large inventories that were never designed with circularity in mind. Their business models remain rooted in linear logic, where value creation relies on selling ownership to consumers. Such models drive excessive consumption of raw materials and generate high levels of waste, as illustrated in the red boxes of Fig. 4. This linear approach has been widely demonstrated to be environmentally and economically unsustainable for companies [29,50]. Converting existing products into circular assets therefore creates significant challenges [30]. Fig. 4 highlights these difficulties by contrasting the problems of the linear economy with those arising in circular value chains. In particular, it illustrates challenges linked to implementing R-strategies for product life extension in blue boxes (reuse, remanufacturing, repair, refurbishment, and repurposing). These challenges include:

- **A major technical barrier** is achieving transparency in usage data, because once ownership of the product is transferred, the OEM loses visibility into product use and cannot accurately assess the state of health (SoH) [52]. This makes implementing circular processes difficult due to the variability in how products should be treated at the end of their life cycle [53]. One reason for this variability is the uncertainty surrounding the timing, quality, and quantity of products at the end of their EoL [54]. This unpredictability results in unreliable control over the circular value chain for OEMs. Therefore, establishing a stable market for second-hand or used products becomes difficult. This uncertainty undermines planning for take-back and circular processes. Moreover, companies often lack the expertise and infrastructure necessary to define and implement appropriate circular strategies for products that are already aging in the market [55].
- **Environmental challenges** arise from the fact that circular economy (CE) processes themselves can generate emissions. If not properly managed, the implementation of an R-strategy may lead to rebound effects, whereby efficiency gains or extended product lifetimes stimulate additional production or consumption that partially offsets the intended environmental benefits [39].
- **Economically**, establishing a circular value chain requires significant initial investments in logistics, facilities, and reprocessing capacity. Uncertainty about the profitability of circular processes contributes to uncertainty about the return on investment, due not only to unstable demand for second-hand products, but also to unreliable control over the circular value chain.

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These factors create doubts among decision-makers when considering shifting to a circular business model, which makes the transition risky, especially when customers are unwilling to pay more [56–58].

- **Socially,** the main challenge to circular economy (CE) implementation lies in prevailing cultural norms and mindsets. Resistance to change, together with entrenched beliefs, often leads to limited acceptance and slow adoption of CE practices [59].

Given these challenges, this thesis proposes a method that holistically incorporates economic, environmental, and technical dimensions to support OEMs in adopting circular approaches. Therefore, understanding SoH and exploring business models that retain OEM ownership is essential to the definition and design of a profitable circular strategy.

2.4. Transition toward circular economy: Systemic approach

Many researchers argue that circular economy adoption requires forging a network of interconnected business models within the value chain to jointly deliver consumer value [26,60,61]. This required thinking about a whole business model in a more sustainable way. This shifts design thinking from isolated products to socio-technical systems, factoring in human, environmental, and economic elements [42]. Business model innovation is key to deeper circularity, as it reframes how value is created and sustained [26]. Transitioning to circularity can be operationalized via five interlinked strategies, such as Narrow, Slow, Close, Regenerate, and Inform, that manage product, component, material, and energy flows [26,62,63]. Takacs et al. have developed a framework categorized into four types of patterns to create a circular ecosystem [60].

- The first pattern, which is “Close the loop,” refers to the R-strategy for product lifespan extension. It occurs during the EOU stage of the PLC. It is closely aligned with the business strategy of slowing the loop for using resources such as products, components, and materials for longer [26,27].
- The second pattern, which is “Improve the loop,” ensures that the objectives of emissions, materials, and waste reduction are met, while reducing the product costs [60]. It also occurs during the EOU stage of the PLC. At this level, the company is looking for the best trade-off between the technical (SoH), economic, and environmental factors.
- The third pattern is “Monetize the loop”. It consists of defining an innovative revenue model to value a circular product that comes from the closed-loop system. It helps to identify innovative ways to capitalize on and capture the value from circular solutions [60]. This business model-related pattern is included in any of the business strategies from Konietzko et al. [26,63].
- The fourth pattern is “Excite the loop”. This pattern is focused on inspired interaction with consumers, empowering and creating awareness for circular change, which should result in long-term relationships and improved customer loyalty. It is the consideration of the social factor within the circular business model.

In this thesis, the investigation of the literature has been ordered following the 4 patterns: starting with the definition and the improvement of circular strategy focused on the product (the first two patterns), then examine circular economic models at the company level that leverage the circularity of products by monetizing them (the third pattern). The social factor has not been considered in the thesis (the fourth pattern). The strategy is described as a bottom-up approach in the thesis, as it begins at the product level and evolves to the company level.

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3. Positioning of the thesis in relation to the literature

Business activities transitioning towards sustainable practices are increasingly supported by ecodesign and CE policies and regulations. Yet, despite strong commitments from both producers and consumers, firms still face significant barriers when adopting such measures. This thesis specifically addresses **internal barriers** within companies relating to defining a **circular strategy** for an **existing product**, selecting the **most appropriate circular economic model** for a company, and equiping engineers and top managers with the **knowledge required to operationalize CE principles**.

This chapter positions our research within the broader scientific landscape. Fig. 5 illustrates the scope of the thesis across five interconnected research areas. The figure is derived from a keyword mapping of relevant articles identified through the systematic literature reviews conducted for the research questions of the thesis (*See chapter 5*). A RIS file containing these articles was created and analyzed using the VOSviewer software. Since VOSviewer is case-sensitive, a standardized thesaurus file was developed to harmonize variations in keywords. For example, terms such as “state of health”, “State-of-health”, “health status”, “SoH”, and “SOH” were consolidated into the single keyword “SoH”. After setting the minimum threshold of 14 occurrences for keywords to form a cluster, five clusters emerged, as shown in Fig. 5. In the visualization, the size of each circle represents the frequency of the keyword across the corpus, while the thickness of the connections between circles reflects the number of articles in which the two keywords co-occur.

In Fig. 5, the central area (*yellow*) focuses on circular economy, including PSS archetypes such as leasing, renting, and pay-per-use, as well as R-strategies like remanufacturing, reuse, and recycling for product life extension. This area is linked to surrounding domains. The green cluster represents research on decision-making in the circular context and on ecodesign strategies (e.g., design for repair, design for recycling, design for remanufacturing). The blue cluster encompasses LCA and life cycle costing (LCC), which support both ecodesign and decision-making. The purple cluster gathers performance indicators such as reusability, repairability, remanufacturability, and recyclability to facilitate circular strategy management. Finally, the red cluster focuses on optimization methods and

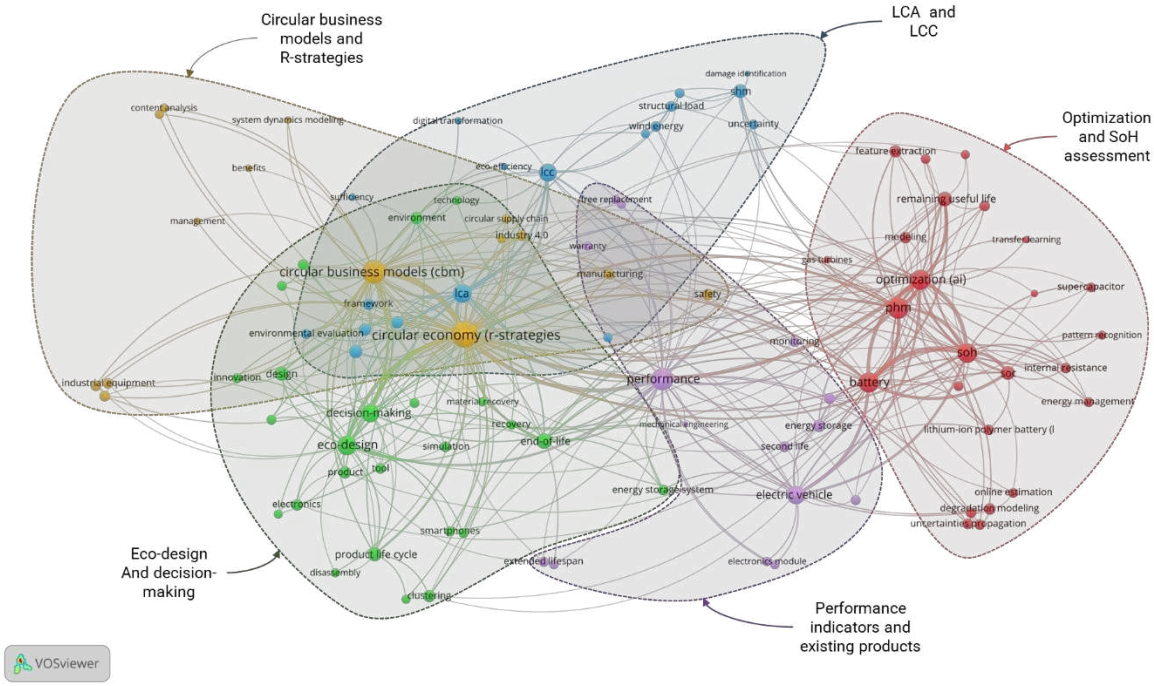

Fig. 5. Position of the thesis within the scientific literature.

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SoH assessment in circular contexts, which has been most extensively explored in the field of batteries for electric vehicle.

Within this scientific landscape, our research seeks to support the transition of companies toward a CE. It does so by addressing four key aspects: closing product loops through circular R-strategies; optimizing these loops using LCA, LCC, and product's SoH assessment methods; monetizing loops through CBM; and aligning them with ecodesign to strengthen the overall corporate strategy. Regarding the CBM, a specific focus is placed on transitions enabled by replicating PaaS models that have already proven successful in other organizations. The engineering approach adopted here begins at the product level, where loops are closed and improved along the value chain. It then progresses toward the monetization of these improved loops. The following sections of this chapter examine each of these dimensions in detail.

3.1. Close the loop: The CE strategies

According to Morseletto, CE strategies align with three primary targets across 10 R-strategies [64]. The Fig. 6 summarizes the mapping of 10 R-strategies and their targets.

- The first target group aims to design and manufacture a smarter product use. The Refuse (R0), Rethink (R1), and Reduce (R2) strategies are defined. The first three R-strategies occur before the others; therefore, they favor extended product lifetime as well as reduce material consumption and waste. This target group directly occurs at the companies to the management's cultural vision to facilitate their transition towards sustainability.
- The second target is closed-loop based, aiming to extend the product lifespan. In this target, the following R-strategies are defined: Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), and Repurpose (R7). These R-strategies are designed during the Design for X stage and put in place at the EOU stage. They aim to retain the product value for as long as possible for several lifecycles. In these R-strategies, the value (SOH) of the product plays a very important role.
- The third group of target aims at the promotion of useful application of materials. The R-strategies encompass Recovery (R9) and Recycling (R10). The goal is to reduce as much as possible the raw material consumption and the amount of product waste. These R-strategies are also integrated during the Design for X stage and take place at the EOL stage of the product lifespan. The value of the product is not very important at this stage.

The most implemented R-strategies are those of the third target group, recycling and recovery, because most of the current products are design and manufactured considering that way they will be recycled [65]. The companies do not have to rethink the design and the manufacturing system of their product, which is risky, and even more so for large companies. However, implementing the R-strategies of the second target group, which aims to extend the product lifespan, requires rethinking the system. The R3 to R7 strategies highly depend on the product's value. This brings uncertainties surrounding the take-back time, quality, and quantity of products at their EOU stage, making their implementation difficult [54]. Then, their adoption by companies is complicated.

These uncertainties have been addressed in the literature by researchers who have proposed optimization solutions to address the issue of uncertainties (*Red cluster in Fig. 5*). Their proposed solutions are based on the concept of an "active and proactive" R-strategy, meaning that they propose taking back a product from its use phase at a point of time at which the application of one specific, previously selected R-process is most beneficial from either an economical or ecological perspective. They differ in the consideration of socio-economic and environmental factors in their optimization

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solutions from both the producer and consumer points of view. The ISO 14044 LCA method is either used or not used to consider environmental factors as well as the LCC method to consider the economic factors.

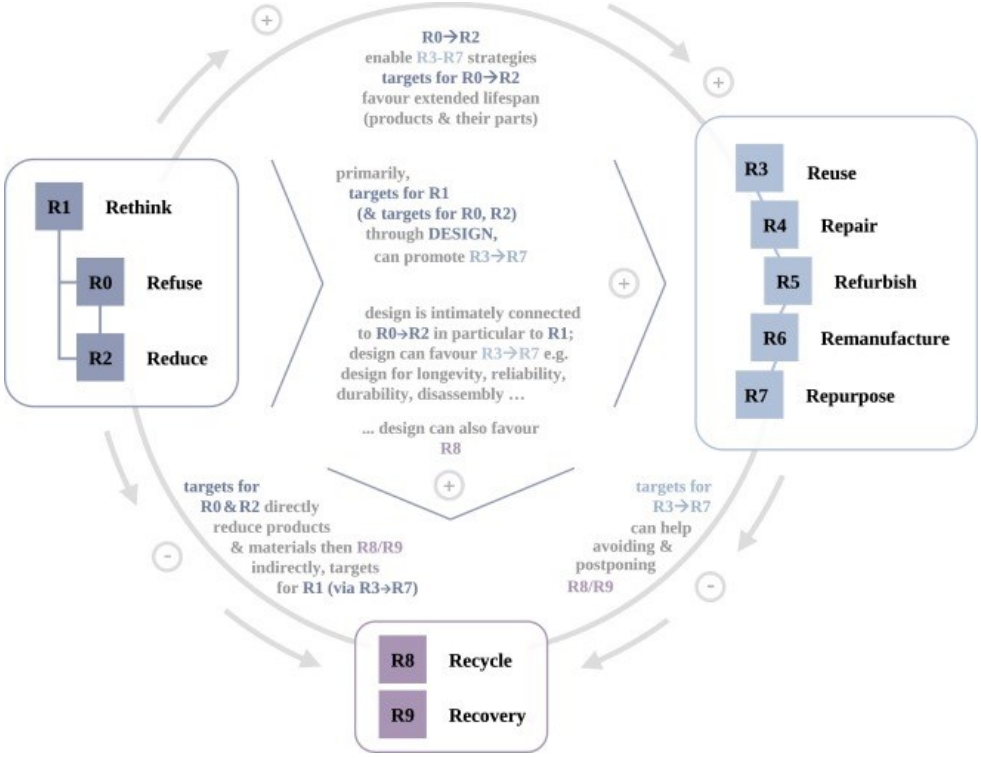

Fig. 6. Mapping of 10 R-strategies and their targets (source: [64]).

Some existing solutions tackle the complexities of planning circular activities, which are often complicated by the uncertainties regarding the quantity of used products as well as the unpredictability of their quality (SoH) [65–67].

Other existing solutions are tailored to enhance the remanufacturing strategy for specific product components by introducing the concepts of active and proactive remanufacturing, to manage the uncertainties related to the timing (take-back time) and quality (SoH) of used products (*connection between yellow and red clusters in Fig. 5*). They incorporate economic, environmental, technical, and social factors, as well as customer perspectives and acceptance, into an optimal timing model for active and proactive remanufacturing. This is the case of Wang et al., who define the product's remanufacturability [68]. This approach is fostered by several researchers, such as Liu et al., who looked at active remanufacturing to determine the optimal time to remanufacture a product component based on its SoH [69]. Song et al., who addressed the proactive remanufacturing, also considered only the structural strength as a SoH factor [70]. Furthermore, Zhou et al. added the economic factor in addition to the technical one to their method for assessing the remanufacturability of a product component [71]. Liu et al., Ke et al., and Ouyang et al. also proposed models to determine an optimal planning for active remanufacturing from an environmental perspective in addition to the technical one [72–74]. Several other existing methods with economic and environmental perspectives were proposed [75–78]. Specifically, Zhang et al. proposed a method for improving the remanufacturing capability of a boom cylinder on a pump truck by determining its optimal take-back time [79]. This, along with the technical (SoH), environmental, and economic perspectives. Gao et al. proposed another optimal timing model from the perspective of company profit in addition to the previous ones [80].

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Table 1. Summary of the existing methods on the take-back time approach for circularity improvement.

Closed-loop processes	Product use case	Ref	LCA[1]	Profit	User satisfaction	LCC[2]	Cost customer perspective	SoH[3]	Applications	Optimization model	Tool implementation	Product-oriented BM	Service-oriented BM
(Pro) active Circular economy	No product	[81]		X		X				X	X	X	
	LiB-EV	[82]	X*			X		X	X		X	X	
	Notebook computer	[83]					X	X		X		X	
	Bearing of a truck	[84]						X				X	
(Pro) active Remanufacturing	Machine tool CA6180	[85]	X*		X	X				X		X	
	Used engines	[76]	X*			X				X		X	
	Used engine	[74]	X*					X		X		X	
	Boom cylinder of a pump truck	[79]	X			X		X		X		X	
	Used engine blades	[75]	X*			X		X		X		X	
	Six-cylinder diesel engine	[77]	X			X				X		X	
	Excavator	[78]				X		X		X			X
	Crankshaft	[72]	X					X		X		X	
	Connecting rod	[80]	X	X		X		X		X		X	
	Diesel engine	[73]	X*			X		X		X		X	
	Crankshaft of an engine	[70]						X		X		X	
	Crankshaft of a six-cylinder engine	[71]		X				X		X		X	
(Pro) active Reuse & second-hand	EEE (washing machines, refrigerators, televisions, computers, and smartphones)	[86]	X		X		X					X	
	Second-hand mobile phones	[87]				X				X		X	
	No product	[88]				X		X		X		X	
	Second-hand electric drills	[89]		X		X		X		X		X	

[1] LCA (Life Cycle Assessment) refers to the assessment of the environmental impact as a factor in the optimization model of the existing solution

* Refer to an LCA application using a method other than that specified in standard NF EN ISO 14044.

[2] LCC (Life Cycle Cost) refers to the assessment of the company cost as a factor in the optimization model of the existing solution

[3] SoH (State of Health) refers to a health indicator considered as a factor in the optimization model of the existing solution

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Very few authors, such as Zhang et al. take into account the social factor, which is the customer perception and its acceptance of the CE [85]. Moreover, very few researchers propose an optimal timing model for the reuse process [86]. The concept of active and proactive reuse is primarily applied in software engineering through the reuse of coding blocks, with a limited focus on hardware [88,90,91]. The few hardware-related studies do not consider together environmental, economic, or technical aspects in their proposals [87,89]. Additionally, optimal models for enhancing other circular strategies, like refurbishment, reuse, and recycling [92] fail to address the critical aspect of optimal product take-back time, highlighting a significant gap.

Finally, there are limited research on active and proactive methods that integrate multiple circular processes into a comprehensive circular strategy for the product. However, the available studies are valuable as they propose decision-support models and frameworks for determining the optimal take-back time for remanufacturing, reuse, and recycling together [81–84]. Especially, Takata et al. developed a tool to model and evaluate circular scenarios by simulating environmental impact, profit, customer willingness-to-pay, and the SoH of lithium-ion batteries (LiB) for various applications, such as electric vehicles and solar panels [82]. These existing solutions effectively incorporate technical, environmental, and economic factors, considering both manufacturer and customer perspectives [83].

In conclusion, existing methods for determining optimal take-back times advance circularity by combining technical condition (SoH) with economic, environmental, and sometimes social criteria. However, important limits remain, most approaches are product-specific, assume a narrow use context, and with little sensitivity to diverse applications or operating environments. True multi-criteria formulations that optimize technical performance across closed-loop pathways are rare. Critically, nearly all frameworks optimize one circular strategy for one component at a time, overlooking that different components of the same product may warrant different strategies. Such a single-strategy approach is useful for firms that already operate a circular strategy and seek incremental improvement. They are far less helpful for firms still selecting the appropriate circular strategies for a given existing product. A summary of related methods is presented in Table 1.

3.2. Improve the loop: State of health (SoH) assessment methods

In view of the existing methods for improving R-strategies, SoH appears to be a key factor in the proposed models. SoH generally refers to the condition or well-being of a system, whether it be a human patient, a machine, or a product, relatively to an ideal or initial state. This concept has been adopted across disciplines. In medicine, SoH is treated as an individual or population health status, increasingly framed as adaptive capacity and quantified via validated instruments [93,94]. In engineering and maintenance, SoH denotes degradation/condition relatively to “as-new,” driving maintenance planning decisions [95,96]. In the CE, SoH is an operational criterion to steer products toward R-strategies (repair, refurbish, remanufacture, reuse, repurpose, or recycle), with batteries a leading case [97,98]. However, the interpretation and assessment of SoH can vary significantly between fields. The research on SoH has exponentially increased in the field of engineering since 2010 due to the assessment of the SoH in LiB (Lithium-ion Batteries). The Fig. 7 shows the number of papers published in the field of medicine/public health, engineering (including maintenance), and other fields such as nature, food, health economics, sociology, political, theology, demography, and finance.

The literature deals extensively with battery SoH assessment in many fields (*Red cluster in Fig. 5*), such as electric vehicles [99] and photovoltaics [100]. But very few articles have addressed other types of products, such as gearboxes, scooters, washing machines, etc. On the other hand, this notion is mainly used in maintenance to predict the remaining useful life of batteries and a few other products, such as

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wind turbines [101], bearings [102], gearboxes [103], etc. However, the use of this notion to foster circularity has received very little attention.

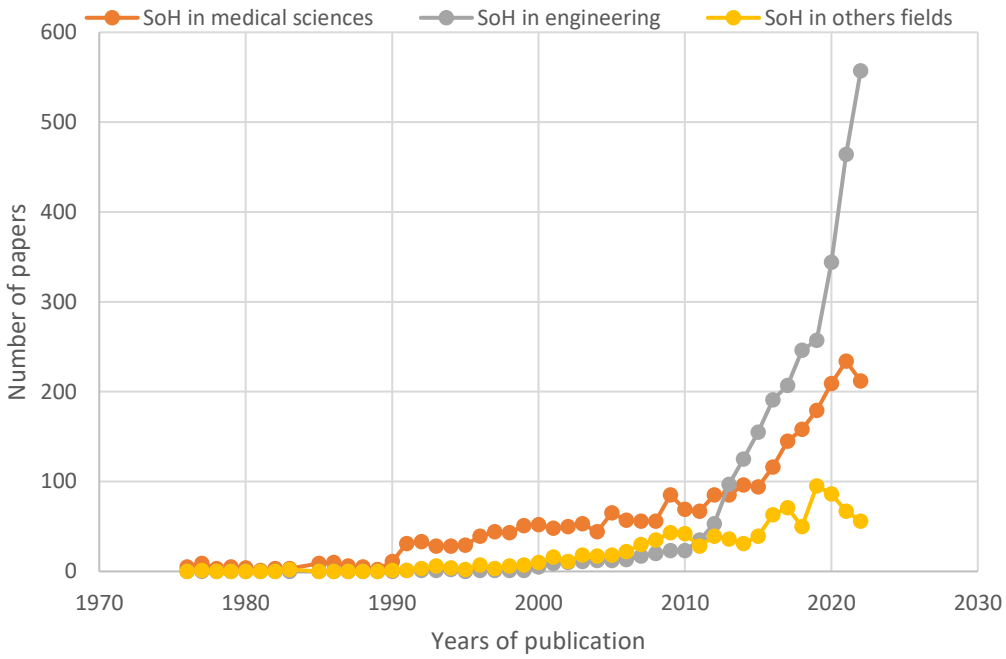

Fig. 7. Evolution of the SoH concept in the scientific literature from 1976 to 2022

3.2.1. SoH in medicine and public health

The notion of SoH was widely used in the field of medical sciences, which frequently use the general state of health [104], health values [105], health status measurement [106,107], self-rated health [108–110] and sometimes well-being [104,111], quality of life, and health-related quality of life [112] to refer to the state of health of the human body.

The World Health Organization (WHO) has historically defined health as a broad state of complete physical, mental and social well-being, rather than merely the absence of disease or infirmity [113]. Contemporary scholarship emphasizes health as dynamic adaptability, arguing that SoH should reflect the capacity to function and self-manage in the presence of challenges rather than an unattainable notion of "complete well-being." [114–116] This adaptive view is consistent with the way health status and Health-related quality of life (HRQoL) are measured, using both subjective and objective indicators, as well as patient-reported outcomes. These range from mortality/morbidity statistics to validated instruments, and acknowledge the multidimensionality of physical, psychological, and social domains [93,106,107,110,117].

At the individual level, self-rated/self-assessed health (SRH/SAH) uses a single 5-point item to predict morbidity and mortality. At the population level, this is summarized as the proportion reporting good or very good health, providing a robust and comparable proxy for SoH [106,107,110,118,119]. Multi-domain tools such as the Sickness Impact Profile (SIP) and SF-36 quantify health status as scores or % dysfunction. SIP is expressed as a percentage (higher = worse), while the SF-36 transforms the domains into a score between 0 and 100 [93,117]. Recent work re-centers SoH on reserves and resilience — the capacity to maintain/restore physical, socio-emotional, cognitive, and physiological reserves — thereby aligning measurement with function and adaptation rather than the absence of disease [116].

It is important to note that an individual's SoH can vary depending on factors such as age, gender, nutritional status, level of physical activity, exposure to environmental factors, and socioeconomic

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status. These factors are health indicators used in practical assessments to estimate an individual's SoH.

3.2.2. SoH in engineering fields

Since 2012, this notion of SoH has been the most widely used in the engineering field, and this trend continues to grow (*Red cluster in Fig. 5*). This considerable increase in the use of the notion of SoH in the engineering field is due to the chemical field, with batteries accounting for up to 95% of the total. In the engineering field, the notion of SoH also has different names, such as the state of health [98], the state of ageing [95,120,121], the ageing rate [122], and the Remaining Useful Life (RUL) [123,124].

In engineered assets, SoH denotes the level of degradation relative to an “as-new” reference and is fundamental to condition-based/predictive maintenance and Prognostics and Health Management (PHM) [96,125]. Reliability models quantify risk and inform thresholds — for example, Weibull reliability with hazard — while practical deployments use composite health indices (H) to fuse normalized indicators for decision-making purposes [126–129]. As the “true” health state is latent, PHM infers SoH from health indicators (i.e., degradation-sensitive features) and updates it with observers (e.g., Kalman Filters or particle filters), physics-based models, and machine learning regressors that map sensor histories onto health and remaining useful life (RUL) [130–132].

The assessment of battery state of health (SoH) is the canonical case: a prevalent definition is the ratio of the current capacity of the battery to its initial capacity, with resistance/impedance-based variants being used when capacity tests are impractical. In the automotive sector, propulsion use is often retired near 70–80% SoH, enabling second-life applications with appropriate derating [121,133–136]. Estimation methods combine coulomb counting, voltage features, state observers, electrochemical and thermal modelling, and data-driven learning. Recent studies have highlighted the use of hybrid physics-machine learning and uncertainty-aware prognostics on real electric vehicle fleets [75,137–139].

Structural Health Monitoring (SHM) complements PHM by identifying and quantifying damage-induced integrity loss using vibration, modal, acoustic, and strain sensing and analytics. Structural SoH is expressed as damage/health indices such as normalized frequency drops ($\Delta f/f_o$), stiffness/energy metrics, and novelty detection. These indices provide guidance for inspection and repair plans in civil, aerospace, and mechanical structures [124,140–146]. Recent SHM studies consolidate multi-sensor and vision-based methods, emphasizing robustness and scalability for infrastructure portfolios [147–149].

Fewer studies were found on SoH assessment using the PHM and SHM methods on other kinds of products. Examples include offshore wind turbines, where these methods enhance their operation and maintenance strategies [101,150]; a turbofan engine degradation where unsupervised learning is used to predict a virtual health index that is used to compute the RUL [151]; as well bearings [102], gearboxes [103], and power connectors for SoH assessment [152,153].

In summary, the concept of SoH in engineering originated in maintenance, where reliability was used as a SoH indicator to optimize the maintenance of machinery and equipment. It has then been widely applied in literature for assessing the SoH of batteries using supervised and unsupervised learning. The objective in this application is to enable the battery management system to optimize energy management for all cells and plan battery life extension through reuse and repurposing strategies in the context of the CE. Very few applications to other products were also observed. In any case, the methods proposed in the literature are product-specific. This complicates their transferability to different products, apart from the lack of complete and realistic data on products for SoH assessment.

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3.2.3. SoH in the circular economy context

In the CE, products are kept in use as long as possible through strategies such as reuse, refurbishment, remanufacturing, and recycling. A pivotal question at end-of-life or end-of-use is therefore: what is the remaining value or State of Health (SoH) of the product? This notion is central to CE decision-making because, just as equipment health guides maintenance, a product's health state should determine whether it is reused as-is, repaired, refurbished, remanufactured, repurposed, or recycled [154].

Several decision-support approaches integrate SoH (or closely related condition metrics) into routing choices. For example, Anityasari et al. developed a tool that directs components at end-of-life toward reuse, remanufacturing, or recycling based on profit margin, market price, life-cycle cost, remanufacturing cost, and warranty cost [155,156]. Similarly, Alamerew et al. assembled multi-criteria decision strategies spanning environmental (e.g., end-of-life impact indicators, CO_2 and SO_2 emissions, energy use), economic (logistics, product, and disassembly costs), and social dimensions (jobs created, exposure to hazardous materials), with optional legal, market, and technical criteria as needed [157,158]. In the same spirit, Vansom et al. proposed a methodology using generalized colored stochastic Petri nets to select the most suitable regeneration pathway by combining the product's SoH, information on available regeneration processes, and market needs [154]. Complementary studies reach analogous conclusions using formal decision-analytic or optimization frameworks that explicitly couple condition data with value-retention objectives [159,160].

A prominent application is the second life of EV batteries, where battery packs are typically withdrawn from vehicle at around 70–80% SoH, yet they still retain substantial capacity for less demanding stationary use, delivering environmental and economic benefits when properly managed [159,161]. The main bottleneck is accurate, rapid SoH assessment at end-of-vehicle-life: operators often lack detailed usage data (e.g., depth-of-discharge profiles, temperature exposure), making it difficult to decide between reuse and immediate recycling without robust SoH (and RUL) estimates [162,163]. In this context, Basia et al. show that efficient SoH estimation workflows are essential to sort batteries into appropriate second-life applications, and they outline data and process requirements to make such sorting reliable at scale [164]. Converging evidence indicates that SoH-driven decision rules (backed by fast testing and trustworthy data) improve both safety and value retention for batteries. Similar diagnostic needs arise for other complex products (electronics, appliances, heavy machinery), where quick and precise tests are required to evaluate used units at scale [160,162,165].

Across the literature, there is no standardized and cross-product SoH assessment method for CE; most approaches remain domain-specific (e.g., batteries, certain machinery) and data-dependent (*Connection between the yellow and red cluster in Fig. 5*). In practice, many products are still collected, recycled, or regenerated (refurbisged, remanufactured, reused, repurposed, repair) without precise SoH evaluation, because of sorting bottlenecks, missing historical data, or the absence of broadly accepted certification protocols for heterogeneous product streams. This gap matters. Without a reliable SoH assessment, defective items may be reused, creating failure risks. Products may be recycled too early, wasting resources. Remanufacturing may occur too soon or too late, reducing both environmental and economic benefits.

3.3. Monetize the loop: Circular Business Model (CBM)

Defining a circular strategy for a product clarifies when to take it back and what to do with it—whether that be repaired, refurbished, remanufactured, repurposed, or recycled—to extend its service life or regenerate its value. From an environmental perspective, this reduces the demand for raw materials and the generation of waste, whereas from an economic perspective, it incurs additional costs (reverse

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logistics, inspection, R-strategy processes, etc.) [166]. Under the traditional product sales model, customers often fail to recognize this embedded circular value when it increases the initial price, so companies require business model innovation to make circular value visible and appealing [167,168]. This is where Product–Service Systems (PSS), as introduced by Tukker, integrate products and services into a single offering, enabling customers to pay for functionality and outcomes (usership) rather than ownership [47]. Recent researches caution that a PSS must be carefully aligned with circular strategies (like product life extension and recycling) to truly realize environmental gains, while avoiding rebound effects [169]. In practice, "Product-as-a-Service" (PaaS) is a market term that usually denotes use-oriented or result-oriented PSS (e.g., subscription or pay-per-use models), and is commonly treated as a subset of PSS [170,171]. More broadly, a circular business model (CBM) is any model designed to generate profit while ensuring that products last longer, materials are recycled, and energy is recovered rather than wasted [172]. In this context, PSS/PaaS are often cited as prime examples of CBMs because they shift the focus of value creation from selling units to delivering performance over time, thereby aligning incentives with durability, maintenance, and recovery [173].

3.3.1. Product-service systems (PSS) and Product-as-a-Service (PaaS)

A classic definition by Tukker (2004) describes a PSS as "*tangible products and intangible services designed and combined so that they jointly are capable of fulfilling specific customer needs*" [47]. This concept emerged in the 1990s from sustainability and management research, and has since gained widespread attention in manufacturing industries [174]. The Tukker's PSS typology classified PSS into three main categories – product-oriented, use-oriented, and result-oriented – with eight sub-categories in total. These range from providing basic product-oriented services (maintenance, take-back agreements), to use-oriented models (leasing, sharing, pooling), and result-oriented offerings (pay-per-service unit, functional results). These categories are summarized in Table 2.

Table 2. PSS model categories with the subsets PaaS examples (adapted from Tukker [47]).

	PSS categories	#	PSS sub-categories	Description		Examples
	Product-oriented	1	Product-related service	Combines product sales with accompanying services needed during its usage phase, such as maintenance, financing, or take-back.		Maintenance contract, consumables supply, product take-back
		2	Advice and consultancy	Offers guidance on how to use the product effectively, which may include organizational or logistical optimization.		Efficiency advice on factory operations
Circular business model - oriented	Use-oriented	3	Product lease	Provider keeps ownership of the product, while the user pays a recurring fee and typically gets exclusive and continuous access.	PaaS type examples	Lighting-as-a-Service (Signify/Philips) [175], Washing-as-a-Service (pay-per-wash) [176], when the pricing is time-based without performance KPIs
		4	Product renting/ sharing	Product remains provider-owned and is used by different users sequentially, without individual exclusive access.		Washing-as-a-Service (laundry) [177] Renting a shared room (Airbnb) [175]
		5	Product pooling	Multiple users access the product at the same time, with shared, simultaneous usage managed by the provider.		Carpooling arrangement (Blablacar)
	Result-oriented	6	Activity management	A third party takes over a specific operational task, often under contracts that include performance targets.		Lighting-as-a-Service (Signify/Philips) [175], if the provider takes responsibility for the whole lighting activity

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		7	Pay per service unit	The user is billed for the actual output or use of the product rather than owning it; the provider handles upkeep and resource supply.		Washing-as-a-Service (HOMIE/Bundles) [178] HP Instant Ink (HP) [179] Tire-as-a-Service (Michelin) [25]
		8	Functional result	Provider commits to delivering a specific result or outcome, and can independently choose the means to achieve it.		Lighting-as-a-Service (Signify/Philips) [178] Rolls-Royce Power-by-the-Hour [180] Compressed-Air-as-a-Service (Kaeser SAU/CROS) [181,182] Storage-as-a-Service (Mob-ion) Mobility-as-a-service (Volkswagen) [183] Heating-as-a-Service [184]

In the manufacturing sector, PSS is strongly linked with servitization: the shift of firms from selling products to providing integrated solutions [185]. Research shows that PSS can create additional value by generating long-term customer relationships, stabilizing revenue streams, and promoting resource efficiency [186,187]. Many manufacturers have found that services now account for a large share of their revenues compared to pure product sales, prompting a shift toward PSS as a competitive strategy [188]. This servitization trend (the transition from selling products to selling integrated product-service-systems) has "pervaded manufacturing" and is often referred to as the product-service transition from pure product to pure service offerings [188]. However, Matschewsky warns that not all PSS models automatically contribute to circularity: product-oriented services may improve customer loyalty but not necessarily reduce material use [189]. For instance, selling a product with a maintenance contract might improve longevity somewhat, but if it does not fundamentally change the ownership or EoU handling, its circular impact could be limited. With this in mind, the PSS models addressed in the thesis are the ones that contribute to CE, namely use-oriented and result-oriented.

Recent studies highlighted that PSS must be designed in alignment with CE principles to achieve sustainability benefits [190]. Rosa et al., in their study of the WEEE sector, stressed that effective PSS must address both technical feasibility and circular value retention [191]. Similarly, Guzzo et al. proposed a Circular Innovation Framework to guide PSS towards sustainability, showing that firms must incorporate lifecycle thinking from the design phase [192].

From a practical perspective, the term PaaS is used to refer to PSS, which is a more academic term. PaaS is not a radically new concept – examples like equipment leasing or car rentals have existed for decades – but its strategic framing as a path to sustainability through the CE is recent. In today's context, PaaS is strongly associated with CE goals, because retaining ownership gives companies control to design for longevity, ensure proper EoU handling and closing the resource loop. They are models where ownership remains with the provider, and customers pay for usage or outcomes via subscription or pay-per-use. Table 2 shows some examples of PaaS models created by firms. PaaS can be considered a concrete business model archetype that falls under the broader PSS umbrella – specifically emphasizing use-oriented or result-oriented PSS categories – and it is heralded for enabling R-strategies like reuse, repair, remanufacturing, refurbishment, repurposing, and recycling due to the shifted ownership paradigm [171].

In summary, PSS/PaaS are key approaches within the family of CBM (*Yellow cluster in Fig. 5*). They shift the focus from selling ownership (linear model) to selling outcomes (circular-friendly model), thereby incentivizing providers to design more sustainable solutions. Pieroni et al. highlighted that configuring CBMs through PSS allows firms to align environmental objectives with business logic, making PSS a primary lever for circularity [193]. Nevertheless, the literature also cautions that simply having a service model does not automatically guarantee environmental benefit; it must be executed with circular design and EoU and EoL plans in mind [169]. The transition of BMs toward the CE is then a crucial topic for firms to keep innovating and stay competitive in a more sustainable way.

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3.3.2. Transition toward Circular Business Models (CBM)

The transition toward CBM, as it is becoming crucial for firms, has been widely addressed in the literature (*Connection between all the clusters in Fig. 5*). It is driven by four main factors:

- **Economic competitiveness**: According to Ugala and Reinartz, product commoditization forces firms to innovate through hybrid offerings [194]. Advanced service strategies enhance profitability but require new capabilities and organizational alignment [195,196]. Firms have learned that focusing on the benefits that a product delivers (the "functional results") can enhance customer satisfaction and loyalty, as customers pay for outcomes and convenience rather than dealing with ownership burdens. A Deloitte analysis notes that many attempts to shift to "as-a-service" models are motivated by their customer-centric nature and potential for continuous value delivery [197].

- **Technological enablers**: Industry 4.0 technologies are reshaping value chains. Maxence et al. emphasized that emerging digital technologies from Industry 4.0 could facilitate CE implementation in manufacturing systems [198]. Awan et al. showed that smart manufacturing and data-driven value chain design are crucial enablers for circular and service-oriented models [199]. Digitalization facilitates predictive maintenance, usage-based pricing, and performance monitoring, which is essential for result-oriented PSS/PaaS and for CBM [200,201]. This technology push encourages companies to rethink their offerings as ongoing services rather than one-time transactions, since they can now stay connected with the product throughout its life. It is, for example, the case of the instant ink service provided by HP, where the ink is automatically delivered when the printer's ink is detected at a low level [179].

- **Environmental and regulatory pressures**: CE policies in the EU emphasize business models that decouple growth from resource extraction. Kjaer et al. and Tukker both confirm that service- and result-oriented models can incentivize longer product lifespans and resource efficiency, provided they are embedded in circular design strategies [169,202]. As Kjaer et al. observed, "*product/service-systems that focus on selling service and performance instead of products are often mentioned as means to realize a circular economy, in which economic growth is decoupled from resource consumption*" [169]. In other words, service-oriented models can allow companies to grow revenue by delivering value rather than by pushing ever more units of physical product, which is a potential route to decoupling profit from resource use. This decoupling is crucial for sustainability. Policy makers have recognized this: the European Commission actively promotes PaaS models as key drivers of the transition to a circular economy [203]. According to EEA, Novel social practices, technologies, and business models are the core innovations that can drive systemic change [8,10,204].

- **Customer demand shifts**: Contemporary consumers increasingly prefer access over ownership, motivated by convenience and lower upfront costs. Han et al. showed that adoption of circular service business models is shaped by local customer expectations and institutional environments, underlining the systemic nature of this transition [205].

Together, these factors make the transition from a product-centric model to a service-centric model not only a necessity, but also a strategic opportunity [206]. However, as Brissaud et al. have pointed out, such transformations require companies to rethink not only their offerings, but also their value creation logic, governance, and collaboration within the ecosystem [207].

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Over the last decade, a rich body of literature has emerged around PSS/PaaS, and circular business models (*Yellow cluster in Fig. 5*). We can categorize the studies into several thematic streams, each addressing different aspects of the transition from product sales to service-oriented circular models.

First, several studies address the managerial dimension of the transition, examining how firms navigate the servitization journey. This perspective falls outside the scope of the present thesis. In this area, researchers outlined stages of service transition for manufacturers [208,209], and more recent work builds on these findings to examine the dynamic capabilities required for servitization, cultural change, and business model innovation processes [188,210]. Storbacka highlighted the need for new sales approaches when moving "from products to solutions" [211]. Adopting a service-oriented model requires extensive organizational change; companies must develop service development processes, new performance metrics, and often restructure units to avoid conflicts between product and service sales [210,212,213]. It is also noted that while adding basic services (product-oriented, such as maintenance) may be relatively straightforward, moving to more advanced use-oriented or result-oriented models entails deeper transformation, sometimes described as a "business model innovation", rather than incremental change [47]. On this basis, the approach of developing an innovative business model has emerged in the literature, leading to the second category of transition studies.

As companies and researchers seek to develop circular business models (including PaaS), a significant line of inquiry has been into methods, tools, and frameworks that facilitate creative business model innovation. Within this second category, a variety of tools have been proposed, going from adapted versions of the Business Model Canvas for circular economy, to specialized ideation toolkits [214], guidelines, and software for circular business model innovation [215]. Rexfelt and Selvefors catalogued 65 circular's design tools into five families, such as activators, enrichers, prompters, analysts/advisors, and flow visualizers [216]. They also noted persistent barriers to adoption, including usability challenges and misalignment with business needs. Bocken et al. conducted a review of circular business model innovation tools and noted that while many tools exist, practical uptake is limited, partly due to a lack of awareness and the tools not being user-friendly or well-aligned with companies' needs. To improve the development of methods and tools, researchers have developed evaluation frameworks for CBM tools to compare and improve, and integrative methods that combine multiple perspectives (engineering, business, design). In this way, Salman et al. proposed a dynamic PSS-LCA advancement by integrating system dynamics to assess the environmental and economic performance of PSS over time [217]. To address social and environmental dimensions more explicitly, Joyce and Paquin introduced the Triple-Layered Business Model Canvas, integrating ecological and social layers into traditional value-creation mapping [218]. Meanwhile, Guzzo et al., operationalized PaaS with a Circular Innovation Framework comprising 21 strategies and 77 practices [192]. Pollard et al. demonstrated its application in the electrical and electronic sector, confirming the tools' practical value [219]. Others incorporate internal capability and external environment factors of the company for eco-innovation in PSS design [220]. Creativity techniques like brainstorming, scenario thinking, and stakeholder co-creation are emphasized to think beyond traditional linear models. A specific area of creativity is designing PSSs that leverage digital technologies (sometimes called Smart PSS), context-awareness, and IoT data, which can unlock new service ideas [221]. Methods and tools proposed in the literature to design an innovative CBM are practically limited in their use by companies because they lack a proof of usefulness. Companies, mainly large ones, often prefer to test a business model that has been proven by another company, to limit risk. This led to the third category of transition addressed in the literature.

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This third category of transition studies research focuses on the duplication of an existing CBM internally and externally of a company. This area is less densely addressed in the literature, but it is gaining attention, as more firms progress in servitization and want to scale up their successes. Studies emphasize that while intra-firm transfer of PaaS/CBM is desirable for scaling benefits, it is not straightforward (*Yellow cluster in Fig. 5*). It requires deliberate knowledge management and sometimes the creation of standardized frameworks within the organization so that a proven model can be adapted efficiently elsewhere. On this basis, Hakanen et al. observed that for a multinational company that developed a PSS in one country and tried to roll it out elsewhere, success depends on local context alignment and internal champions to tailor the model [222]. Other studies highlight the importance of standardized processes or "templates" for PSS design that can be reused. This is the case of Frederiksen et al., who provided companies with a way to classify and select PSS models that fit their situation [174]. They introduced a method using the PSS archetypes from Tukker and guiding factors to help a company scope a new PSS by analogy to existing ones. Very few formal methodologies exist that guide a company on how to take a PSS implemented in Division A and roll it out in Division B, or how Company X can learn from Company Y's successful PaaS model. The gap is often filled by consultants or informal benchmarking, rather than well-researched tools. Some recent efforts, like the one from Frederiksen et al. is a step toward standardization, because they provide templates that can be reused [174]. However, these are early-stage and not yet widely adopted. Going one step further with the duplication of a PaaS/CBM model across different companies. The challenge highlighted here is that even if a business model concept is known, each organization has unique value networks and capabilities. A model proven in one firm might fail in another if that second firm lacks the complementary assets or market position to make it work. It is inefficient if every firm must design a circular model from scratch; ideally, successful models could be emulated and adapted by others.
Although numerous tools support the design of PaaS/CBM model, and many case studies describe individual transitions with associated managerial guidelines and frameworks, companies still struggle to scale and replicate these models internally. In other words, moving from isolated success stories to a more widespread, standardized practice remains difficult.

3.4. Summary of the thesis' position

In summary, the literature provides a wide range of solutions to support the transition toward the circular economy, spanning both engineering and managerial dimensions at product and company levels. The managerial perspective concerned with cultural transformation and governance from a more philosophical angle is beyond the scope of this thesis. From an engineering standpoint, important advances have been made in developing LCA and LCC methods, optimization models for specific R-strategies, and circularity indicators such as repairability or remanufacturability, all intended to improve product design and extend useful life (*See Fig. 5*). At the company level, engineering-oriented studies have focused on servitization pathways, business model innovation, and the organizational capabilities required to integrate circularity into operations (*See Fig. 5*). While these contributions have significantly enriched the field, their application remains fragmented, context-specific, and difficult to replicate across sectors. Existing models generally target a single product, component, or strategy, and rarely capture the interplay between technical, environmental, and socio-economic dimensions. As a result, despite substantial scientific progress, firms continue to struggle with scaling, replicating, and operationalizing CE practices.

It is within this context that the main gap addressed by this thesis emerges: the absence of integrative knowledge and methods to help companies define appropriate circular strategies for existing products while simultaneously considering technical, environmental, and economic criteria (*See chapter 4*). This thesis positions itself at this intersection by proposing a comprehensive methodology. The first step is

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to “close and improve the loop” at the product level (*See Sections 3.1 and 3.2*). The aim is to optimize performance across technical, environmental, and socio-economic dimensions. The second step is to “monetize the loop” through use-oriented and result-oriented PSS archetypes, also known as PaaS models (*See Sections 3.3*). The scope is deliberately focused on firms aiming to transition with products already on the market, with case studies in the electrical, electronic, and mechanical sectors, but designed to offer broader relevance across industry.

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4. Research gaps and research questions

The previews of Chapters 2 and 3 demonstrated that companies struggle with transitioning their business models to a circular economy. This highlights the main issue addressed in the thesis: the appropriate selection of a circular business strategy that considers both the technical (SoH) aspect of the product and socio-economic and environmental criteria. This issue is key to the successful transition of companies toward a CBM. Several researchers suggest integrating circular R-strategies into business model design from the outset [26,60,62,63]. The hypothesis put forward in this thesis is that it is possible to facilitate the adoption of the circular economy by more manufacturing companies. The resulting overarching research challenge, which structures the entire research project of the thesis mainly with an engineering perspective, is: **How to appropriately select a circular business strategy suitable for a company, considering technical, environmental, and economic criteria?**

This thesis mainly concerns the transition (engineering-oriented) of companies with products already on the market and under a product sales business model (product-oriented offering). This bottom-up approach (from circular strategy at the product level to circular business strategy at the company level) allows us to derive three sub-issues from the main target issue. This chapter presents these sub-issues in the form of the gaps and the research questions formulated. These issues and questions are summarized in Fig. 8. This figure will be updated throughout the following chapters to provide a cohesive overview of the entire thesis manuscript.

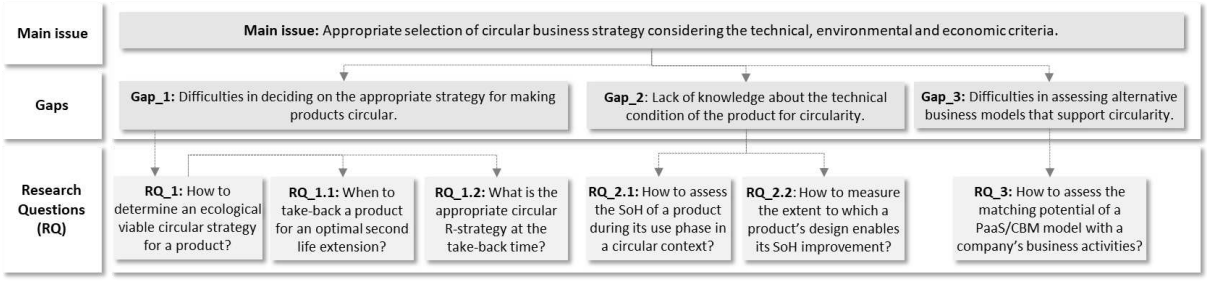

Fig. 8. Summary of the main issue, gaps, and research questions addressed in this thesis.

4.1. Gap_1: Difficulties in deciding on the appropriate strategy for making products circular.

Following the bottom-up approach suggested by many researchers and experts, as highlighted in section 2.4, the first challenge of transitioning toward circularity is closing the loop. The main issue is assessing whether it is possible to make a product circular by considering four criteria: technical, environmental, economic, and social. The first gap is linked to the main issue addressed in the thesis, which is the difficulty of deciding on the appropriate strategy for making products circular. This issue gives rise to the first research question (**RQ_1**): **How to determine an ecologically viable circular strategy for a product?**

This question aims to select the appropriate circular strategy for a product, considering its technical condition (its SoH), the economic aspect of the strategy to reduce costs and make it attractive to companies, and the environmental aspect to reduce company emissions and increase consumer perception of the circular product. We made the choice to follow the ISO 14040 standard on the Life Cycle Analysis method (LCA) to assess the environmental aspect of the product. This method was coupled with parameters of R-strategies' performance. This method, named parametric LCA (P-LCA), is presented in the **Conference Article 1** (*See section 8.1*) to facilitate the answer to the first research question [223]. Similarly, a parametric Life Cycle Cost (P-LCC) method has been developed for the assessment of the economic aspect. The P-LCC is presented in **Article 1** (*See section 7.1*). The question RQ_1 is answered in **Article 1,** which proposes a circular simulation method as a decision-aid tool for

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producers intending to define a circular strategy [224]. Section 3.4 points out two crucial challenges addressed by this first research question.

The first challenge is knowing when to take a product back from the market. This is crucial for production management and satisfying demand in a circular context. The first research question refining RQ_1 is (**RQ_1.1**): **When to take back a product for an optimal second life extension?**

Article 1 (*See section 7.1*) presents an optimization algorithm within a holistic method that answers this question, which is highly related to a second challenge: What should be done with the used product when taken back to extend its life under economic and environmental conditions? This is the basis for the second research question refining RQ_1 (**RQ_1.2**): **What is the appropriate circular R-strategy at the take-back time?**

The second research sub-question is also addressed in **Article 1** (*See section 7.1*), which proposes a decision tree for selecting the appropriate circular R-strategy based on a product's SoH. Knowing when to take back a product and how to handle it afterward is essential to determining an appropriate circular strategy. However, both the literature review in **Article 1** (*See section 7.1*) and the one in section 3.1, pointed out the key importance of product SoH as a technical criterion in determining an ecologically viable circular strategy for a product. Nevertheless, assessing the technical condition of products in a circular economy remains complex, is mainly LiB-tailored, and is very limited in recent literature for other types of products. This thesis addresses this issue in the second gap.

4.2. Gap_2: Lack of knowledge about the technical condition of the product for circularity.

The literature review in this area revealed that methods for assessing the product's SoH during its use phase help improve the loop. They mainly concentrate on the specific field of the battery. Very few methods exist to assess the SoH of other kinds of products, such as wind turbines [101], bearings [102] and gearboxes [103]. There are even fewer methods in the context of the circular economy, many due to the lack of data and knowledge. Following this, two research questions were formulated in this thesis to tackle the lack of knowledge about the product's SoH in the circular context. As the concept of SoH is relatively new in circular economy research, the first research question seeks a general approach at both the component and product levels. The question formulated in this case is (**RQ_2.1**): **How to assess the SoH of a product during its use phase in a circular context?**

To answer this question, we proposed a generic framework for the assessment of the SoH for complex systems [225] in our **Conference Article 2** (*See section 8.2*). This proposal was generalized to a wide range of products. Furthermore, in the **Conference Article 3** (*See section 8.3*), we presented the adaptation of this method to a product in the field of electronic and electrical equipment [226].

Section 3.2 shows that SoH assessment is objective-dependent : both medicine and engineering rely on health indicators (HI) tailored to what is being evaluated. For example, medical studies may use age, gender, or nutritional status as HI, whereas in battery studies, impedance or capacity are typical HI. This implies that designers must specify, early on, which performance and degradation objectives matter for the product's intended context. Since design for circularity requires building life extension into the product from the outset, OEMs need a way to determine how far life extension is technically feasible for a given design. With this in mind, the second research question related to the research Gap 2 is formulated as follows (**RQ_2.2**): **How to measure the extent to which a product's design enables its SoH improvement?**

To address this question, we first compiled a comprehensive, yet unexhaustive list of repairability criteria used in existing methods, as presented in **Conference Article 4** (*See Section 8.4*). We then

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developed a user-centric, repairability index (RI) assessment method, which is implemented in an Excel tool to guide design toward sustainability across a wide range of products. It is detailed in **Article 2** (*See section 7.2*) and applied to the case studies of power converters in a **Joint Article 3** (*Section 7.3*).

Together, these two research questions (RQ_2.1 and RQ_2.2) structure this thesis's contribution to SoH knowledge, its use in circular decision-making, and its improvement in design. They directly target the knowledge gaps in SoH assessment and its improvement for circular products.

Finally, this thesis positions these gaps within a three-step transition logic from an engineering system approach (*See Fig. 5*). **Gap 1 concerns closing the loop** (foundational SoH assessment to enable circular flows). **Gap 2 concerns improving the closed loop** (designing for repairability and SoH enhancement). Prior research confirms that economic motivation is a key driver for firms to pursue circular strategies [227–229]. Building on this, the second strategy leads to **the third gap: monetizing the loop**, which frames the next research question.

4.3. Gap_3: Difficulties in assessing alternative business models that support circularity.

This gap addresses the case of companies seeking to integrate circular economy principles into their business strategies. As highlighted in section 3.3.2, firms continue to encounter significant difficulties in scaling and replicating PaaS or CBM models, both within their own organizational boundaries and across external contexts. The development of an innovative circular business model is inherently complex, as it requires the simultaneous consideration of economic, environmental, and technical dimensions.

Consequently, many companies opt to replicate an existing business model that has already demonstrated success rather than designing a new model from scratch. Despite this practical orientation, formal methodologies that guide replication remain scarce. Questions such as how a PaaS/CBM model implemented in Department A can be effectively transferred to Department B, or how Company X can replicate a model successfully adopted by Company Y, are often addressed through consultancy services or informal benchmarking rather than through standardized, research-based approaches. This gap underlines the necessity of developing a standardized method to evaluate the replication potential of PaaS/CBM models. Accordingly, the research question underpinning this research gap is formulated as follows (**RQ_3**): **How to assess the matching potential of a PaaS/CBM model with a company's business activities?**

This thesis provides a partial response to this question. **Conference Article 5** (*See section 8.5*) investigated the suitability of replicating PaaS/CBM models within different departments of the same company. The objective was to propose a method enabling firms to evaluate such internal replication. Since, we did not publish results yet, we included them in **Article 4** form in Chapter 7.4. This result is a morphological box, building on prior research in this area. This approach allows for a qualitative assessment of suitability, functioning as an initial screening tool to narrow down the range of potential PaaS/CBM models available to firms.

This qualitative approach serves as a preliminary screening step. It allows companies to narrow down the range of potential PaaS/CBM models under consideration and to structure the pathway of their transition. The subsequent step, concerning the creation of value chains for the selected models, has also been addressed in this thesis, specifically for the case of subscription model. This part is presented in **Conference Article 6** (*See section 8.6*) where additional explanations are provided. The third step, which could not be undertaken within the scope of this thesis, would involve a quantitative assessment of the value chains developed for this model. This would include an evaluation of their socio-economic

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and environmental performance. This stage remains an important avenue for future research and it is expected to build upon the qualitative framework developed in the present work.

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5. Hypotheses and Research Methodologies

To address each of the research questions formulated in Chapter 4**Erreur ! Source du renvoi introuvable.**, we need first to set hypotheses. Based on them, we defined the research methodology, allowing us to propose an answer to each research question. This chapter aims to present these hypotheses and the research methodology defined for each research question. Fig. 9 is an extension of Fig. 8, adding to the latter the hypotheses and the summaries of the chosen research methodologies.

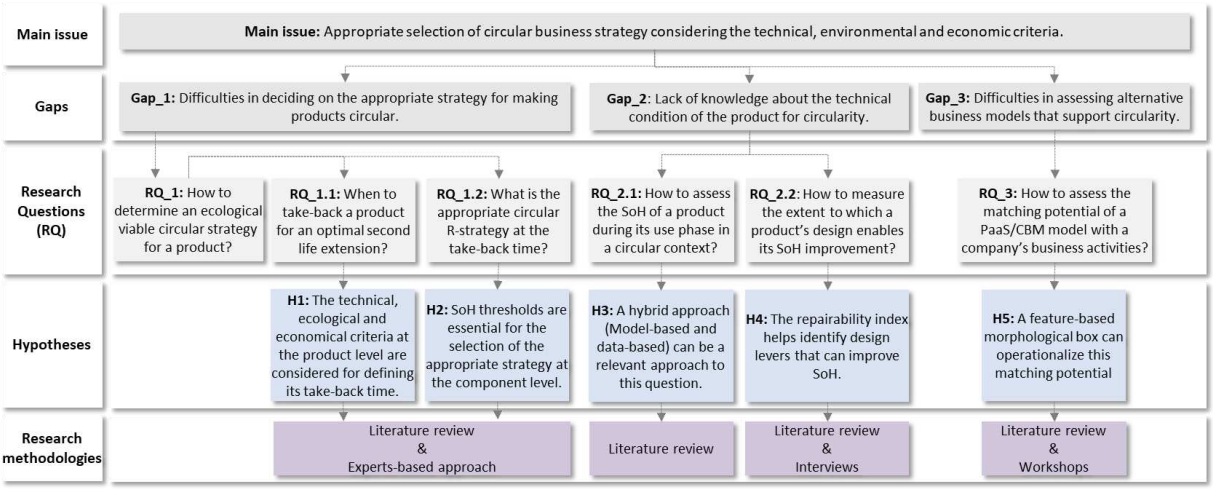

Fig. 9. Summary of the hypotheses set and the research methodologies used in this thesis.

5.1. Hypotheses and research methodologies in relation to the RQ_1

5.1.1. Hypotheses of research

The first research question is broken down into two research sub-questions, RQ_1.1 and RQ_1.2 (*See section 4.1*). For each research sub-question formulated, we set a hypothesis to frame the method used for providing an answer.

In this case, we set two hypotheses for the two research sub-questions derived from the first research question, addressing the determination of an ecologically viable circular strategy for a product.

- For the first research sub-question (RQ_1.1) on when to take back a product, we assumed that considering the technical, economic, and environmental criteria in the definition of the take-back time of the used product for its life extension could help to define a complete and more realistic circular strategy (H1 in Fig. 9).
- For the second sub-research question (RQ_1.2) on what to do with the collected used product, we made the hypothesis that defining SoH thresholds for a decision tree analysis purpose could be a game-changer in the selection of the appropriate R-strategy of the collected used product. The thinking behind this hypothesis was to frame the decision on the valorization of a used product at its EoU phase (H2 in Fig. 9).

Based on this thesis's hypotheses, we used two research methodologies, an expert-based approach and literature review, to answer the two research sub-questions RQ_1.1 and RQ_1.2. This enabled the development of a decision-aid method to support the transition of products toward a circular economy by selecting appropriate R-strategies for their component (*See Section 6.1*).

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5.1.2. The research method based on an expert involvement approach

This research method consists of involving experts from academia and professional fields to support the selection of a method and to gather some information and data based on their experience in specific fields or on specific types of products.

For the first hypothesis (H1 in Fig. 9), we consulted two academic experts involved in defining the method and two professional experts involved in applying the defined method to the breakers use case.

- The first academic expert in the field of operations research was consulted for the selection of a multi-criteria optimization method that could be efficient when it comes to decidin based on several criteria that are assessed differently. The three criteria considered, within the first hypothesis H1, are the SoH of the product, the economic, and the environmental aspects of the R-strategy that the product will undergo. The constraint of using the ISO 14040 standardized Life Cycle Assessment (LCA) method for assessing the environmental aspect (*See **Conference Article 1** in section 8.1*) was a strong limitation of applying certain multi-criteria analysis methods. The two interviews made with the first academic expert were determinant to use the weighted sum method as well as to define the algorithm for calculating the optimal takeback-time (including the weighted sum) presented in the **Article 1** (*See section 7.1*).
- The second academic expert in the field of mathematics and statistics was consulted to define the right way to assess the sensitivity of the model to assess its robustness, its confidence, and dependency.
- The two professionals interviewed, each having more than 30 years of experience in their domains, were in the field of power products for safety, such as circuit breakers. Our goal was to understand the function of the breakers and gather data on its SoH through its life cycle within several applications. They were involved in the definition of the critical parameters of the ageing of the breakers and its components. They were asked to rate it and its components' SoH in EoL from 1 to 5, where 1 means the worst state, and 5 means an as-new state. The goal was to adapt and validate the SoH threshold found in the literature to their product case. This approach is highlighted in **Article 1** (*See section 7.1*).

We used this expert-based approach as a complement to the literature review because the multi-criteria optimization methods were used in almost all the relevant scientific papers found in the literature on the take-back time assessment, and we had access to such experts.

5.1.3. The research method based on the literature review

The analysis of the literature was based on a systematic review using the PRISMA method [230]. This method was used because of its strong capability to select relevant papers on the topic among a huge number of papers. It was applied to gather relevant papers on the topic of the determination of an ecologically viable circular strategy for a product, considering the first two hypotheses, H1 and H2.

In the literature, the first research question (RQ_1) has been addressed through two main concepts, such as the optimal timing and active remanufacturing. To explore these concepts further, a search was conducted in the Web of Science database using keywords such as "take-back time" and its alternatives, including "recovery time" and "timing," alongside circular process terms like "active or proactive" remanufacturing, reuse, recycling, and refurbishing. The terms "active" and "proactive" were used alongside other circular process terms, such as reuse, refurbishing, and recycling, to assess whether methodologies were proposed for the entire circular lifecycle. "Optimal take-back time" and "optimal timing" are synonymous in this context, but "take-back" was preferred to narrow the search

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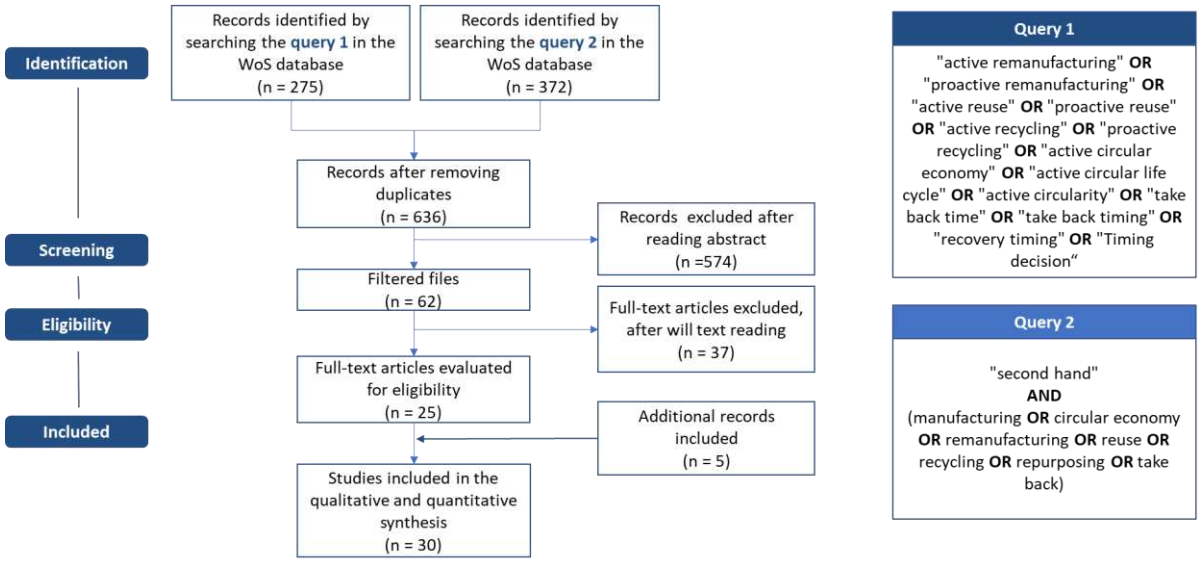

Fig. 10. Systematic literature review on RQ_1.

results for a more focused exploration of the research question. Using "optimal timing" yielded around 10,000 papers, which was too broad for the study. The PRISMA method for systematic literature analysis was employed to conduct the literature review efficiently. Two keyword queries were made in the Web of Science database, for which 275 and 372 papers were found respectively. When the terms ("optimal time" OR "optimal timing" OR "optimal recovery time") were added to the query using an AND operator, the number of papers dropped to 150, all of which were already included in the initial query 1. Following the PRISMA method, 11 duplicated papers were removed from 647, which is the sum of the two queries, reducing the number of papers to 636. Then, a selection by title and abstract reduced the amount of paper to 62. After reading the full 62 papers, the 25 most relevant were selected and 5 additional papers were added. 30 relevant papers were then selected. The PRISMA is shown in Fig. 10 presented in **Article 1** (*See section 7.1*).

5.2. Hypothesis and research methodologies in relation to RQ_2.1 and RQ_2.2

5.2.1. Hypotheses of research

As the second research question has been split into two sub-research questions, namely RQ_2.1 and RQ_2.2, we set two hypotheses, one for each.

- Considering that the term SoH comes from the medicine domain, and that it has been used for decade in maintenance as maintainability concern, we assumed that using a complementary hybrid approach (model-based and data-driven) to assess the SOH might be relevant and innovative (H3 in Fig. 9). Moreover, the literature on this subject in the battery sector mainly focuses on this point, emphasizing the limitations of reliability in the context of a circular economy.
- Regarding the research sub-question RQ_2.2 on integrating SoH improvement at the design stage, we assumed that the Repairability Index (RI) is an appropriate design-phase metric (H4 in Fig. 9). It could indicate how far a firm could technically extend product life by improving SoH through repair actions. Several reasons motivated this hypothesis. First, the repair process occurs during the use phase of a product. It is a maintenance operation that is aligned with the product life stage defined in the bathtub curve, which is a graphical representation of the failure rate of a product or system over its lifetime. In addition, the repair process is focused

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on the capacity of a product to fulfill its primary function according to the maintenance. Based on this, we assumed that in the circular economy, the repair process is linked to the capacity of a product to fulfill a primary, secondary or tertiary function. This means that the technical value of the product is considered for multiple functions. Here is the key essence of the circularity: keeping materials and products in a closed loop until no value retention is possible anymore, then recycle them to recover their raw materials. We considered that a replacement of components is always a repair operation.

Based on this thesis's hypotheses, we used two research methodologies, namely the literature review approach and the interview-based approach, to answer the second research sub-questions RQ_2.1 and RQ_2.2.

5.2.2. The research method based on the literature review in relation to RQ_2.1

We conducted a systematic literature review to identify methods for assessing a product's State of Health (SoH). Searches were run in the Web of Science (WoS) for records containing the phrase "state of health" over 1976–2022 period. The initial retrieval returned 6,596 records.

Because the term is widely used in medicine, we complemented the base query with medical keywords: "medical", "medicine", "patient", "individual", and "cell". In engineering—where battery research is the most advanced on SoH—we added: "battery", "batteries", "fuel cell", "fuel cells", "structure", "structural", "power", "sensor", and "capacitor". We formulated four complementary queries. Query 1 targeted engineering papers and excluded medicine. Query 2 targeted medicine and excluded engineering. Query 3 captured documents bridging both domains. Query 4 covered papers outside medicine and engineering. These yielded 2,072, 2,251, 1,662, and 984 records respectively. After deduplication, 6,278 unique items remained.

Screening proceeded in two stages. First, titles and abstracts were reviewed for topical relevance and citation influence, reducing the set to 312 items. Second, a rapid full-text screening identified 199 core papers. We then added seven additional articles that explicitly linked SoH to the circular economy but were missed by the keyword filters. The final corpus comprised 206 publications. Fig. 11 summarizes the search strategy and the screening flow.

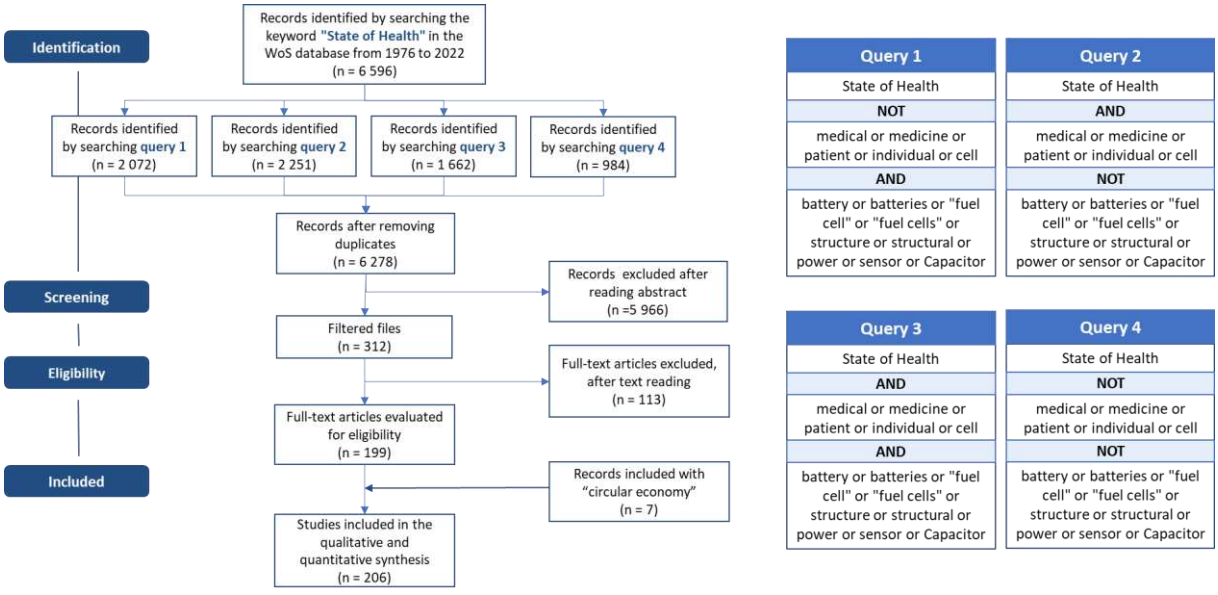

Fig. 11. Systematic literature review on the sub-research question RQ_2.1

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The selected papers enabled the proposal of a generic method for SoH assessment and supported the identification of SoH thresholds for circular R-strategies reported in the literature (*See section 6.2)*.

5.2.3. The research method based on the literature review in relation to RQ_2.2

The systematic literature review was also used in this case to identify relevant papers, first on the assessment methods of the RI (Reparability Index) for a wide range of products, and second on methods for assessing the RI for products or over their use phase. In this framework, a query was formulated in the WoS (Web of Science) database in addition to two exclusions to screen the results. The query was: Repairability OR Reparability to record all papers related to repairability. This search query gave 1576 papers as a result. This result was screened using three exclusions. The first exclusion was about to complete the query with "AND (method* OR Evaluat* OR Assess*)". The asterisk is used to find all the alternatives of the keyword starting with "method", "Evaluat", and its synonym "Assess". This exclusion screened the records from the query to 877 papers. The second exclusion consisted of only considering papers between 2017 and 2025, as recent regulatory developments in the field of reparability assessment date back to this period. It reduced the number of papers to 630. This was the time of the Circular Economy Action Plan [8], the French AGEC law [16] and the start of discussions on the EN 45554 standard [231], which was published in 2020. However, papers found during this period should cite earlier papers on the subject, if they exist. Furthermore, the EN 45554 standard was established in 2020. A third screening for eliminating papers related to medicine was applied. Therefore, the result was reduced to 316 papers. After a title and abstract reading, 284 papers were removed because they were not aligned with the goal of the literature analysis. 14 more papers were removed from the remaining 32 papers after a full-text reading. Finally, 3 more reports were added to the 18 remaining papers. A final number of 21 relevant papers (including reports) were used to characterize the research gap and to well structure our proposal. This literature review analysis is summarized in Fig. 12.

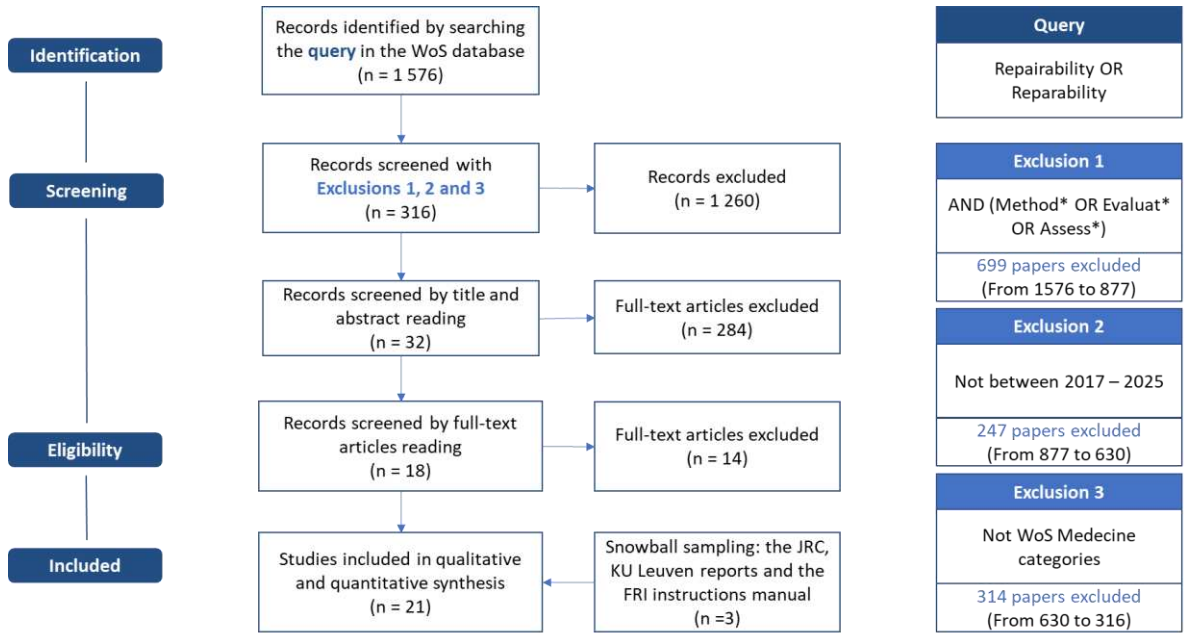

Fig. 12. Systematic literature review on the sub-research question RQ_2.2.

The papers found through this systematic literature review either presented a method for assessing the repairability index of EEE/ErP products, or a comparative study between existing methods, or critical and sensitivity analysis of the repairability index, including consumer perspectives and reliability

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of the index, or the design for repair guidelines. However, no papers were found on the consideration of the repairability score for all types of products or for second-hand and used products. The perceptions of the repairability index by handymen with different levels of experience in repair, have received little attention by the literature. It is important to notice that adding the exclusion "AND ("used product" OR "used-product" OR "second-hand" OR "second hand")" to the query shows 0 results, regardless of other exclusions. Based on this result, we investigated the founded papers to understand the similarity in the methods for assessing the repairability index. It allowed the identification of key stakeholders in the repair process value chain who might need the repairability index indicator in their work, but also to set a non-exhaustive list of criteria used in the different methods found.

5.2.4. The research method based on interviews in relation to RQ_2.2

From the literature review, we identified three stakeholder groups in the repair value chain that are directly affected by product repairability: (i) the OEM design team, (ii) the maintenance team of B2B clients, and (iii) independent repairers/"handymen" representing B2C clients.

On the basis of the list of criteria built from the literature review (*See section 5.2.3*), we conducted six semi-structured interviews with industry experts. The goal was to capture their perception of each criterion and its effect on repair processes. Three interviewees had design roles, and three had maintenance roles. We adopted an expert-based approach to enhance the reliability of findings. Experts were selected from different companies and sectors to broaden the perspective and reduce bias (*See Table 3*). Each expert ranked every criterion on a 0–5 scale according to its influence on repair: 0 = no influence; 1 = insignificant; 2 = low; 3 = moderate; 4 = acceptable; 5 = strong. An "I do not know" option was available to avoid forced responses.

To elicit rankings from the independent repairer (B2C) profile, we organized a workshop with six participants. They disassembled a product and recorded all information needed to assess the repairability criteria. This hands-on activity clarified the meaning of each criterion and enabled informed 0–5 rankings of their influence on repair.

The interviews and the workshop enabled the selection of relevant criteria per stakeholder profile (design, maintenance, and independent repairer). We then applied the Analytic Hierarchy Process (AHP) to derive weights for each criterion by profile. The AHP matrix was completed with three additional experts—one representing each profile—during follow-up interviews. Participant characteristics are summarized in Table 3.

Table 3. Summary of the participants to the interviews and workshops

	Stakeholder type	**Experience**	**Current position**	**Industry/Research**	**Sector**
Interviewees for criteria's selection					
Expert 1	Design	+18 years	Product expert	Industry	Energy
Expert 2	Design	+24 years	Product expert	Industry	Energy
Expert 3	Design	+10 years	Design engineer	Industry	Food packaging
Expert 4	Maintenance	+ 10 years	Facilities Technician	Industry	Electronic
Expert 5	Maintenance	+20 years	Maintenance technician	Industry	Energy
Expert 6	Maintenance	35 years	Product engineer	Industry	Energy
Workshop for criteria's selection					
6 Participants	independent repair	Various	Student & researchers	Research	Academia
Interviewees for applying AHP to weighted the criteria					
Expert 7	Maintenance	+20 years	Maintenance Director	Industry	Air transport
Expert 8	Design	+30 years	Assistant professor	Research	Research
Expert 9	independent repair	-	Post-doctorate	Research	Research

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The research methods in sections 5.2.3 and 5.2.4, enabled the proposal of a generic assessment approach (*See section 6.3*) to assess the repairability index across a wide range of products, both new and second-hand, and for three stakeholders' profiles. Involving stakeholders from the repair value chain through interviews and workshop was essential to ensure the robustness of the method.

5.3. Hypothesis and research methodologies in relation to the RQ_3

5.3.1. Hypothesis of research

The third research question (RQ_3) addresses the matching potential between circular business models (CBMs) — in particular PaaS — and a firm's capabilities. Answering this question requires two parallel assessments and their linkage. First, an assessment of the PaaS itself. Second, an assessment of the company's capabilities. Third, a matrix that connects both assessments to reveal matching (or mismatching) areas. Following this idea, we assumed that this matching can be operationalized using a morphological box, based on features of the Circular Business Model Canvas with those specific to PaaS (H5 in Fig. 9). This enables a structured mapping between "what the model requires" and "what the firm can deliver."

To test H5 and address RQ3, we employed two complementary research methods: (i) a systematic literature review to derive CBM/PaaS features and capability dimensions, and (ii) workshop-based inquiry to validate, refine, and apply the mapping in practice.

5.3.2. The research method based on the literature review in relation to RQ_3

To address RQ_3, we conducted a systematic literature review aimed at identifying methods for assessing the replication of successful PaaS models within companies. Relevant keywords were combined to build the query illustrated in Fig. 13. The search in the WoS database initially yielded 1051 records. Two exclusions criteria were applied. First, we discarded publications older than 10 years, as the literature on CBM has emerged relatively recently. Second, we restricted the scope to studies in the fields of management, economics, finance, and engineering, providing they integrated a sustainability perspective. After these exclusions, the number of papers was reduced to 474 papers. A two-step screening process followed. Title and abstract screening narrowed the corpus to 117 papers, while full-text assessment further reduced it to 27 papers. To avoid missing seminal contributions, we also included key sources either not indexed in WoS or not covered by our research analysis: one handbook on business models, foundational PSS work older than 10 years (e.g., Tukker, 2004), and selected grey literature from companies presenting widely adopted CBM canvases. In total, 38 relevant papers were retained as the final reference set to address RQ_3. The overall review process, conducted according to the PRISMA protocol, is summarized in Fig. 13.

The retained papers provided the basis for identifying the core features of the CBM canvas as well as the possible options associated with each feature. These options, extracted from the literature, represent the specific capabilities required by a company to deliver a particular PaaS model, with reference to Tukker's user-oriented and result-oriented archetypes. Building on these insights, we constructed a morphological matrix with features listed vertically, PaaS model types horizontally, and the corresponding options placed in the intersecting cells (*See **Article 4** in section 7.4*). To validate and refine the allocation of options across the different PaaS models, we organized a workshop with participants, who evaluated the relevance of each option to the assigned archetype.

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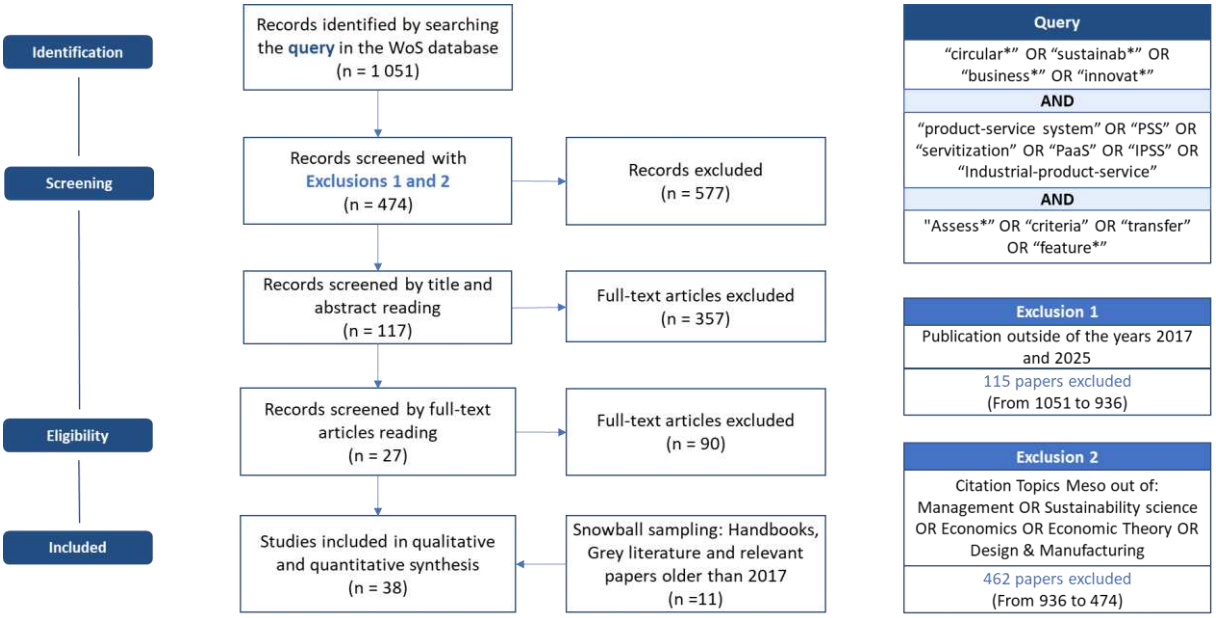

Fig. 13. Systematic literature review on the sub-research question RQ_3.

5.3.3. The research method based on workshops in relation to RQ_3

To validate the corresponding options of the morphological matrix, we organized a workshop with participants with diverse levels of expertise in CBM. It held place at an EcoSD[1] seminar. The objective was to assess the relevance and applicability of the features and options for user-oriented and result-oriented archetypes, namely, Product leasing, product renting/sharing, Product pooling, pay per service unit, and functional result.

The workshop was structured around five groups of 3 to 4 participants, with each group assigned one of the five PSS archetypes. To facilitate interaction, we provided physical materials: the complete morphological matrix was printed and displayed, and individual cards representing each option under a given feature were prepared.

Over a two-hour session, teams collaboratively reviewed the features and their options, evaluating whether each was consistent with their assigned PSS archetype. Participants placed option cards under the corresponding features when they were considered relevant. Where options did not clearly fit the archetype or raised debate, teams attached post-it notes with justifications, comments, or improvement suggestions.

This interactive approach fostered direct engagement with the matrix and promoted open, critical discussion on the adequacy of its content, thereby strengthening its validation.

These research methods led to the development of a qualitative CBM assessment method, structured as a morphological box, to facilitate and standardize the replication of PaaS models within companies (*See Section 6.4*). This method supports and accelerates the transition of companies toward circular economy.

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6. Summary of contributions

This chapter presents the main contributions of the thesis, which take the form of four distinct proposals developed to address the research questions defined in Chapter 4. Taken together, these proposals fully answer the first and fourth research questions, while partialy adressing the second and third, as explained in the following sections. The presentation of each contribution emphasizes its originality, explains the extent to which it addresses the associated research question, and details its validation through case studies, followed by a discussion of its limitations. The section also highlights the scientific publications in which each contribution has been fully or partially disseminated. These contributions of the thesis are summarized in Fig. 14, which is an updated version of Fig. 9. It highlights the link between each contribution and its corresponding research question, and shows the articles through which these contributions are valorized in the scientific literature.

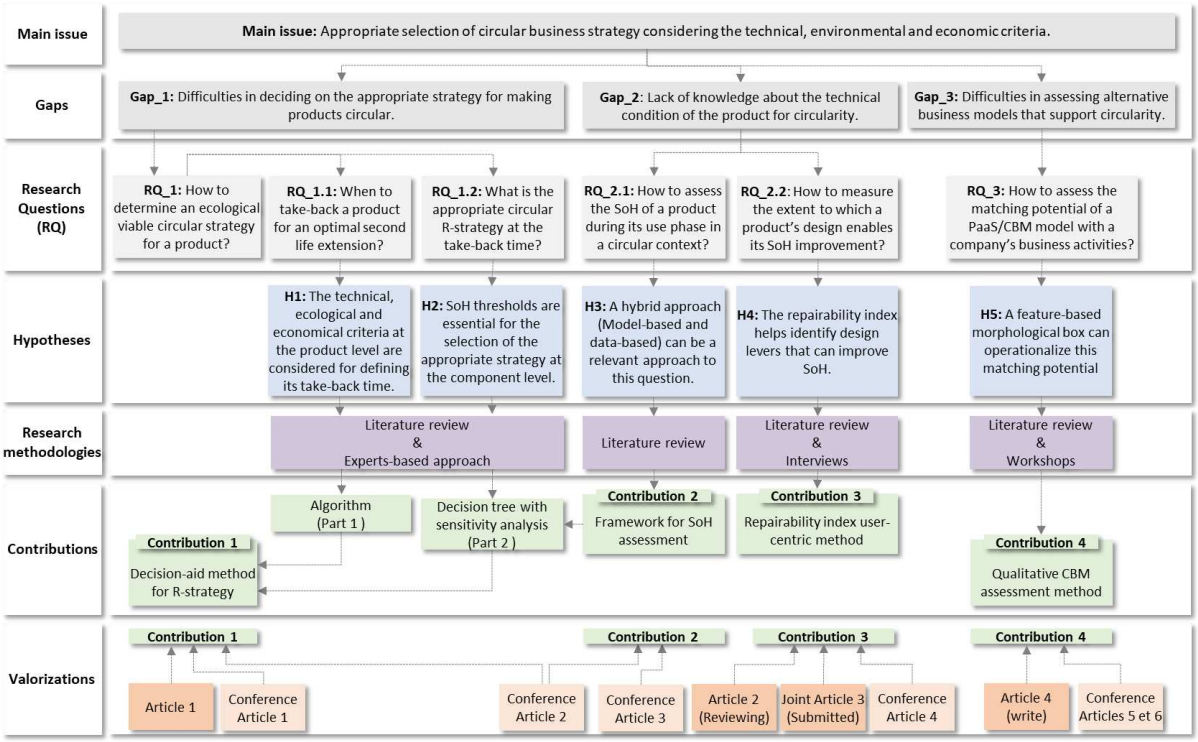

Fig. 14. Summary of the thesis' contributions and their valorization in scientific articles.

To illustrate how the contributions of this thesis collectively address its overarching objective, Fig. 15 is provided. The main aim of the thesis is to support companies in their transition toward the circular economy, focusing on existing products and relying on a decision-aid methodology. In Fig. 15, the contributions reflect their role in the transition process towards circularity (axis ranging from linear to circular) and the three patterns form the basic of the bottom-up approach of the transition toward a circular ecosystem: closing, improving and monetizing the loop.

Contribution 1 (decision-aid method) builds on the outcomes of Contribution 2 (SoH assessment framework), integrating them into a decision tree to determine the appropriate R-strategy for each component (*see Fig. 14*). Together, these two contributions operate iteratively to define the optimal take-back time and appropriate R-strategy for a product, balancing economic and environmental performance. In doing so, they enable both to close and improve the loop (*see Fig. 15*). On this basis, Contribution 4 (CBM assessment method) guides companies in identifying the circular business model better aligned with the chosen R-strategy. Its purpose is to support the monetization of closed loops

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(*See Fig. 15*). Finally, Contribution 3 addresses the redesign of products for improved circularity. By applying the Repairability Index, it provides means to embed repair, reuse, and other circular options at the design stage, thereby further strengthening loop improvement.

The methods developed in Contributions 1, 3, and 4, together with the framework proposed in Contribution 2, form the basis of this decision-aid methodology. It is primarily designed for sustainable development managers within companies, who are responsible for initiating and guiding the transition. The outcomes of the methodology provide these managers with concrete evidence and structured arguments to persuade decision-makers and other stakeholders of both the potential and the imperative of moving toward a circular economy for environmental and economic performance.

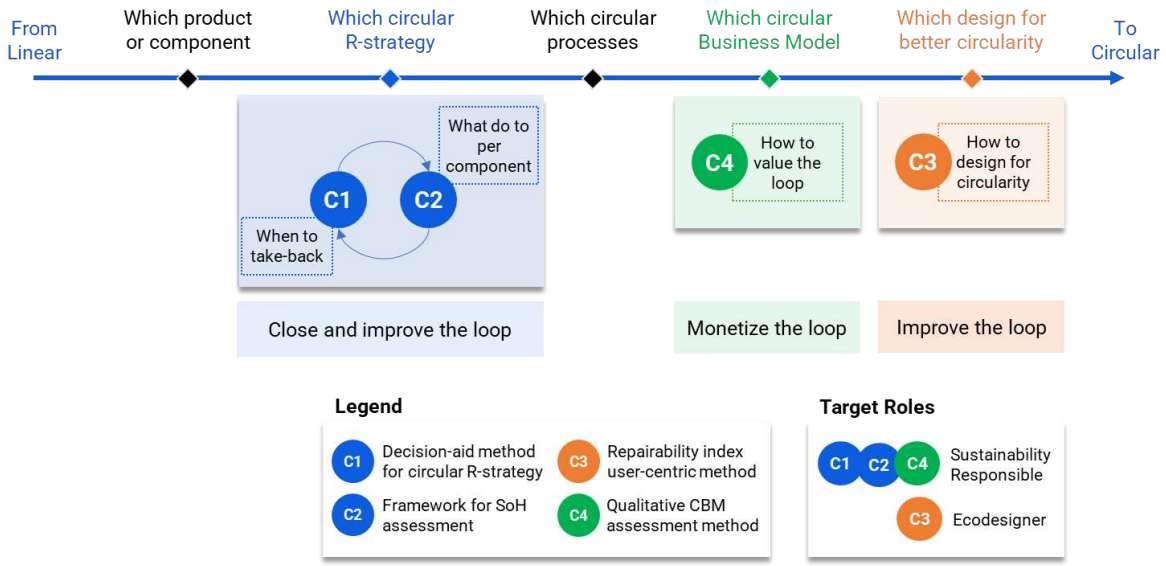

Fig. 15. Overview of thesis contributions within the transition process toward circularity

6.1. Contribution 1: Development of a decision-aid method for circular R-strategy

The first major contribution of this thesis is a method for selecting the appropriate circular R-strategy for a product, balancing profitablity and environmental perfomance, based on the product's take-back time. The method proposed ensures that the chosen circular strategy is optimized for both economic and environmental criteria. It is based on three main evaluation criteria:

- The technical aspect (SoH) of each component during the product's first life cycle.
- The environmental impacts of the product throughout its entire life cycle, including impacts from circular loops.
- The economic aspect in terms of costs and profit (gross margin) from the company's perspective, associated with the circular R-strategy.

This method is structured around a decision tree that incorporates the technical aspects of the product's components, combined with an algorithm to balance environmental and economic criteria.

In practice, the method is applied at the component level of a product. For each year of the product's life, both criteria environmental and economic impacts aspects are assessed, while SoHs of the components are assumed. Based on this and the decision tree built with thresholds (based on the contribution 2 *in section 6.2*), an appropriate R-strategy is selected to extend the component's life. The environmental impacts associated with the component's use, as well as those generated by the corresponding R-strategy, are evaluated using the P-LCA method. Similarly, the costs for the

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component during its first life cycle, as well as those for the selected R-strategy, are assessed using the P-LCC method. An algorithm is used to determine the optimal take-back time, which is the point in the product's use phase where both environmental impacts and lifecycle costs are minimized.

The proposed method is not product-specific. It was implemented in an Excel-based tool called the Circular Simulation Tool (CST) (*See **Article 1** in Section 7.1*), in a general way, taking into account its use for multiple types of products. The methods P-LCA and P-LCC, as well as the trade-off algorithm, which constitute the proposed method, are not product-specific. This makes our first contribution applicable to a wide range of products. The innovation of this method lies in its holistic approach. It evaluates multiple R-strategies for a given product to optimize the one that is most beneficial in terms of both environmental and economic factors, based on the product's take-back time. By combining the outcomes of P-LCA, P-LCC, and SoH assessments into a unified algorithm, this method facilitates the identification of the best trade-offs between environmental, economic, and technical criteria. Such a contribution is designed for the roles having sustainability responsibility in a company, as shown in Fig. 15.

This method was applied to a circuit breaker manufactured by the industrial partner 1. After nearly a year of collaboration with the team on the circuit breaker case of the industrial partner 1, we collected data to apply the proposed method. The breaker is an air circuit breaker used in high-voltage systems. The case study showed significant advantages in terms of environmental impact and profitability for the company. For example, in the Genset and Hospital applications, where the breaker lasts 12 and 15 years, respectively, the method identified the optimal take-back time as 9 years in Genset and 10 years for Hospital applications. This led to a remanufacturing of key components, reducing CO_2 emissions by 5% and 4%, respectively, compared to the baseline scenario, where breakers are discarded at the end of their life. Additionally, the costs of the circular strategy were 1% lower than the baseline, but the margin was 2% higher, resulting in a 22% profit increase in both applications. This case study is detailed in **Article 1**. The industrial partner 1 project team also highlighted the value of this method in structuring their approach to designing circular strategies for the breaker and other products in their range.

This first contribution is presented in three articles (*see Fig. 14*). The method for assessing the optimal take-back time using an algorithm is presented in **Article 1** entitled **"Maximizing circular economy benefits for manufacturing companies: A simulation tool for defining and implementing a circular product strategy"** (*see Section 7.1).* The CST built based on this method is also presented in **Article 1.** The parametric LCC method used in this method is also presented in **Article 1**. The method also uses a P-LCA to assess the environmental impact of the product and its components according to the ISO 14040 and 14044 standards, while considering the efficiency of each process of the product value chain. The P-LCA method is presented in the **Conference Article 1** entitled **"Parametric LCA integrating a product's State of Health: A decision-making tool based on environmental impact in the context of circular strategy"** (*See section 8.1*)**.** On the other hand, the assessment of the product and component SoH with the decision tree related to the R-strategy is presented in the **Conference Article 2** entitled **"Characterization of the state of health of a complex system at the end of use"** (*see Section 8.2*)**.**

This contribution addresses the first two research sub-questions of the research question **RQ_1**: "How to determine an ecologically viable circular strategy for a product?" (*See section 4.1*)

Still, there are limitations to these answers. Firstly, it was assumed that product degradation remains consistent across all life cycles, without delving deeper into the value gained from the product or its components as they progress through the R-strategy. The selected R-strategy for a component was assumed to remain constant, regardless of whether the product undergoes a third or even more life

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cycles. The design of R-strategy processes, such as the steps involved in remanufacturing, was not included in this study. Accurately assessing the impact and costs of R-strategies is essential, and this was approximated in this thesis based on existing literature and refined by experts on the product in the specific case study of the circuit breaker. Another significant limitation is the exclusion of consumer perspectives. Consumer perceptions of the value delivered by products in a circular value chain are crucial for decision-making in product commercialization. The case study on circuit breakers showed profitability for the company but indicated a higher cost for consumers. This limitation will be addressed in future research, as part of the continuation of this thesis, particularly through Contribution 4, which focuses on the qualitative assessment of Circular Business Models (CBM) to identify the most effective way to monetize the circular loop. Finally, as the thesis targets the case of existing products on the market, the question of their design after the circularity transition was raised at a certain point. Because not all the products on the market were designed to last longer or under a circular design thinking, their redesign is necessary to perfectly align the design with the circular strategy of the company. This revision of the product design to support circularity is partially addressed in Contribution 3.

6.2. Contribution 2: Proposal of a framework for SoH assessment

In the context of the circular economy, SoH has emerged as a critical criterion for determining strategies to extend a product's life. However, methods to assess SoH remain underdeveloped for many product categories, with existing approaches largely focused on Lithium-ion Batteries (LiB) for electric vehicles (EVs). This second contribution of this thesis proposes a general framework for assessing the SoH across a broad range of products. It is designed for data analyst engineers, while its results are intended for use in the decision tree of Contribution 1 within a company's sustainable development department.

The development of this framework was guided by principles from medicine and maintenance engineering, both recognized as advanced domains in SoH assessment. Across these fields, SoH is a unifying concept indicating the condition of a subject, whether a person, machine, or product, along the continuum from an initial perfect state to end-of-life (EoL). In medicine, SoH is often multidimensional and adaptive, measured via multiple health indicators (HI), focusing on functionality and resilience. In engineering and maintenance, SoH is typically a percentage-based performance metric, assessed using sensor-derived indicators and increasingly sophisticated models, such as PHM, SHM, and reliability-based approaches. Despite differences in context, both domains share several common elements (*See section* 3.2):

- SoH is defined relatively to a reference state (healthy individual or as-new component).
- Indicators are created to quantify SoH (e.g., SF-36 in medicine; impedance or modal features in engineering).
- These indicators are aggregated to form a SoH.
- Decisions are linked to this state (e.g., therapy, maintenance scheduling, derating, or shutdown).

Based on these insights, it was necessary to define SoH in a circular economy context. Notably, the choice of HI depends on the objective of the assessment. For example, LiB in EVs may use impedance, capacity, or incremental capacity, while others use RUL. In maintenance, reliability rates are common SoH indicators. Accordingly, this thesis proposes the following definition for SoH in a circular context:

"SoH is a composite indicator that measures the ageing and degradation state of a product's critical components and their relative contribution to overall performance, to estimate the residual capacity

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of the product to remain functional and circular (i.e., repaired, reused, refurbished, remanufactured, or recycled)".

This definition allows residual value to be considered throughout the product's life rather than only at EoL, emphasizing the potential for life extension through R-strategies.

We have then proposed a generic framework for assessing the SoH of a product in a circular context. This framework is made of three main steps:

- The Condition-based maintenance (CBM) approach to identify the critical component of the product and their main cause and consequences of failures.
- The Prognostic and Health Management (PHM) approach to create the health indicators, assess, and estimate the SoH or the RUL.
- The decision-making tree based on a threshold to define where to direct a product according to its SoH.

The CBM is primarily used to identify critical components. It consists of either making a functional analysis followed by a Pareto chart to determine the 20% of components responsible for 80% of product failure, and/or the Failure Mode and Effects Analysis (FMEA) or the Failure Mode, Mechanism and Effect Analysis (FMMEA), when reliable data on the product are available or not. Then, this list of critical components and their failure cause is challenged through a Fault Tree Analysis (FTA) of the product, in order to check that the actual critical components are identified.
Secondarily, the PHM approach is applied for the SoH assessment of each critical component identified. This approach was chosen for several reasons, such as because it incorporates the principles of CBM as well as those of Reliability-Based Maintenance (RBM). Another reason is that it can be applied at the component level, and both when recorded data on the system are available and when they are not due to its data-driven and physics-based principles. The PHM approach first consists of selecting the important physical parameters that well describe the cause of the component failure. Second, these parameters are used as Health Indicators (HI) to estimate the component SoH, either using machine Learning (ML) on data, or based on physical models of damage models, or a hybrid of the two approaches. The SoH value is comprised between 0 and 1. Third, the SoH of critical components are aggregated in a weighted sum equation to calculate the SoH of the product. In this case, weights are defined using an AHP method.
In the previous two steps (CBM and PHM approaches), a hybrid approach (model-based and data-based) was adopted to ensure SoH assessment, regardless of whether data were available. Finally, based on the SoH on the component, the decision of what R-strategy to extend the product or component life can be made using the decision tree. It is a tree that sets the threshold of SoH to reuse a component/product with SoH higher than 0.8, or repurpose/refurbish/remanufacture if SoH is comprised between 0.8 and 0.2, and recycle if less than 0.2. These thresholds were set based on the literature (*See section 5.2.2*), so they have some uncertainties and must be adapted to each product case.

This contribution is a generic framework that might be adapted to a specific product case. Following this, an adaptation of the framework was made on the case of electronic products. This adaptation, based on a hybrid approach, consisted of combining the analysis methods FMMEA and FTA to identify the critical component and their cause and mechanism of failures at the CBM step. Then physic-based principle with physical models of damage was used to calculate the SoH of each critical component. Finally, weighted sum based on AHP was used to calculate the product SoH.

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The originality of this second proposition is the combination of the CBM and PHM approaches for estimating the SoH of a product for decision-making in the context of the CE. Second, the decision-making tree is based on thresholds.

This proposition has not been fully applied to a real case due to several reasons. The decision tree SoH-based threshold was used in the circuit breaker case study with the first contribution (*See **Article 1** in section 7.1*). The lack of reliable data on the physical parameters representing the failure of critical components, the high cost of making an experiment in a laboratory to gather an experimental SoH value on the product of the industrial partner. These constraints made the use of a data-driven approach complex. Considering the physics-based approach, due to the complexity of current products, it would be time-consuming to physically model a product well for the SoH assessment. As this part was not the core of the thesis, we made the choice not to go further on the application of this proposition to a real industrial case.

This second contribution is presented in two articles (*See Fig. 14*). First, the generic framework method for assessing the SoH of a complex system is presented in the **Conference Article 2** entitled **"Characterization of the state of health of a complex system at the end of use"** (*See section 8.2*)**.** The **Conference Article 3,** entitled **"Characterization of the State of Health of Electronic Devices for Fostering Safety and Circular Economy"** (*See section 8.3*), presented the adaptation of the framework to the electronic products.

This contribution addresses the research question RQ_2.1: "How to assess the SoH of a product during its use phase in a circular context?" (*See section 4.2*). While the framework is conceptual, it partially answers the question, pending real-case application.

However, although this contribution is still a concept and was not fully tested, potential limitations must be considered. The main limitations are first the thresholds used in the decision tree. They were defined based on literature and supplemented by expert knowledge in the circuit breaker case in contribution 1. However, extrapolating these thresholds to other product types may require further investigation. The SoH of the product and its components represent an important input needed by the decion making process of Contribution 1. This latter limitation was partially addressed in Contribution 2. The second limitation id the interactions between components that could affect failure propagation are not explicitly modeled. Third is the aggregation method for product-level SoH may not be appropriate in all cases. Finally, the lack of real industrial data limited the validation of the method. Physics-based modeling of complex products would require significant time and resources. Despite these limitations, the framework provides a general, adaptable approach to estimate SoH for a wide range of products, forming a foundation for circular economy decision-making.

6.3. Contribution 3: Repairability index user-centric method.

The State of Health (SoH) of a product is a critical factor in defining a circular strategy. However, assessing SoH in an industrial context remains challenging due to limited data and expertise. Following the approach commonly used in the literature, SoH assessment typically relies on identifying health indicators (HI) that reflect product degradation. In this work, we propose using the Repairability Index as a design guideline tool for circularity, with the objective of extending product life through improving its SoH (*See Fig. 15*). This choice is justified by the widespread use of RI among manufacturers and consumers and its support in legislation, such as the AGEC law in France, which encourages sustainable product design.

Our third contribution introduces a user-centric method for assessing RI across a wide range of products throughout their use. The method, named RIUP (Repairability Index per User Profile), is based

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on the EN 45554 standard for Energy-related Products (ErP) and incorporates user perspectives. Prior studies have shown that RI is perceived differently depending on the user's role or objective—for example, designers and maintenance teams prioritize different aspects of repairability. RIUP aims to provide design teams with actionable information to develop sustainable products that are aligned with the circular strategy of the company and reflect the diverse perspectives of users. The RIUP method consists of three main steps:

- Identification of relevant reparability criteria from the litterature and from experts intervews, that cover a wider range of product and user objectives.
- Definition of a weighting and scoring system within a comprehensive assessment matrix.
- Estimation of the RI evolution over the product life cycle, based on its condition of use and the availability of support and assistance.

Using the user profiles, relevant criteria are selected and assigned weights. The criteria were drawn from existing RI methods in the literature and supplemented by industry insights. Weights were determined using an expert-based Analytic Hierarchy Process (AHP) approach. A scoring system, independent of user profile, is applied at both the product and priority-part levels, based on a priority-parts identification method from the EN 45554 standard. This scoring system translated the qualitative assessments using class-rating principles made by a user on the RI assessment of the product into numerical values ranging from 0 to 1 (or 0–10, in line with the French repairability scale). Finally, the method provides the RI score of the product at its current stage in the lifespan, and estimates the RI evolution curve to illustrate changes over the product life, considering usage conditions, product age, and producer supports or assistance.

Among the 38 reparability criteria considered, 22 were identified as affected by product use and condition. Examples include the time and steps of disassembly, the type of tools used for the disassembly, the duration availability, and the accessibility of supports, documentation, or spare parts on the product, the price of the spare parts, the commercial guarantee, the remote assistance, and the estimated reliability of the priority parts of the product. A univariate sensitivity analysis showed that variations in single criteria could alter RI values by 5 –15%, while simultaneous changes in multiple criteria could lead to variations exceeding 15%. The RI evolution curve is therefore modeled approximately, with the aim of demonstrating that RI is dynamic, reflecting product condition, support availability, and age.

RIUP has been implemented in an Excel-based tool, accommodating four user profiles: a generalist (all criteria weighted equally), a design team, a maintenance team, and a typical end handyman consumer (independent repairer). This approach is characterized by several original elements. First, the proposed method for assessing the repairability has been designed to be applicable for a broader range of products. This contrast with existing methods on the ErP/EEE, which are product-specific. Secondly, the user-centric approach is a fundamental consideration for designers seeking to create sustainable products, with the objective of aligning product usage with consumer needs. It is also a salient point for the user, such as a maintenance manager for example who is planning to by equipement with high levels of reparability and durability. Thirdly, the strategy of increasing the RI through the continuous monitoring of product degradation, complemented by producer support and assistance, represents a substantial improvement of the process circularity. Products resulting from a circular strategy (i.e., those that have been repaired, reconditioned, reused, or remanufactured) may have a repairability index adapted to their age and condition of use. Furthermore, this contribution facilitates the tracking of the evolution of the RI throughout product's life cycle, allowing the design team to measure to what extent they are able to improve the SoH during its use phase.

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The method was tested in workshops with students and professionals, and applied to several case studies, including electrical circuit breakers, desktops, kettles, electric charging stations, power electronic converters, and heat-sealing machines. The RIUP tool was applied to the industrial case study of a heat-sealing machine in the food packaging industry with the industrial partner 2, showing RI values of 8.4/10 for the design profile, 8.1/10 for the end-consumer profile, and 17% lower for the maintenance profile. It was demonstrated that, in accordance with the objectives of the user, the perception of repairability might be divergent. The design team was using the RIUP tool to improve their product design toward a more repairable one. The tool highlighted the key actionable elements, allowing the company to improve the product SoH through its repairability.

This third contribution is presented in two main articles. The **Article 2** entitled **"A stakeholder-centered repairability index supporting circular product design"** (*See section 7.2*)**.** This article presented the method RIUP with its application to the case study of the heat-sealing machine. The list of criteria for RIUP method were identified in all the existing methods for assessing the repairability, and presented in the **Conference Article 4,** entitled **"Leveraging circularity through repair standards: A comparison of methods for assessing product reparability for extended use on mechanical products"** (*See section 8.4*)**.** Furthermore, RIUP was applied in a collaborative study with Mondragon University to assess the RI of two power electronic converters, resulting in a **Joint Article 3** entitled **"Circularity assessment of power electronic converters: manual disassembly, bill of material, circularity indicators and actionable guidelines"** (*See section 8.3*). Our contribution included designing the disassembly protocol to collect the required data and assessing the RI of the two converters.

This third contribution partially answers the sub-research question RQ_2.2: How to measure the extent to which a product enables improvements in its SoH? (*See section 4.2*). The study demonstrates that the repairability could be used as a design guideline, allowing the company to assess its capability to improve the product's SoH during its use phase. Investigating additional design for circularity guidelines could further strengthen this assessment and fully answer RQ_2.2.

However, the RIUP method has several limitations. First, it relies heavily on expert judgment, both for selecting profiles and for setting weights. The number of experts consulted may be insufficient to generalize the outcomes. Second, the scaling system (0–1) used in scoring may limit precision, and the method did not address the balance between aspects of accuracy and usability of the results. Finally, the demonstration of the evolution of RI is still under developement.

6.4. Contribution 4: Qualitative circular business model (CBM) assessment method.

Researchers have developed a wide range of Circular Business Model (CBM) methods and tools to support companies in their transition toward the circular economy. Yet, the specific challenge of replicating existing Product-as-a-Service (PaaS) models has received relatively little attention. To address this gap, we developed a qualitative method enabling companies to assess their capabilities of implementing the PaaS models that best fit their organizational context. The selected models form the basis for designing the value chain and, in future work, for quantitatively assessing their economic and environmental performance. This objective is the foundation of the thesis's fourth contribution.

The core of this contribution is a morphological box designed to assess the alignment between company capabilities and PaaS models. The method focuses on user-oriented and result-oriented PSS archetypes as defined by Tukker: product leasing, product renting/sharing, product pooling, pay-per-service-unit, and functional result. The morphological box is structured as a matrix in which columns correspond to the five PaaS archetypes, and rows correspond to features of the Business Model Canvas, including circularity-related sub-features. Each cell contains "options", defined as specific

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company capabilities that can fulfill a given sub-feature for a particular model. For example, the option of remanufacturing a product or component represents a firm's ability to carry out remanufacturing internally. This option maps to the "circular product" sub-feature under "value proposition" and matches the PSS models' product leasing and product renting/sharing.

The morphological box is applied in practice through workshops involving cross-functional company teams (e.g., designers, technicians, maintenance engineers, marketing, and sales managers). Using option cards, participants assess the degree of alignment of their capabilities with each sub-feature. Results are transcribed into the morphological box and visualized as a color-coded heat map: grey (0–20%), orange (21–40%), yellow (41–60%), blue (61–80%), and green (81–100%). The column score is then calculated as the mean of all option values, enabling the identification of the PaaS models with the highest alignment, those for which the score is above 50%. The method is available both as a printed board game and as an online tool in Miro.

The originality of this contribution lies in the systematic identification of options characterizing PaaS models. These options were first derived from the literature *(See section 5.3.2)*, and then refined through a workshop *(See section 5.3.3)*. Their combination establishes the concrete link between company capabilities and PaaS features.

The method was applied to a case study in the water department of the Industrial partner 3[1]. Results indicated that pay-per-service-unit and functional result were the most suitable models for this department. The analysis not only identified the strong points that justified this conclusion but also highlighted critical aspects requiring attention during implementation.

This fourth contribution is presented in **Article 4** entitled **"Design methodology for analysing the feasibility of Product-Service Systems models: The case of the pay-per-unit model"** (*see Section 7.4*)**.** The Design methodlogy presented in this article shows the case of pay-per-unit model of the complete morphological box. This morphological box-based method is inspired by an earlier version developed for assessing the transferability of PSS models within the same organization, as presented in **Conference Article 5,** which is entitled **"Qualitative Assessment for the Transferability of an Industrial Product-Service Systems from One Application Field to Another Within the Same Organization"** (*See section 8.5*)**.** The next step, following model selection, is the creation of detailed value chains in flowchart form. This process has been initiated for the component-as-a-service model and is described in **Conference Article 6** entitled **"Transitioning Towards a Component-as-a-Service: A Business Model Design Overview"** (*See section 8.6*).

This fourth contribution directly addresses the research question RQ_3: How to assess the matching potential of a PaaS/CBM model with a company's business activities? (*See section 4.3*). The morphological box provides a structured and replicable method to evaluate this matching potential.

Nevertheless, limitations remain. First, the list of options identified from the literature is not exhaustive; future work should extend and validate these options across a wider set of PSS models. Second, validation is currently based on a limited number of workshops, whereas stronger reliability would require at least three iterations in different organizational contexts.

[1] The industrial partner 3 is a Water and Air equipment supplier

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7. Journal Articles

This chapter summarizes the peer-reviewed journal articles developed to support the contributions of the thesis. In total, three journal articles (one published, two under review) and one manuscript in preparation are presented.

Article 1 introduces the decision-aid method for defining an ecologically viable circular strategy at the product level. The method, implemented as an Excel tool, is designed to address the circularity of existing products and to support sustainability departments within companies. It was published on December 4, 2024, in Sustainable Production and Consumption. This paper underpins the first contribution of the thesis and relates to the first phase of the bottom-up approach to circular economy transition, namely closing and improving product loops.
https://doi.org/10.1016/j.spc.2024.12.002

Article 2 presents the user-centric repairability index assessment method. This criteria-oriented tool can be used as a design guideline to foster product circularity at the design stage. Implemented in an Excel tool, it supports the third contribution of the thesis and aims to enhance the effectiveness of closed loops in the development of new products. The paper was published on March 5, 2026, in the Cleaner Environmental Systems journal.
https://doi.org/10.1016/j.cesys.2026.100419

Article 3 is the outcome of a joint collaboration with Mondragon University, conducted within a three-month mobility funded by EIT Manufacturing. We contribuated on the development of a methodology for disassembly protocols in workshop settings and for assessing the repairability index of power converters. The paper evaluates several circularity indicators to provide actionable guidelines for improving product design and thereby reinforcing closed-loop circularity. It was published on February 10, 2026, in the Journal of Cleaner Production.
https://doi.org/10.1016/j.jclepro.2026.147774

Article 4 presents the morphological box-based design method developed to analyse the feasibility of replication of pay-per-unit model as a result-oriented PSS archetype. It primarily supports the fourth contribution of the thesis and relates to the second phase of the bottom-up transition approach, which focuses on monetizing closed loops.

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7.1. Article 1: Maximizing circular economy benefits for manufacturing companies: A simulation tool for defining and implementing a circular product strategy

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Maximizing circular economy benefits for manufacturing companies: A simulation tool for defining and implementing a circular product strategy

Christian Wandji [a,*], Andreas Riel [a], Helmi Ben Rejeb [a], Mohammad Kanso [b], Florent Pitis [b]

[a] Grenoble Alpes University, CNRS, Grenoble INP, G-SCOP, 46 Avenue Félix Viallet, 38000 Grenoble, France
[b] Schneider Electric, 31 rue Pierre Mendès France, 38320 Eybens, France

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ABSTRACT

Achieving a balance between reducing environmental impact and ensuring economic viability is essential for Originals Equipment Manufacturers adopting circular product strategies. A critical aspect of this process is determining the optimal time to take a product out of operation to facilitate the implementing of an appropriate circular strategy. However, decision-makers often lack the tools and methods to effectively answer this question, making it difficult to define and implement a strategy that is both ecologically sound and economically viable. This article presents a methodology that uses the State of Health of a product as a key indicator to identify the most advantageous year for taking back the product and applying a specific circular process (i.e., reuse, remanufacturing or recycling). Based on the State-of-Health, the environmental impact and total cost of the product are calculated annually over its lifetime using defined parameters. A circular strategy is proposed for each take-back year, determined by State of Health thresholds for various circular processes. To determine the optimum take-back year, an algorithm is applied, using a weighted sum as the objective function. This methodology is implemented within a dynamic circular strategy simulation tool to support decision-making for stakeholders. The approach is demonstrated using a case study on a circuit breaker in Genset and hospital applications. The results show environmental and economic benefits of up to 7 % and 18 %, respectively, highlighting the potential value of using this circular strategy simulation tool.

1. Introduction

The main objective of Circular Economy (CE) strategies is to extend the life of products by keeping as long as possible, in a closed circuit, the energy and value attributed to the product during its initial manufacturing (Kirchherr et al., 2023). Recycling, one of the most widely used circular process (10R) options, by many actors in the product value chain, requires huge amounts of energy to obtain recycled raw materials and also destroys product value. Other circular processes, such as reuse, repurposing, remanufacturing, refurbishing, are more difficult to implement due to the high variability in how products need to be handled at the end of their life cycle (Zhang et al., 2021). One of the main reasons for this variability is the uncertainty surrounding the timing, quality, and quantity of products at their end-of-life (EoL) phase (Tolio et al., 2017). The timing, also referred as take-back time, corresponds to the time when the product is collected from operation after its End of Use (EoU). This unpredictability results in unreliable control, by manufacturing companies, over the circular value chain. As a consequence, it becomes difficult to establish a stable market for second-hand or used products (Hauschild et al., 2020).

Manufacturing companies consequently have limited influence over what can be done effectively with their EoL products using current circular processes. The complexity, variability, and diversity of circular scenarios make it hard for Original Equipment Manufacturers (OEMs) of electrical, electronic, or mechanical goods to adopt these strategies. This often leads to doubt about the true benefits of circularity for OEMs. Circularity offers them a sustainable way to conduct business, and is very advantageous for them. Environmentally, it helps reduce the use of virgin materials, lowers energy input, and minimizes waste and emissions. Socially, it creates new employment opportunities, fosters cooperation, promotes the sharing economy, and strengthens the sense of community. Economically, it reduces costs related to raw materials, energy, environmental regulations, taxes, and insurance. Additionally, it opens new markets and attracts potential investors (Korhonen et al., 2018). Many manufacturing companies struggle to decide which Circular Strategy (CS) would be most appropriate for their business while

* Corresponding author.
E-mail address: christian-berenger.wandji-wouapi@grenoble-inp.fr (C. Wandji).

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remaining profitable both economically and environmentally. But also, how can they implement an appropriate CS to cope with the uncertainty surrounding the quality and quantity of EoL products.

This raises two major issues. Firstly, how to define a circular product strategy for an OEM. Secondly, how to implement it, in such a way as to maximize its environmental and economic benefits.

The methodology proposed in this article aims to address these concerns by introducing a tool designed to help companies, particularly OEMs, to define a CS tailored to their product. This tailored CS is based on two decisions: the take-back time of the product, and the circular process among reuse, remanufacture or recycling at the component level. The product obtained out of its components can be reused either by its previous user or by a new customer. It could be applicable to a wide range of products and can be used by OEMs. Consultancy companies can also use it to guide OEMs or other kinds of companies in transitioning their products from a linear economy to a circular one. The proposed methodology enables the most appropriate CS of a given product to be determined at its component level. Based on this methodology, a Circular Simulation Tool (CST) is designed to help both OEMs and consultancy companies make informed decisions based on environmental and economic considerations.

The present article reports on the proposed methodology and results of its application to a case study involving a circuit breaker. Section 2 reviews the state of the art on defining and implementing circular strategies. Section 3 gives an overview of the holistic methodology, while Section 4 details the results from applying the proposed methodology to the circuit breaker case study. Section 5 discusses the methodology and the outcomes obtained, and Section 6 concludes by highlighting the key takeaway.

2. Literature review

Given the benefits that circularity offers to OEMs, along with the pressures of Europe-wide environmental regulations, transitioning from a linear to a circular business model is becoming a necessity. However, the wide range of circular scenarios and the uncertainty surrounding their implementation make it difficult for OEMs to fully understand and adopt them. As a result, they struggle to define a CS that effectively reduces environmental impacts, such as CO2 emissions, while also cutting costs.

On the basis of the major issues mentioned in the introduction, the following research question is formulated: how can an OEM define a CS for a given product at a component level, in a way that minimizes both economic and environmental factors based on the hypothesis of the State of Health (SoH)?

In the literature, the issues of variability and uncertainty in circularity have been addressed through two main concepts. The first is the optimal timing for active remanufacturing, which identifies the point in time that maximizes economic and environmental benefits for remanufacturing a product (Gao et al., 2016). The terms “optimal timing for active remanufacturing” and “optimal take-back time” are nearly synonymous. However, in this article, ‘optimal take-back time’ specifically refers to a more active approach within the circular economy framework. The second concept is active remanufacturing; and is defined by Wang et al. (2012) as “*sustainable design research that takes the green design as the core and takes recycle, reuse, disassemble and environmental load into consideration during the design stage, which could endow the product with environmentally friendly characteristics*”. Besides “active”, “proactive” is sometimes used to designate “*a series of engineering activities made to implement the remanufacture of products actively at some point during their service life, aimed at ensuring the function and performance of the products of the original design, and taking high-quality, high efficiency, energy and material saving, environmental protection and the longest possible total service life as principles*” (Zhou et al., 2014).

To explore these concepts further, a search was conducted in the Web of Science database using keywords such as “take-back time” and its alternatives, including “recovery time” and “timing,” alongside circular process terms like “active or proactive” remanufacturing, reuse, recycling, and refurbishing. The terms “active” and “proactive” were used alongside other circular process terms such as reuse, refurbishing, and recycling to assess whether methodologies were proposed for the entire circular lifecycle. “Optimal take-back time” and “optimal timing” are synonymous in this context, but “take-back” was preferred to narrow the search results for a more focused exploration of the research question. Using “optimal timing” yielded around 10,000 articles, which was too broad for the study. The PRISMA method for systematic literature analysis was employed to conduct the literature review efficiently (Moher et al., 2009). Two keyword queries were made in the Web of Science database, for which 275 and 372 articles were respectively found. When (“optimal time” OR “optimal timing” OR “optimal recovery time”) were added to the query, the number of articles dropped to 150, all of which were already included in the initial query 1. Following the PRISMA method with a selection by title and abstract and an eligibility step by reading the full article, 30 relevant articles were selected from the 647 found. The PRISMA is shown in Fig. 1. The selected articles are presented by circular processes, with a brief discussion of optimization in a circular context preceding this.

Firstly, optimizing product circularity is widely discussed in the literature. Several optimization methods exist at the design stage, such as modularity, which facilitates product repairability at the EoL stage. Additionally, design-for-reuse, remanufacturing, and recycling approaches support closed-loop systems at the material, part, or product levels (Kara et al., 2022). Other methods focus on optimizing the circular supply chain itself, such as the robust programming framework for turbine blade remanufacturing proposed by Liu and Urgo (2023). Bensmain et al. (2019) introduced a hybrid genetic algorithm, combining Fix and Relax and Rolling-Horizon heuristics, to optimize production and remanufacturing planning with the goal of minimizing the product's life cycle cost from the user's perspective. Oh and Behdad (2017) addressed similar challenges by proposing a method for determining optimal reassembly and provisioning plans using a network flow graph and integer linear programming. These methods tackle the complexities of scheduling circular activities, which are often complicated by the variability, uncertainties, and unpredictability of the SoH of products.

Secondly, within the same optimization framework, the concepts of active and proactive remanufacturing are explored to manage the uncertainties related to the timing and quality of used products. According to Wang et al. (2012), to define the product's remanufacturability, the environmental and safety protection technical indexes should be taken into account at the design stage, along with profit, cost and performance of processes. This approach is being fostered by several researchers such as Liu et al. (2013), who looked at active remanufacturing to determine the optimal time to remanufacture a product component based on its technical value. Song et al. (2015), who addressed the pro-active remanufacturing, also only take into account the structural strength as a technical index. The term “technical” used in this article refers to the product's physical degradation, which is the SoH. Furthermore, Zhou et al. (2014) added the economic index in addition to the technical one to their method for assessing the remanufacturability of a product component. Liu et al. (2016), Ke et al. (2016) and Ouyang et al. (2021) also proposed models to determine an optimal schedule for active remanufacturing from an environmental perspective in addition to the technical one. Several others proposed methods with economic and environmental perspectives (Chen et al., 2019; Gong et al., 2022; Qingdi et al., 2019). Specifically, Zhang et al. (2020) proposed a method for improving the remanufacturing capability of a boom cylinder on a pump truck by determining its optimal timing. This, along with the technical, environmental and economic perspectives. Gao et al. (2016) proposed another optimal timing model with the perspective of company profit in addition to the previous ones. Very few authors, such as Zhang et al. (2023), take into account the social aspect, which is the customer perception and its acceptance of the circularity. In summary, this

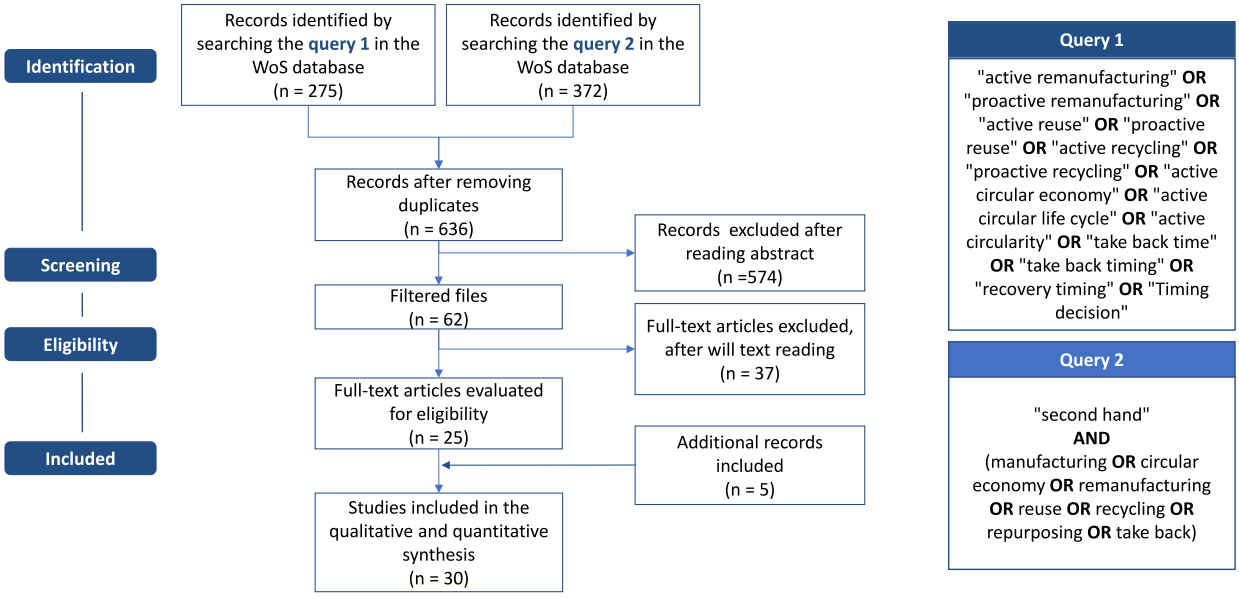

Fig. 1. Systematic review using PRISMA.

research is highly relevant for advancing remanufacturing processes, particularly for mechanical products like engines, wheels, excavators, and machine tools. It incorporates economic, environmental, technical, and social factors, as well as customer perspectives and acceptance, into an optimal timing model for active and proactive remanufacturing. These models are tailored to enhance the remanufacturing process for specific product components.

Thirdly, in the CE context, refurbishment is closely related to remanufacturing, with the primary difference being the level of performance ensured for the circular product. However, no studies were found that specifically address active or proactive refurbishment.

Fourthly, in addition to the above-mentioned circular processes, there is the reuse process. Few researchers propose optimal timing model for the reuse process. Hischier and Böni (2021) proposed a method to assess the reuse potential of second-hand electrical and electronic equipment. The Environmental Impact (EI) and the cost from the user and the company perspectives are considered in this study. This approach is passive. The process of active, proactive reuse has been explored. Few articles were found in the field of Software engineering and communications for the active and proactive reuse of coding block in software development (Boldoczki et al., 2020; Sabouri and Khosravi, 2013). This reused process enables a considerable reduction of market time of the software. There is few research on the reuse of second-hand or used products. In this way, Jalali Naini and Shafiee (2011) defined a decision-making model to determine the right balance between price and warranty for upgrading a second-hand product, with the aim of maximizing the reseller's profit. Furthermore, another pricing model for second-hand products was proposed with an optimization algorithm by Ehimwenma et al. (2022). According to the authors, the take-back time and user behaviour are the most impactful for defining the second-hand product price. Active recycling relies primarily on the customer's behaviour in reverse logistics, and on their education and knowledge of recycling methods (Zen et al., 2014). In summary, the concept of active and proactive reuse is primarily applied in software engineering, with limited focus on hardware. The few hardware-related studies do not consider environmental, economic, or technical aspects in their proposals. Additionally, optimal models for enhancing other circular processes like refurbishment, reuse, and recycling are either lacking or fail to address the critical aspect of optimal product take-back time, highlighting a significant gap.

Finally, active and proactive circular processes have been explored to some extent, particularly in the combination of CE processes. However, only a few decision-making methods in CS design have addressed two or three circular processes while considering environmental, economic, and technical aspects. For example, Xiang and Zhang (2016) proposed a decision-making model to determine which CE processes—such as remanufacturing, reuse, or recycling—are most appropriate for product components, based solely on reliability thresholds using the SoH index. Fang and Rau (2017) focused on determining the optimal take-back time for remanufacturing or reusing product components from the customer perspective. Their model accounts for economic value through the Total Cost of Ownership and technical aspects via product value. In terms of implementation, Takata et al. (2019) developed a life cycle simulation tool for the reuse and recycling of lithium-ion batteries (LiB) in electric vehicles (EVs). This tool models and evaluates circular scenarios by simulating EI, profit, customer willingness-to-pay, and the SoH of LiB for various applications, such as EVs and solar panels. In this context, willingness-to-pay refers to the amount a customer is willing to pay for a refurbishing or remanufacturing or second-hand product within the CE framework. To sum up, limited research exists on active and proactive methods that integrate multiple circular processes into a comprehensive CS. However, the available studies are valuable as they propose decision-support models and frameworks for determining the optimal take-back time for remanufacturing, reuse, and recycling. These models effectively incorporate technical, environmental, and economic factors, considering both manufacturer and customer perspectives.

In conclusion, the proposed methods for determining optimal take-back times are valuable for advancing circular thinking by considering technical factors (SoH), economic costs and benefits, and environmental and social concerns. However, these approaches have limitations. Few account for diverse applications or environmental contexts, and even fewer focus on multi-criteria optimization that evaluates technical performance in closed-loop systems. Most methods are product-specific, optimizing a single circular process for one component, overlooking the potential for other components to benefit from different circular processes like reuse or recycling. A summary of related methods and tools is provided in Table 1.

While existing research primarily focuses on optimizing a single circular process for a specific critical component in a product sold in a linear economy, our proposal offers a broader approach. The methodology we propose determines the appropriate circular process for each critical component at a given take-back year, with the objective of

Table 1
Summary of the existing methods and tools rely on in the take-back time approach for circularity improvement.

Closed-loop processes	Products use case	Authors	LCA	Profit	Social impact (user satisfaction)	Cost company perspective	Cost customer perspective	SoH	Diversity of p applications
(Pro) active Circular economy	LiB-EV	(Takata et al., 2019)	x			x		x	x
	Notebook computer	(Fang and Rau, 2017)					x	x	
	Bearing of a truck	(Xiang and Zhang, 2016)						x	
(Pro) active Remanufacturing	Machine tool CA6180	(Zhang et al., 2023)	x		x	x			
	Used engines	(Gong et al., 2022)	x			x			
	Used engine	(Ouyang et al., 2021)	x					x	
	Boom cylinder of a pump truck	(Zhang et al., 2020)	x			x		x	
	Used engine blades	(Chen et al., 2019)	x			x		x	
	Six-cylinder diesel engine	(Qingdi et al., 2019)	x			x			
	Excavator	(Q. Liu et al., 2019)				x		x	
	Crankshaft	(Z. Liu et al., 2016)	x					x	
	Connecting rod	(Gao et al., 2016)	x	x		x		x	
	Diesel engine	(Ke et al., 2016)	x			x		x	
	Crankshaft of engine	(Song et al., 2015)(Chen et al., 2019)	x			x		x	
	Six-cylinder diesel engine	(Qingdi et al., 2019)	x			x			
	Excavator	(Q. Liu et al., 2019)				x		x	
	Crankshaft	(Z. Liu et al., 2016)	x					x	
	Connecting rod	(Gao et al., 2016)	x	x		x		x	
	Diesel engine	(Ke et al., 2016)	x			x		x	
	Crankshaft of engine	(Song et al., 2015)						x	
	Crankshaft of a six-cylinder engine	(Zhou et al., 2014)		x				x	
(Pro) active Reuse & second-hand	EEE (washing machines, refrigerators, etc.)	(Hischier and Böni, 2021)	x		x		x		
	Second-hand mobile phones	(Ehimwenma et al., 2022)				x			
	Second-hand electric drills	(Jalali Naini and Shafiee, 2011)		x		x		x	

minimizing both environmental impact and cost within the context of the overall CS. In contrast to current methods, where the circular strategy is predefined, our approach begins with an unknown strategy that is determined and optimized throughout the simulation. The SoH of the product plays a pivotal role in defining the appropriate circular process for each component, which represents a distinctive aspect of this study.

Ultimately, the methodology proposed in this article addresses the limitations of current approaches by providing a comprehensive method and a CST to guide OEMs in their transition toward the circularity of their products. The objective is to provide a global solution for OEMs seeking to make their products circular, with strategies tailored to both their products and components.

3. Materials and methods

The objective of this article is to provide a comprehensive solution to help OEMs define the most appropriate CS for their products. This is achieved by determining the year (t_{TB}), where taking back a product during its use phase has the lowest EI and incurs the least cost to begin a second life. The CS for the second life, consists of a combination of circular processes for each critical product component in that year t_{TB}. A critical component is defined as a part with a high average failure rate that either performs or contributes to the product's primary and secondary functions (Wandji et al., 2022a, 2022b). The circular processes addressed in this article include remanufacturing, reuse, and recycling. The overall methodology is outlined in Fig. 2.

The proposed methodology for identifying t_{TB} involves the following steps:

(1) Assessment of the product and component SoH.
Proposal of the circular processes for each component SoH with respect to the result obtained in this assessment;
(2) Definition of the closed-loop circular processes mapping;
(3) Assessment of the product's EI using the Parametric Life Cycle Analysis (P-LCA) method;
(4) Assessment of the cost of giving a product a second life using the Parametric Life Cycle Cost (P-LCC) method;
(5) Apply a minimization algorithm for calculating t_{TB};
(6) Presentation of the dynamic circular simulation tool (CST) including the holistic method.

At each year of the use phase of the product, the SoH, EI and cost assessments are carried out. A minimization algorithm is used with the EI and Cost from the company perspective as parameters to determine the t_{TB} of the appropriate CS for giving a second life to the product. If multiple t_{TB} years emerge as potential solutions from the minimization algorithm, the SoH value is used as an additional criterion to determine the favourable t_{TB}. The algorithm takes this into account. Pareto set is used to define the set of solutions where the variables EI and Cost are optimized from the OEM's perspective. The cost from the customer perspective is not taken into account in this article to simplify the simulation model. Fig. 3 illustrates the concept combining SoH with product take-back year (t_{TB}) for circularity enhancement.

The steps of the proposed methodology are outlined in the following subsections.

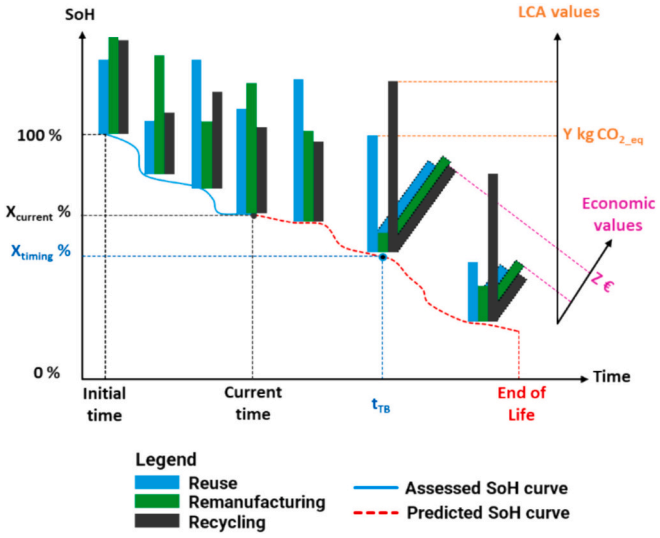

Fig. 3. Concept combining SoH with product take-back year (t_{TB}).

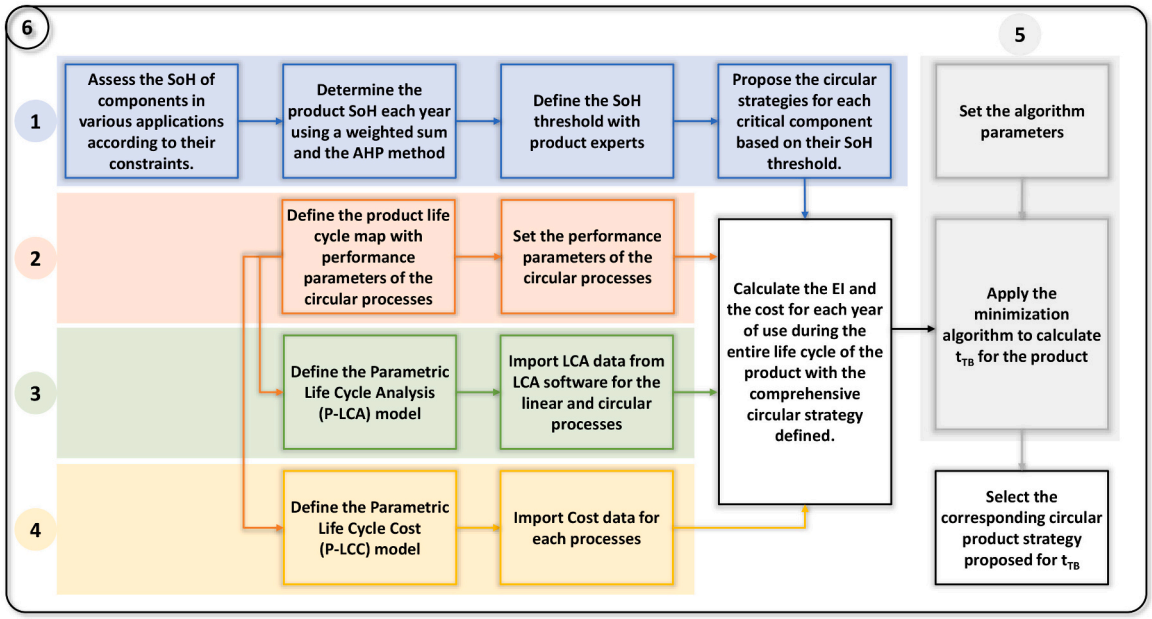

Fig. 2. Proposed methodology.

3.1. Assessment of the product SoH

The focus of this article is not to assess the product's SoH. Models for assessing product SoH are mainly developed in the context of electrical vehicle batteries (Basia et al., 2021). Wandji et al. (2022a) proposed a general framework for assessing the SoH of a complex system. The proposal involves in defining the causes and consequences of product failure linked to each component. On this basis, the parameters of the physical laws at the origin of the failure are identified and used as features to train a machine learning model. This model is used to assess and predict the SoH of critical components. The critical components are identified either using the Pareto chart method (Karuppusami and Gandhinathan, 2006) if quantitative data are available, or using the Failure Mode, Mechanism and Effects Analysis method (Liu et al., 2014) by assessing the criticality of each component. As products are typically a series/parallel/cascade structural configuration of critical components, the value for product circularity depends solely on the ageing of the critical components separately. The SoH is the state of component ageing for circularity. Based on this systematic view of the product, it is relevant to consider the relative importance of each component. For this reason, the product SoH can be calculated by a weighted average of the critical components SoH, in which the weights reflect their relative importance. This weighted average is illustrated by the Eq. (1) (Wandji et al. (2022b).

$$SoH_{prod} = \sum_{i=1}^{n} \alpha_i \times SoH_{Comp_i} \qquad 0 \leq \alpha_I \leq 1 \text{ and } \sum_{i=1}^{n} \alpha_i = 1 \tag{1}$$

where SoH_{prod}, SoH_{Compi} denote the SoH of the product and the components i $(i = 1, \ldots, n)$, respectively. α_i denotes the weight of each component i, and n the total number of critical components.

The Analytical Hierarchy Process (AHP) method, defined by Saaty (1996) is used to determine the weight of each critical component in the overall ageing of the product. First, critical components are categorized into three types: mechanical, electronic, and mechatronic. The AHP method is then applied with a product expert to determine and validate the weights of each component within its group, as well as the weights assigned to each group. Finally, the weight α_i of a critical component is calculated by multiplying its individual weight by the weight of its group.

Since the SoH of each component represents its technical value used to decide whether it could be used for circularity, it is important to determine the SoH threshold for each circular process. The definition of the SoH threshold for the mentioned circular processes is based on multiple factors. First, the health value grading system for mechanical equipment proposed by Li et al. (2011), which outlines five grades: Best (SoH between 100 % and 80 %), Healthy (SoH between 80 % and 60 %), Ill (SoH between 60 % and 40 %), Stiff (SoH between 40 % and 20 %), and Worst (SoH between 20 % and 0 %). This classification is supported by vibration standards and experimental data. Second, according to Standridge and Corneal (2014), approximately 10 % of components need to be replaced during the remanufacturing process of lithium-ion batteries. Finally, studies by Ma et al. (2024) and Chuang et al. (2024) examined the SoH threshold for lithium-ion batteries in electric vehicles (LIB-EV), focusing on decision-making for reuse, refurbishment, or recycling. These studies, along with expert input, inspired our approach to defining the SoH threshold.

There are other methods for assessing the technical value of a product using the failure rate in Preventive maintenance decision-model for circularity (Xiang and Zhang, 2016; Yeh et al., 2011). Some others estimate the residual strength (Song et al., 2015). The condition-based monitoring and predictive maintenance can also be used to assess the product value for circularity (Huang et al., 2024). Even if the product and component SoH data are used in our method as input data, the entire methodology is general enough to work with other metrics such as those cited above.

3.2. Closed-loop circular process mapping

The closed-loop process mapping shown in Fig. 4 begins with the manufacturing of the product which includes raw materials extraction, component manufacturing, internal logistics and product assembly. The distance (d_1) is from the raw materials supplier to the OEM facility. The assembly product is then transported to and installed on the customer site. The distance between the OEM and the customer site is (d_2). It is used for a certain period of time before being recovered through reverse logistics. The reverse logistics process involves deinstalling the product on the end-user's premise and the supply chain back to the assembly plant. The distance between the end-user and the OEM facility is (d_3). These distances are all expressed in [km]. Available means of transport include road, rail, air and sea. Depending on its SoH, the product is directed either to the recycling process, or to the sorting centre where it is disassembled. Depending on the SoH of its components, they are either remanufactured or directly reused as spare parts to remanufacture a product at the assembly stage within the manufacturing stage. Or as spare part for repairing an in-service product. The latter is not taken into account in this article. Waste materials, components or parts in the process are incinerated or landfilled. To each closed-loop process, an efficiency parameter has been added to demonstrate the sensitivity of the mathematical model. The efficiency of circular processes influences the product's total EI (Wandji et al., 2024).

The first parameter (ρ) is related to the efficiency of the collection process. The performance of this process may vary depending on certain factors. For example, the product's quality or visual condition can influence the decision to collect it, which in turn affects the performance of the process. The second parameter (λ) represents the efficiency of the reverse logistics process. Transportation back to the facility can have a significant impact on reverse logistics efficiency. The third parameter (β) represents the percentage of components directed to the remanufacturing process, calculated by dividing the number of remanufacturable components by the total number of components the product contains. The fourth parameter (η) reflects the efficiency of the remanufacturing process itself. Components may fail or break during this process for various reasons. The remanufacturing process is designed to restore the product to an as good as new state and involves several stages, including disassembly, testing, sorting, replacement, cleaning, and reassembly. Although these stages are part of the remanufacturing process, they are not shown individually in Fig. 4, as they are grouped under the remanufacturing block. The reuse block in Fig. 4, similarly includes several stages such as disassembly, testing, cleaning, and reassembly. The reuse process entails using a component several times within the same application domain, with its efficiency indicated by parameter (δ). The final performance parameter (ε) relates to the efficiency of the recycling process. Components that cannot be recycled at their EoL are treated as waste. Consequently, the proportion of components in "waste treatment" phase is determined by the factor that is multiplied by (1-ε) in Fig. 4. All the above parameters related to the performance of circular process phases are expressed as percentages, ranging from 0 % to 100 %. They are all considered as input data, except for (β).

Additionally, the variable (n_c) denotes the number of product cycles, defined by the product profile, while (n_{c_i}) represents the number of cycles for each component i. This latter variable is inputted in specific cases. Both variables (n_c) and (n_{c_i}) can be expressed in cycles or years. Directing a component into a closed-loop process depends on certain conditions, such as the component's SoH, SoH threshold, and expected service life.

3.3. Parametric LCA (P-LCA) method

The P-LCA method uses parameters at each stage of the product life

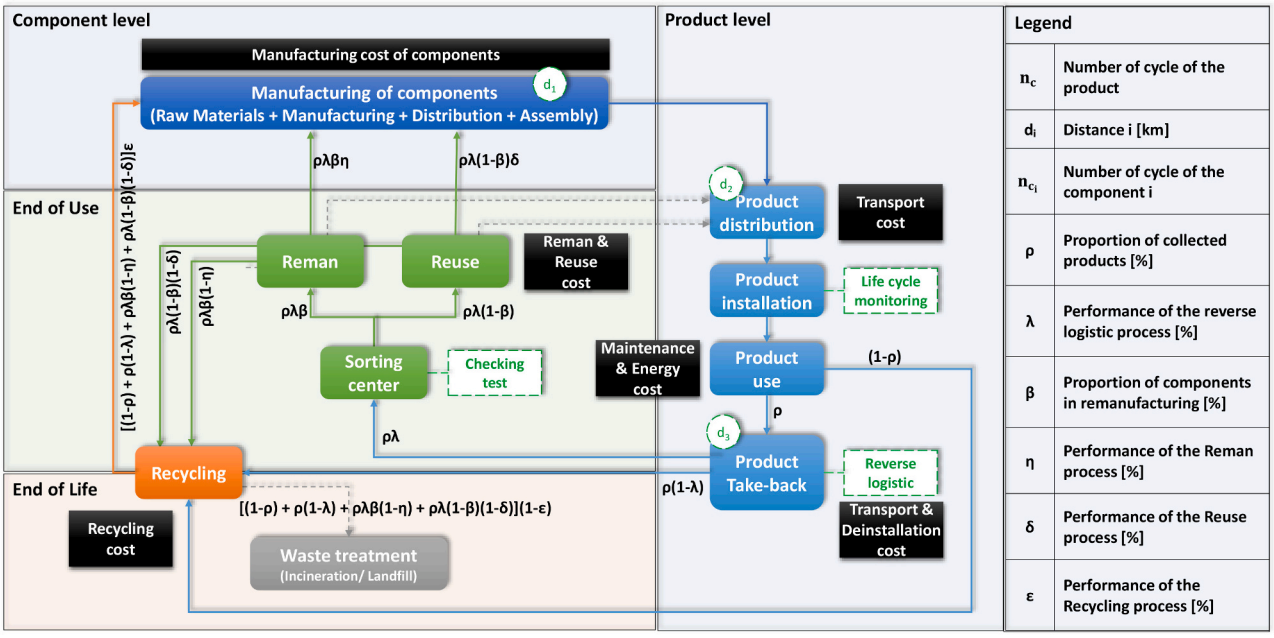

Fig. 4. Closed-loop circular process mapping.

cycle to simulate the EI of a CS scenario in accordance with the 4-step structure as conventional LCA, recommended in NF EN ISO 14044. The main difference between LCA and P-LCA is the identification of parameters in the life cycle inventory phase. But also, the definition of their values to be set in the assessment phase. This method is used to assess the EI of the product's CS each year in its use phase, as illustrated in Fig. 3. P-LCA has also been used to calculate the EI as a function of various performance parameters in the circular value chain (Wandji et al., 2024). The performance of the processes in the value chain makes it possible to determine the least EI at a given take-back year. The EI is calculated per unit of use, using the database CODDE and for each stage in the closed-loop circular process shown in Fig. 4.

The EI of processes phases are calculated using the PEF EF 3.0 method within the LCA Environmental Improvement Made Easy (EIME) software. All sixteen indicators of the PEF EF 3.0 method are assessed as data, and they are directly exported from the EIME software in Excel format for use in the proposed tool. The indicators include: Resource use, minerals and metals (kg SB eq.); Resource use, fossils (MJ); Acidification (mol H+ eq.); Ecotoxicity, freshwater (CTUe); Human toxicity, cancer (CTUh); Human toxicity, non-cancer (CTUh); Eutrophication, freshwater (kg P eq.); Eutrophication, marine (kg N eq.); Eutrophication, terrestrial (mol N eq.); climate change (kg CO2 eq.); Ionising radiation, human health (kg U235 eq.); Land use (No dimension); Ozone depletion (kg CFC-11 eq.); EF-particulate Matter (Disease occurrence); photochemical ozone formation - human health (kg NMVOC eq.); Water use (m3 eq.).

For any of these indicators, the total EI (EI_{Total}) is calculated using Eq. (2).

$$EI_{Total} = EI_{man} + EI_{dist} + EI_{inst} + EI_{use} + EI_{take-back} + EI_{reman} + EI_{reuse} + EI_{recy} \quad (2)$$

where EI_{man}, EI_{dist}, EI_{inst}, EI_{use}, $EI_{take\text{-}back}$, EI_{reman}, EI_{reuse} and EI_{recy} are respectively the Environmental Impact at the manufacturing, distribution, installation, use, reverse logistic, remanufacturing, reuse and recycling stage in the closed-loop process. The EI_{Total} is calculated for the entire life cycle of the product (i.e., the first and the subsequent lives of each component). It corresponds to the "steady state" that is established after deciding the take-back time.

The impact in manufacturing (EI_{man}) is calculated using Eq. (3). EI_{man} includes the impact of the process of raw materials extraction, component manufacturing, their distribution and product assembly.

$$EI_{mat} = \sum_{i=1}^{n} EI_{man_{components}} \times \left[\left[1 + (n_{c_i} - 1) \times \left(1 - \left(((1-\rho) + \rho(1-\lambda) + \rho\lambda\beta(1-\eta) + \rho\lambda(1-\beta)(1-\delta))\varepsilon + \rho\lambda\beta\eta + \rho\lambda(1-\beta)\delta\right)\right)\right] / n_{c_i}\right] \quad (3)$$

where parameters ρ, λ, β, η, δ, ε are defined in Fig. 4 and subsection 3.2; n is the total number of components; n_{c_i} the number of cycles of each component i; and $EI_{man_components}$ the impact generated by the processes of raw materials extraction, component manufacturing, their distribution and the product assembly themselves. $EI_{man_components}$ is computed using the method PEF EF 3.0 within the LCA EIME software.

The conventional equations are used to calculate the EI_{dist} at the distribution phase, EI_{inst} at the installation phase and the EI_{use} at the use phase.

Eq. (4) is used to calculate the EI at the take-back stage (EI_{take_back}).

$$EI_{take_{back}} = \left(\frac{(n_c - 1) \times (\rho)}{n_c}\right) \times EI_{take_{back_{product}}} \times d_3 \quad (4)$$

where $EI_{take_back_product}$ is the impact generated by the reverse logistic process itself. It is also calculated with EIME. EI_{take_back} includes the reverse transportation (d_3) and the de-installation.

Finally, the EI of the Reuse, Remanufacturing and recycling process are given by the following equations.

$$EI_{reman} = \sum_{i=1}^{n} EI_{reman_{Component_i}} \times \left(\frac{(n_{c_i} - 1) \times (\rho\lambda\beta)}{n_{c_i}} \right) \quad (5)$$

$$EI_{reuse} = \sum_{i=1}^{n} EI_{reuse_{Components_i}} \times \left(\frac{(n_{c_i} - 1) \times [\rho\lambda(1-\beta)]}{n_{c_i}} \right) \quad (6)$$

$$EI_{recy} = \sum_{i=1}^{n} EI_{recy_{EoU}} \times \frac{(n_{c_i} - 1)[1 - ((1-\rho) + \rho(1-\lambda) + \rho\lambda\beta(1-\eta) + \rho\lambda(1-\beta)(1-\delta))]}{n_{c_i}} + EI_{wt} \times \frac{[1 + (n_{c_i} - 1)[((1-\rho) + \rho(1-\lambda) + \rho\lambda\beta(1-\eta) + \rho\lambda(1-\beta)(1-\delta))(1-\varepsilon)]]}{n_{c_i}} \quad (7)$$

where $EI_{reman_{Component_i}}$, $EI_{reuse_{Components_i}}$, $EI_{recy_{EoU}}$ and EI_{wt} are the impacts generated in the Remanufacturing, reuse, recycling and waste treatment processes, respectively. They are also calculated using the EIME PEF EF 3.0 method. As illustrated in Fig. 4, waste is treated via incineration and landfill. In this article, these processes are combined into a single process designated as "waste treatment". The components of the product that are treated as waste at the recycling phase, are those that cannot be recycled.

The above equations are related to the take-back year through the number of cycles of the product (n_c) and for each component i (n_{c_i}). The product lifetime, also referred as service life, is denoted by N (in years). At any given take-back year, the number of cycles (n_c) of the product is calculated as N divided by this take-back year. This means that each component will have a number of cycles (n_{c_i}) ranging from 1 to n_c, where 1 represents the minimum, corresponding to the linear economy line from the first manufacture, and n_c represents the maximum. It is assumed that n_{c_i} cannot exceed n_c.

3.4. Parametric LCC (P-LCC) method

The P-LCC has been conducted to assess the total cost of implementing the product's CE strategy. The Total LCC (*TLCC*) is the sum of the cost at all stages in the closed-loop circular process in Fig. 4. It is calculated using the Eq. (8) below.

$$TLCC = C_{man} + C_{dist} + C_{inst} + C_{use} + C_{take_back} + C_{reuse} + C_{reman} + C_{recy} + C_{carbon_tax} \quad (8)$$

where C_{man} is the cost related to the manufacturing phase of all the product's components, C_{dist} represents the cost of the transportation of the product to the customer site, C_{inst} is the cost of the installation phase, C_{use} is the cost incurred during the product operation phase, $C_{take\text{-}back}$ is the cost of the reverse logistics that includes the de-installation and the reverse transportation costs, and C_{reuse}, C_{reman}, C_{recy} are the costs of the reuse, remanufacturing and recycling processes, respectively.

The manufacturing cost C_{man} is the sum of the costs of raw materials (C_{RM}), transport (C_t) and labor (C_{lab}) for n components of the product, multiplied by the parameter factor at the manufacturing stage, which are captioned in Fig. 4 and explained in subsection 3.2. Labor cost in this article is calculated by multiplying the hourly rate (r) by the labor time (t_k). Its expression is given by Eq. (9) below.

$$C_{man} = (C_{RM} + C_t + C_{lab})\{[[(1-\rho) + \rho(1-\lambda) + \rho\lambda\beta(1-\eta) + \rho\lambda(1-\beta)(1-\delta)]\varepsilon] + \rho\lambda\beta\eta + \rho\lambda(1-\beta)\delta\} \quad (9)$$

The product's distribution cost C_{dist} is the sum of the product transport and storage costs.

The installation cost C_{inst} is obtained by multiplying the hourly rate (r) by the installation time required.

The take-back cost C_{take_back} is assumed to be equal to the sum of the distribution and installation costs, as it is also the sum of the de-installation cost and the reverse transportation. They are assumed to be equal to the installation and transportation costs.

The cost of use C_{use} is determined by the end user. This is mainly the cost of energy consumption and product maintenance.

The costs of reuse C_{reuse} and remanufacturing C_{reman} are calculated by multiplying the hourly (r) rate by the labor time (t_k) required to reuse or remanufacture each component. The number of components (x) in each process is determined by multiplying the parameters at the reuse and remanufacturing stage, shown in the caption to Fig. 4, by the total number of components (n). Their respectful expressions are given by Eq. (10) and Eq. (11).

$$C_{reuse} = \sum_{k=1}^{\rho\lambda\beta\eta \times n} t_k \times r \quad (10)$$

$$C_{reman} = \sum_{k=1}^{\rho\lambda\ (1-\beta)\delta \times n} t_k \times r \quad (11)$$

The cost of recycling C_{recy} is obtained by adding the cost of waste treatment (C_R) (Wu et al., 2023) with the cost of recovery (C_V), multiplied by the parameter at the recycling stage in Fig. 4, and the cost of CO_2 pollution (penalties). Waste is treated by incineration and landfill. (C_V) is the cost of the recovery process to get some recycled raw materials for example. The Eq. (12) summarizes the cost of recycling.

$$C_{recy} = C_R + C_V[1 + (1-\rho) + \rho(1-\lambda) + \rho\lambda\beta(1-\eta) + \rho\lambda(1-\beta)(1-\delta)] \quad (12)$$

The carbon tax (C_{carbon_tax}) is obtained by multiplying the total quantity of CO_2 (T_{CO_2}) generated throughout the entire product lifecycle (from raw materials extraction to EoL phases) by the price per metric ton of CO_2 in Europe (P_{ton_CO2}). C_{carbon_tax} is given by the Eq. (13) below.

$$C_{carbon_tax} = T_{CO_2} \times P_{ton_{CO_2}} \quad (13)$$

TLCC represents a total cost indicator, while Profit and Gross Margin (*GM*) have been integrated into the simulation system as economic indicators (Miah et al., 2017) based on the revenues from product sales, following the approach of (Miah et al., 2017). Their expressions are given in Eq. (14) and Eq. (15) below.

$$\text{Profit} = \text{Revenue} - \text{TLCC} \quad (14)$$

$$GM(\%) = \frac{Revenue - TLCC}{Revenue} \times 100 \quad (15)$$

where the Revenue is the total amount received by the OEM for each product sold. It is the product of the quantity of products sold and the unit selling price set by the OEM, and corresponds to the revenues received by selling the product, without taking into account the margins or costs of other stakeholders such as distributors, collectors or waste treatment companies. It is important to note that while the TLCC includes costs over the entire product life cycle (including distribution, collection and waste treatment costs), the Profit and GM calculated here

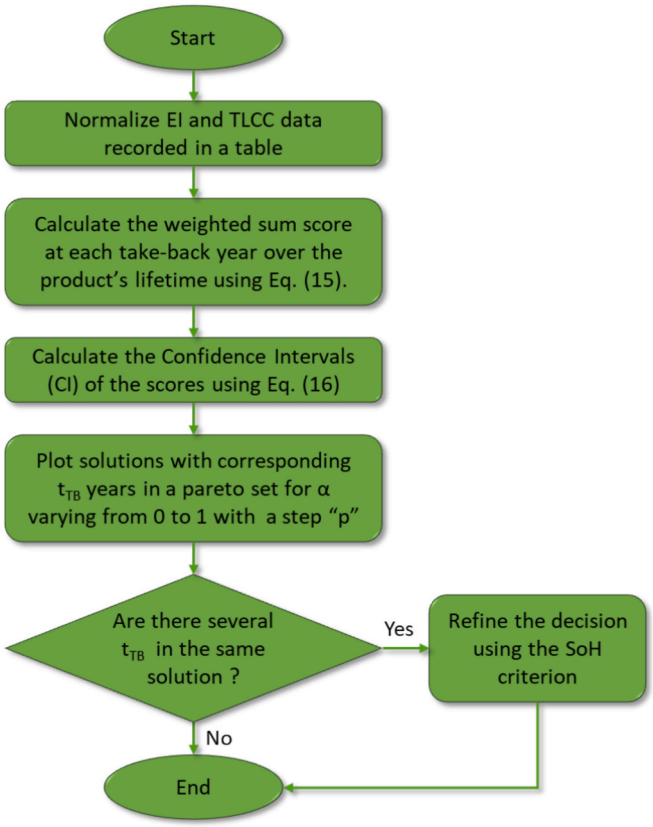

Fig. 5. Algorithm for calculating the t_{TB}.

reflect only the OEM's perspective. This means that the costs incurred by other stakeholders in the value chain are included in the TLCC, but are not directly accounted for in the Profit or GM calculations, which only consider the OEM's costs. This is also why the TLCC is used in the algorithm presented in the next subsection.

It has been assumed that the market demand remains constant over time, which simplifies the economic projections. Moreover, to keep the model simple and transparent, economies of scale have not been included in this simulation, although they may affect costs in real-world scenarios.

3.5. Algorithm for calculating t_{TB}

The goal is to find the time in years with the least EI and TLCC during the entire product's life. In instances where the weighted sum scores resulting from the algorithm for the lowest EI and the least TLCC are not the same, multiple years may emerge as potential solutions. In such cases, the SoH value is used as an additional criterion to support the final decision on the favourable t_{TB}. The algorithm is summarized in Fig. 5.

The steps in the t_{TB} calculation algorithm in Fig. 5 are detailed as follows:

(1) Normalize the data of the decision variables EI and TLCC between 0 et 1.

In accordance with the systems of equations described in subsections 3.3 and 3.4, the EI and TLCC values calculated are summarized in table form for each take-back year throughout the product's life cycle. In the normalization process, each value of EI is divided by the maximum value of all EI values. The same normalization method is employed for the TLCC values.

(2) Apply the weighted sum score to the normalized data

The objective function of the algorithm is defined as a weighted sum of the normalized values of EI and TLCC for each take-back year. The algorithm parameters **α** and **γ** are weights set by the user according to their preferences. The weight **α** is assigned to variable EI and **γ** to TLCC. The goal is to find the t_{TB} with the lowest weighted sum across the product's lifetime from year 0 to N. The weighted sum scores are calculated using the Eq. (16):

$$\text{Weighted sum score} = \alpha \times \text{EI} + \gamma \times \text{TLCC} \tag{16}$$

where **α** and **γ**, were varied between 0 and 1, reflecting their complementary relationship, where γ is defined as $\gamma = 1 - \alpha$.

Given of the structure of the equations used to calculate EI and TLCC, their models are mainly convex under typical conditions. This is because they are based on specific variables, such as n_{c_i}, which decreases as the take-back year increases. Consequently, the decrease in n_{c_i} affects the TLCC and EI models in such a way as to give them a convex appearance. Non-convexity might arise due to the change in these variables throughout the product's life cycle, possibly occurring in rare instances, especially in the last years of the product service life. This non-convexity can result in complex phenomena such as the degradation of some components or the increase in the product's maintenance cost in long term. However, it has no impact on the multi-objective model solved using the proposed algorithm, as the underlying optimisation problem is transformed into a set of systems of equations. This approach was therefore chosen because of its simplicity and low computational cost to identify the t_{TB} year with the lowest EI and TLCC.

(3) Apply Pareto front to find the ideal value ranges for the weights, along with their corresponding 95 % confidence intervals.

The Pareto front contains the set of all solutions of the algorithm. In this case, the pareto front represents solutions for all combinations of **α** and **γ**. The weights **α** and **γ** in the weighted sum, were varied from 0 to 1 and from 1 to 0 respectively, with a variable "p" step. Then, for each of their combination, the weighted sum score is calculated each year over the product's lifetime to determine the t_{TB}. Therefore, for each variation of **α** and **γ** between 0 and 1, a t_{TB} is identified. Finally, a table is constructed with the values of the EI and TLCC for each identified t_{TB}. From this table, the Pareto front is represented with the normalized values of EI in x-axis and normalized values of TLCC in y-axis. This approach allows for the identification the set of solutions where EI and TLCC are minimized, representing all t_{TB}. Following this, Confidence Intervals (CI) are calculated for each solution using Eq. (17) (Arfken et al., 2013).

$$CI = \left[\mu - \frac{t^*\sigma}{\sqrt{m}}, \mu + \frac{t^*\sigma}{\sqrt{m}}\right] \tag{17}$$

where *CI* is the confidence interval, μ is the mean of the data, σ is the standard deviation of the data, t is the t critical value from the Student's t distribution for a confidence interval of 95 % with a freedom degree of $(m - 1)$, and m is the number of data points (the sample size). The t distribution is used because it is designed to be used with low data points (<30), as in our case where the data points of the algorithm's solutions are generally <30.

3.6. Dynamic circular simulation tool (CST)

Simulating a CS that includes P-LCC, P-LCA, along with a take-back year method, is a challenging task. Moreover, simulating and comparing multiple CS is even more complex. To address this challenge and enable the use of a holistic approach, a dynamic and interactive simulation tool was developed in Excel, in collaboration with an industrial partner. The aim of this tool is to assist and guide decision-makers in simulating and comparing various CS options, ultimately helping them adopt a CS that ensures the lowest possible EI and TLCC. This tool, referred to as the "Circular Simulation Tool" (CST), is a software implementation of the

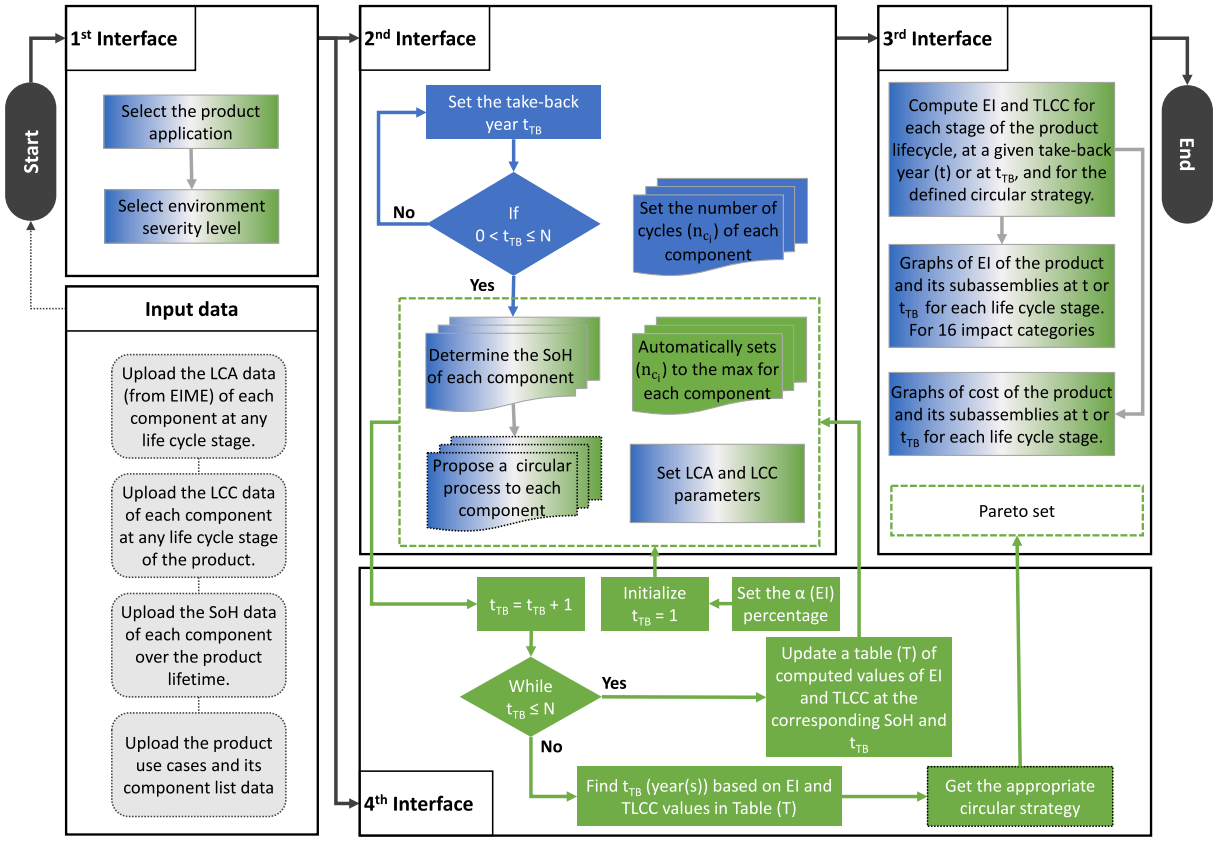

Fig. 6. Circular simulation tool flowchart.

holistic method designed to determine the CS for a given product, focusing on t_{TB} for a specific OEM. The development of the CST took approximately eight months of collaborative work with key experts from the partner company to collect accurate and relevant data for simulations. Several workshops were conducted during this period.

The first workshop, called the "Product ageing," involved technical and marketing experts. Its objectives included defining various applications and environmental constraints for each application, identifying reusable subassemblies and components across multiple product life cycles, and providing SoH data for each identified subassembly along with the product's SoH thresholds.

The second workshop, named "LCA," brought together an ecodesign expert and a technical expert. The goal was to gather data on the current LCA of the product, reorganize this data by previously defined subassemblies, and establish assumptions about the impacts of circular processes such as reuse and remanufacturing, supported by scientific literature.

A third working group, called "Circular Economy," comprised technical experts, ecodesign specialists, and sustainable development professionals. This group focused on collecting data on manufacturing and/or purchasing costs for subassemblies, defining and validating relevant parameters for TLCC and EI calculations, determining processing times, and making assumptions regarding the times and costs of circular processes.

These workshops contributed to structuring the tool's interfaces and gathering the necessary data for simulations. The CST architecture is illustrated in Fig. 6. The tool operates as follows:

(0) **Input Data Loading**: Users load input data, including EI data from LCA software (like EIME) for each step of the complete value chain and for each product subassembly; cost data for each subassembly and each step of the value chain; a list of product subassemblies, their various applications, and the expected service life of each subassembly by application; and SoH data for subassemblies during their use phase across different applications.

(1) **Application Selection**: In the first interface, the user selects an application from a dropdown menu and specifies the severity level of the application environment in which the product is used. These responses help identify the corresponding product profile and the SoH of its subassemblies.

(2) **Parameter Setup**: Upon confirming this first step, the user is directed to the second interface, which is used to set performance parameters for circular processes (ρ, λ, β, η, δ, ε), distance parameters, the number of cycles for each subassembly (n_{c_i}), and cost-related parameters like processing times and hourly rates, etc. It also used to input a valid take-back year for the product, which allows the calculation of the SoH of the subassemblies of the product at that time. These are then compared against predefined SoH thresholds to propose an appropriate circular process for each subassembly.

(3) **Results**: Using equations defined in previous sections for the closed-loop process illustrated in Fig. 4, the tool calculates results, which are presented in the third interface. These include the EI and costs of the product and its subassemblies at each stage in the closed-loop process, for each year. Users can view EI results across 16 environmental indicators and also see economic indicators like profits and gross margin. A comparative analysis between the simulated strategy, a linear strategy, and a circular strategy without take-back year is also displayed for the complete product lifecycle.

Advanced results: The tool calculates the t_{TB}, and proposes a CS for each subassembly at that time. A simulation for determining t_{TB} is planned in the fourth interface using the algorithm in Fig. 5. In this interface, users input their preferences (in percentage weights terms for **α** and **γ**) between EI and TLCC. This preference is considered in calculating t_{TB}, which is the take-back

year where EI and TLCC are the lowest according to user preferences. The algorithm is computed as follows: EI and TLCC are calculated annually for take-back year iteratively varying from 1 to N. These data are stored in a table with the SoH values of the product corresponding to each year. The algorithm is then applied to these data to determine t_{TB}, which has a CS proposed at the second interface. A Pareto set of all possible solutions is finally represented with a 95 % confidence interval to help users in their decision-making process.

3.7. Empirical data collection and parameterization of the CST

The proposed method has been applied to the case of an industrial circuit breaker to define the appropriate CS based on the concept of take-back year. The circuit breaker is an electrical product used to protect installations. it is made up of 19 subassemblies presented in Table 3. The weight of subassemblies in the degradation of the circuit-breaker was determined using the AHP method with the help of industrial experts in ageing models.

To determine the SoH thresholds for the circular processes, a workshop was organized with two experts: one is a technical product expert and the second is a product ageing expert. They were asked to rate the SoH of each sub-assembly in different use cases. They determined that a subassembly which has a SoH of 20 % or less is unhealthy and therefore can be recycled and considered as waste; and the one with a SoH of >70 % is considered as healthy and can be reused. To this end, it was assumed that a subassembly is remanufactured when its SoH is between 20 % and 70 %. Coil and trigger unit subassemblies are subject to replacement after 10 years of use. A new circuit breaker is sold at €10,000 for a 12-year and 15-year service life in the Genset and Hospital applications, respectively. The two applications also differ significantly in their environmental conditions. For instance, vibrations are intense in the Genset, while negligible in the Hospital setting. Additionally, their operating conditions vary: the load factor ranges from 20 % to 85 % in the Genset, compared to 40 % to 60 % in the Hospital. Lastly, their maintenance schedules also differ, in particular regarding preventive replacement plans. In the Genset, key components like coils and the Trigger Unit are replaced every 15 years, whereas in the Hospital application, the same parts are replaced every 10 years. We have also assumed that a remanufactured circuit breaker can be sold 30 % cheaper. The parameters ρ, λ, η, δ and ε of the closed-loop process in Fig. 4 were varied from 0 % to 100 % with a deviation of 20 %. Subassemblies are set to their maximum number of cycles (n_{c_i}) during the simulation.

The proposed methodology can be applied to implement a decision-support tool enabling the comparison of three scenarios. The aim is to see whether the proposed circular strategy (Sc_2) is economically and environmentally advantageous compared with the basic strategy (Sc_0) and the conventional circular strategy (Sc_1). The scenarios are presented in Fig. 7. LCA is calculated with the functional unit: "To protect an installation against overloads and short-circuits in circuits with a rated voltage of up to 690VAC and a rated current of 2500A, for a period N of use". N is 24 years and 30 years Genset and Hospital application, respectively. The reference flow for a pairwise comparison between scenarios is a unit of use. The LCA is conducted with the defined study boundary being the cradle-to-cradle boundary, as illustrated in Fig. 4. The original LCA data for the product are empirical data supplied in EIME format by the industrial partner. It was assumed that the EI of the remanufacturing and reuse processes themselves represented 20 % and 5 % of the EI of the manufacturing process from the original LCA data. The LCC is calculated over the circuit breaker's entire life cycle. Data on manufacturing cost are also empirical data supplied by the OEM partner. The hourly rate (r) was set to €24/h. Remanufacturing time was assumed to be equal to the manufacturing time for each subassembly. The cost per metric ton of CO2 considered is €100/t CO2_eq. We have assumed that the installation time (duration) is double the time required to uninstall the circuit breaker in a system. The energy consumed by the circuit breaker in service has not been taken into account, as it is not the OEM's responsibility. The number of maintenance operations has been set at twice a year, and operating costs have been set at €500 for 30 years of operation. The distance d_1 is 3000 km, d_2 and d_3 are equal to 750 km and the distance to the recycling site is neglected.

Sc_0 is the basic 2-cycle scenario in which a new circuit breaker is used in each cycle, and then disposed of at the end of its life cycle. Sc_1 is a classic circular scenario, in which a new circuit breaker is remanufactured and/or reused at the end of its first life cycle, to be used in the second cycle as a remanufactured product. At the end of its second cycle, it is disposed of as waste. Sc_2 is the proposed circular scenario based on the take-back year method. In this scenario, the product is remanufactured before reaching its EoL, meaning it undergoes remanufacturing at a certain point during its use phase. As a result, the total service life (N) in Sc_2 is longer than in the other two scenarios. However, for a fair comparison between all three scenarios, the functional unit should be the same. Conversely, the total service life should be the same. This means that the last cycle of the product in Sc_2 is halted, thereby eliminating the need for recycling since the product is still operational.

The values of the results presented in this article have been normalized as a percentage for confidentiality reasons.

3.8. Sensitivity analysis

The methodology proposed contains a number of parameters and

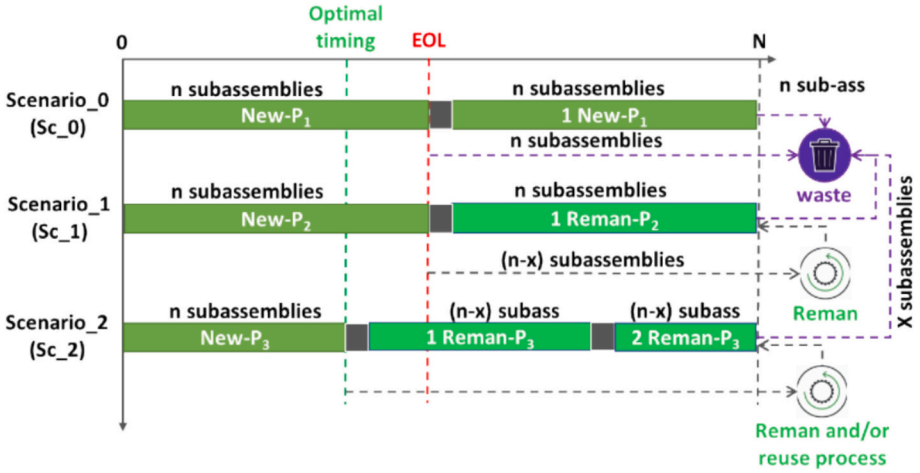

Fig. 7. Circular comparative scenario.

assumptions that could potentially lead to errors and variability in the results. In order to assess the sensitivity of these parameters and to determine the impact of this sensitivity on results for decision-making, a sensitivity analysis is carried out. The parameters and assumptions involved in the analysis are classified into two categories: (1) the parameter of the SoH threshold and (2) the parameter of the closed-loop process.

(1) The parameter of the SoH threshold

The dependency rate is used to assess the variability of EI and TLCC results for variations in SoH thresholds. The dependency ratio is calculated by measuring the relative change in EI and TLCC values in response to variations in SoH thresholds, compared to their reference values at SoH thresholds of 20 % to 70 %. It is defined as the difference between the variable value and the reference value, divided by the reference value. The upper (70 %) and lower (20 %) SoH thresholds were individually reduced by 10 %, then 20 %, then increased by 10 % and 20 %. This resulted in the following thresholds variations:

- 10 % - 70 %: below 10 %, subassemblies are recycled; between 10 % and 70 %, they are remanufactured; and above 70 %, they are reused.
- 0 % - 70 %: between 0 % and 70 %, subassemblies are remanufactured; above 70 %, they are reused.
- 30 % - 70 %: below 30 %, subassemblies are recycled; between 30 % and 70 %, they are remanufactured; above 70 %, they are reused.
- 40 % - 70 %: below 40 %, subassemblies are recycled; between 40 % and 70 %, they are remanufactured; above 70 %, they are reused.
- 20 % - 60 %: below 20 %, subassemblies are recycled; between 20 % and 60 %, they are remanufactured; above 60 %, they are reused.
- 20 % - 50 %: below 20 %, subassemblies are recycled; between 20 % and 50 %, they are remanufactured; above 50 %, they are reused.
- 20 % - 80 %: below 20 %, subassemblies are recycled; between 20 % and 80 %, they are remanufactured; above 80 %, they are reused.
- 20 % - 90 %: below 20 %, subassemblies are recycled; between 20 % and 90 %, they are remanufactured; above 90 %, they are reused.

The sensitivity analysis involves varying the SoH thresholds as indicated above, calculating the EI and TLCC results and determining the t_{TB} and corresponding CS for each variation.

First, calculate annually the dependency rate on each EI and TLCC result obtained for each variation with respect to the reference SoH thresholds of 20 % to 70 %. Represent the annual dependency rates in the form of a heat map for EI and TLCC and interpret the results. The dependency rates calculated allow the sensitivity of the CST to the uncertainty in the SoH thresholds to be assessed.

Finally, apply the Pareto front to the AR and TLCC results obtained for each variation of the SoH thresholds, with a variation of the weights **α** and **γ** of the algorithm with a given step, in order to determine the set of solutions. Represent all these solutions in the form of a scatter plot with the Pareto front and also interpret the results. The purpose of this final analysis is to assess the consistency of the definition of the SoH thresholds for minimizing as much as possible its impact on CST.

(2) The parameter of the closed-loop process

The sensitivity of the parameters within the closed-loop process may potentially influence the resulting outcomes. The objective of the sensitivity analysis is to assess the extent to which the results may vary as the performance of the circular process is either reduced or enhanced. To demonstrate this sensitivity, the values 100 %, 80 %, 60 %, 40 %, 20 % and 0 % were, in turn, assigned to the parameters ρ, λ, η, δ and ε in the closed-loop process illustrated in Fig. 4. The weighted sum scores for each take-back year were calculated using the Eq. (16), which represents the weighted sum of the normalized EI and TLCC values, with both **α** and **γ** weighted at 50 %. The weighted sum results for each parameter value (i.e., 100 %, 80 %, 60 %, 40 %, 20 %, and 0 %) are then plotted on the same graphical curve to observe the deviations. It should be noted that the sensitivity of each circular process has not been assessed individually in this article, but this remain possible in the CST.

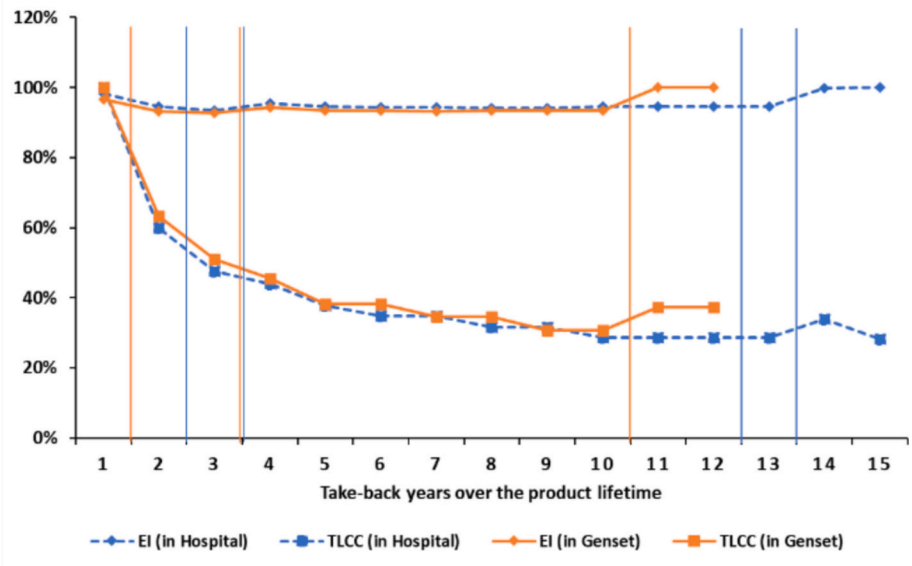

Fig. 8. Normalized values of EI and TLCC each year for Genset and Hospital applications.

Table 2
Take-back years by combination intervals of **α** and **γ**.

Genset			
Years	SoH	**α** (EI)	**γ** (TLCC)
2	84%	100%	0%
7	53%	94 - 99%	1 - 6%
9	35%	0 - 94%	7 - 100%
10	25%	0 - 94%	7 - 100%
Hospital			
Years	SoH	**α** (EI)	**γ** (TLCC)
3	76%	96 - 100%	0 - 4%
8	46%	86 - 95%	5 - 14%
9	39%	86 - 95%	5 - 14%
10	36%	9 - 85%	15 - 91%
11	34%	9 - 85%	15 - 91%
12	31%	9 - 85%	15 - 91%
15	3%	0 - 8%	92 - 100%

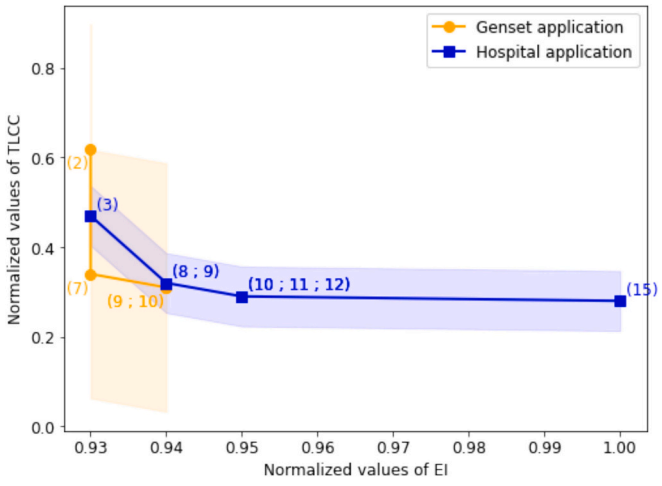

Fig. 9. Pareto front of normalized values of EI and TLCC.

4. Results

4.1. Circular strategy simulations

The CST is used to define the CS through simulations. First, the EI and TLCC for each year of take-back were calculated. All parameters ρ, λ, η, δ and ε in the closed-loop process were set to 100 %. Fig. 8 shows the results of this calculation for the above-mentioned Genset and Hospital applications. The "climate change" indicator was used to calculate the EI shown in Fig. 8. Based on the assumptions made for circular process thresholds in subsection 3.7, subassembly service life, constraints and take-back year, the circular process is recommended by the tool.

In the case of Genset, for example, the reuse process is assigned to all subassemblies if the take-back year is the first year of use (*represented by the area delimited by the first orange vertical line in* Fig. 8). In the second and third years, the remanufacturing and reuse processes are assigned to subassemblies in different proportions (*represented by the area between the first and second orange vertical line in* Fig. 8). The remanufacturing of all subassemblies is assigned to the tool when the take-back year is between the fourth and tenth year (*represented by the area between the second and third orange vertical line in* Fig. 8). Finally, if the take-back year is between the eleventh and twelfth year, the circular process assigned is recycling (*represented by the last area from the third orange vertical line on* Fig. 8).

After calculating the EI for the "climate change" indicator and the TLCC for each year, the t_{TB} is determined using the algorithm. The program is run by varying the weights **α** and **γ** from 0 to 100 % with a step of 1 %. They are initialized to 0 % and 100 % respectively and, at each iteration, **α** is increased by the step, while **γ** is decreased by the same step. Table 2 summarizes the years of take-back with the combination intervals of **α** and **γ** in addition to the product SoH. The SoH values in this table are empirical data supplied by the industrial partner, and based on ageing model.

The Pareto front was used to determine the set of optimal solutions of normalized EI and TLCC values as a function of take-back year determined with the combination of **α** and γ. Fig. 9 shows the Pareto front for both applications with confidence intervals. The orange curve corresponds to the Genset application, the points 0.62 and 0.34 on the TLCC axis are linked to years 2 and 7, respectively, while the point 0.31 is linked to years 9 and 10. The point with the value of 0.62 on the TLCC axis appears to be a weak Pareto optimal, in contrast to the other points, which are strong Pareto optimal. According to Table 2, for a variation of **α** of between 0 % and 94 % and **γ** of between 7 % and 100 %, years 9 and 10 represent the t_{TB}. In terms of product SoH for these years, year 9 has a higher technical value than year 10 for the same economic and environmental value. Year 9 is therefore the most appropriate. The CS simulation with year 9 assigned all subassemblies to the remanufacturing process. These results were obtained with 95 % confidence, illustrated by the shaded bands around the lines (orange for Genset, blue for Hospital). These bands show the margins of error around the TLCC values calculated from the standard deviations.

In the case of Genset, the recommended CS is thus to take-back the product after 9 years of service and remanufacture it for a second life of 9 years. The large orange band indicates a less precise confidence interval at 95 %. This indicates significant variability in the TLCC data.

Applying the same reasoning to the Hospital application, years 10, 11 and 12 correspond to the normalized TLCC value, 0.29 on the blue curve. The remanufacturing process is also recommended to give the product a second life at these take-back years. Here, the appropriate year should be selected taking into account the point of view of the product owner (end user), as the difference in technical value (SoH) for these three years is acceptable. The narrower blue band shows greater precision and less variability in the TLCC data from this application.

In both applications, the variability of EI data is very low, if not negligible.

4.2. Circular strategy comparison

A comparison was made between the three scenarios defined in

Table 3
Lifecyle (n_{c_i}) of subassemblies by applications and scenarios.

N°	Subassemblies	Genset			Hospital		
		Sc_0	Sc_1	Sc_2	Sc_0	Sc_1	Sc_2
1	Mobile Contact	1	1	3	1	1	3
2	Fixed Contact	1	2	3	1	2	3
3	Arc Chamber	1	1	3	1	1	3
4	Charging Motor	1	2	3	1	2	3
5	Clusters	1	1	3	1	1	3
6	Connection Terminal	1	2	3	1	2	3
7	Trigger Unit Base	1	2	3	1	2	3
8	Trigger Unit	1	1	2	1	1	1
9	Coils	1	1	2	1	1	1
10	Sensors	1	2	3	1	2	3
11	Filerie (Electrical Cable)	1	2	3	1	2	3
12	Housing And Accessories	1	1	3	1	1	3
13	Plastron	1	2	2	1	2	3
14	Mechanism	1	1	3	1	1	3
15	Pole Shaft	1	2	3	1	2	3
16	Mechanism Chassis	1	1	3	1	1	3
17	Chassis base	1	1	3	1	1	3
18	Auxiliary contacts	1	2	3	1	2	2
19	Other accessories	1	1	3	1	1	3
	Circuit-breaker lifecycles	1	2	3	1	2	3

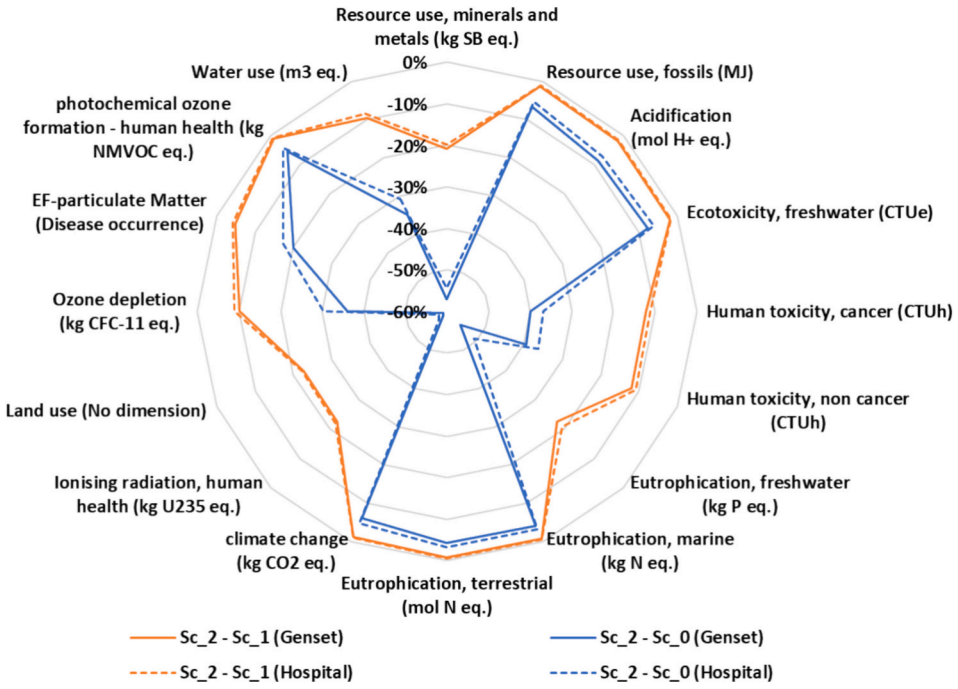

Fig. 10. EI comparison by scenario for Genset and Hospital application.

Fig. 7, to highlight the advantages of a CS based on the take-back year method. The parameters ρ, λ, η, δ and ε of the closed-loop process were set to 100 %. Product EIs were assessed for all three scenarios in the ideal case. In the Sc_0 scenario, two new products are used, one life cycle for each subassembly. Due to their lifetime and technological constraints, the coil and trigger unit subassemblies can only have one lifecycle in Sc_1 and Sc_2 of the Hospital application. But two lifecycles in Sc_2 of the Genset application. The other subassemblies are used for two cycles maximum in Sc_1 and three max in Sc_3. In Sc_1, nine under nineteen sub-assemblies are refurbished at their end of first life, the others are recycled and replaced by new ones. This is the conventional circular strategy defined for the Sc_1 in both applications as shown in Table 3.

The EI of the Sc_2 is assessed at t_{TB} equal 9 in Genset and 11 in Hospital application. The EF 3.0 PEF indicators are taken into account, and the comparison is made at two levels. Firstly, between Sc_2 and Sc_1, and secondly between Sc_2 and Sc_0. Fig. 10 shows the results of this comparative analysis for all the indicators.

The EI deviation of the Sc_2 in relation to the Sc_1 is between −1 % and − 29 % according to the indicators, and for the two applications. For the climate change, it is −1 % per unit of product use in both applications. Which means, the CO_2 emissions is reduced by 1 % with a proactive circular economy (*circular economy based on take-back year method*).

Compared to the previous comparison, the difference between Sc_2 and Sc_0 is much greater. The difference ranges from −3 % to −59 % for both applications. In the case of climate change indicators, the deviation is −6 % for Gensets and − 5 % for Hospitals, as well as for the fossil resources indicator. As for the use of mineral resources and metals, SC_2 reduced them by 57 % for Genset and 54 % for Hospital. This is very significant for the environment.

This demonstrates the advantages of a proactive CE over the linear economy and the conventional CE. Sc_1 also has a considerable EI advantage over Sc_0. Across all the indicators, the difference is between −3 % and − 47 %. This represents −5 % CO2 reduction for the Genset and − 4 % CO2 reduction for the Hospital.

In addition to EI, cost, profit and gross margin were calculated and

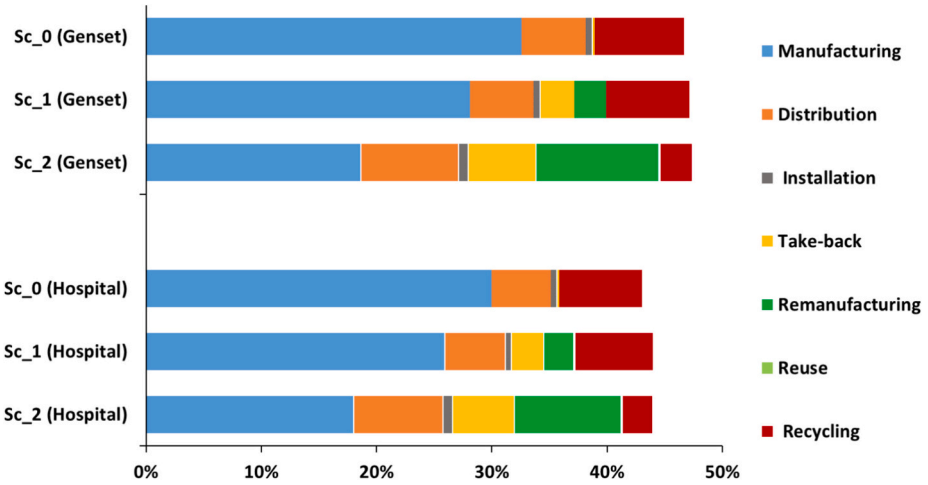

Fig. 11. TLCC per applications in each scenario.

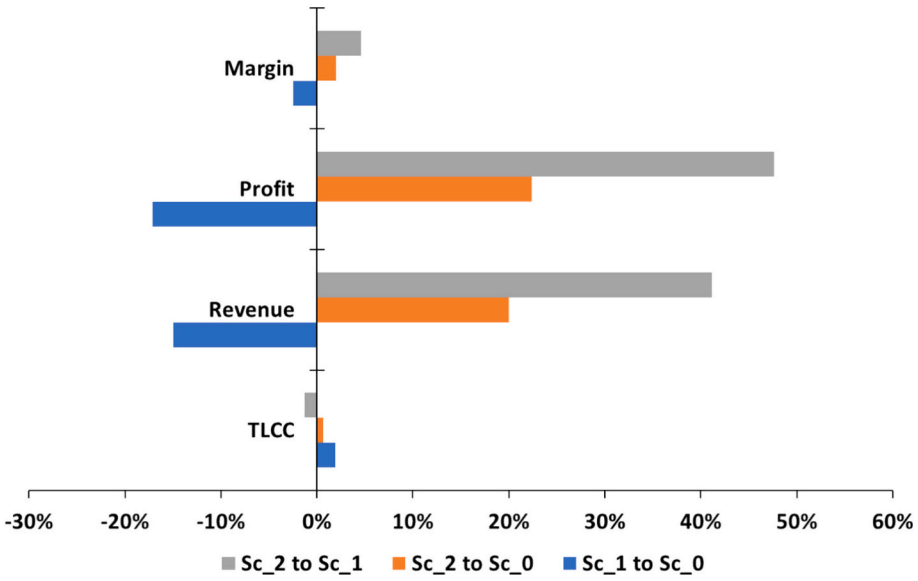

Fig. 12. Economic benefits of the breaker pro-active circularity in Genset.

compared between the three scenarios. The three strategies defined in section 3.7 are simulated in CST for cost proposed. The Fig. 11 presents the cost per application in each scenario and for each life cycle stage of the product.

The circular scenario reduces the cost of manufacturing in Genset and Hospital applications. Sc_1 is 13 % cheaper than Sc_0, Sc_2 is 31 % cheaper than Sc_1 and 40 % cheaper than Sc_0. The proactive CS reduces manufacturing costs by almost half. On the other hand, the proactive CS adds other costs associated with closed-loop processes, such as remanufacturing, reverse logistics, sorting centres, etc. With manufacturing costs accounting for over 50 % of the TLCC, the added costs of closed-loop processes can offset the reduction, and even less if their processes

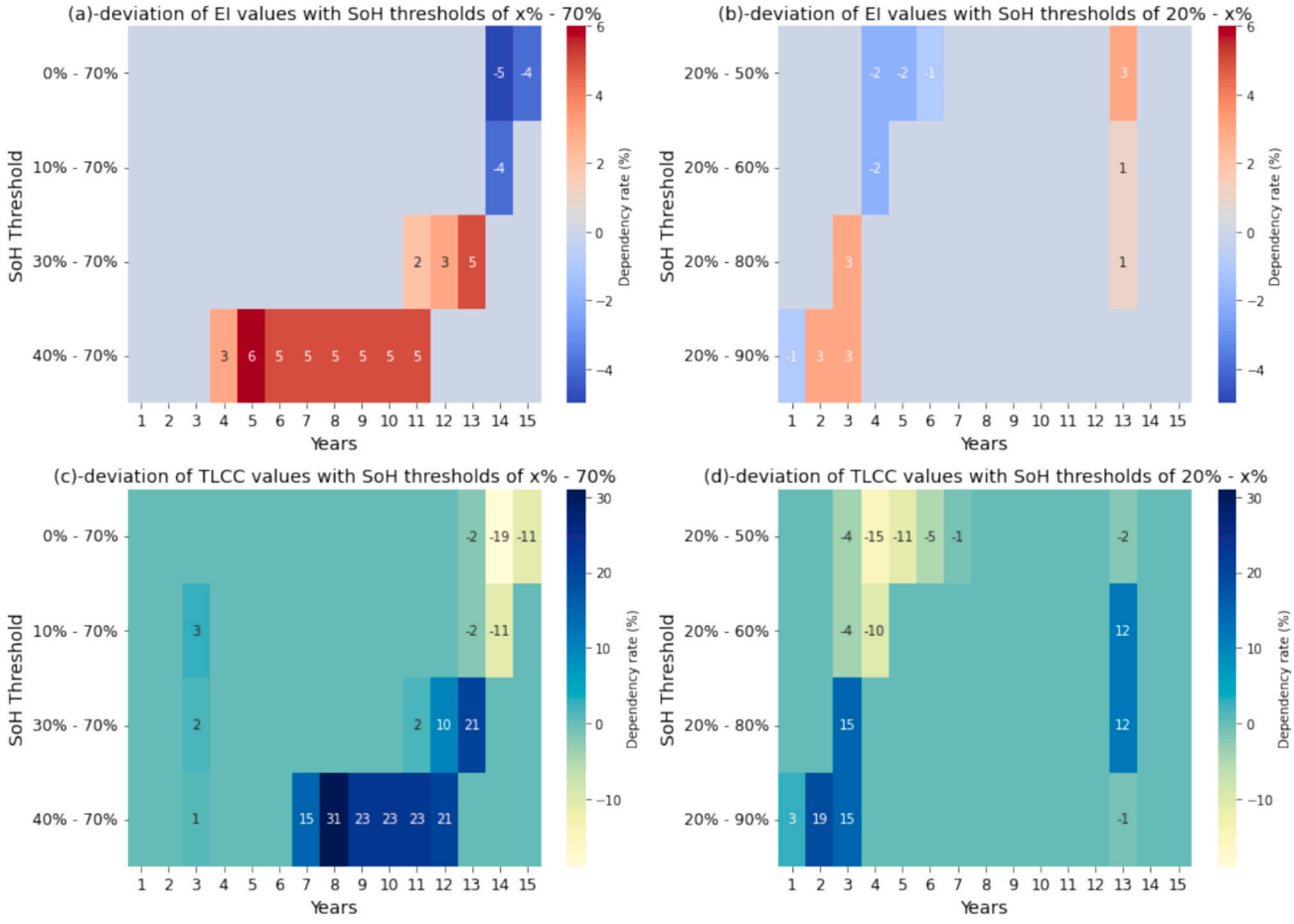

Fig. 13. Heatmaps of the annual dependencies rate of EI and TLCC results in Hospital application, based on SoH threshold.

are optimized. In Fig. 11, the TLCCs of Sc_2 and Sc_1, are both <1 % higher than Sc_0 in both applications. The TLCC of Sc_2 is 0.1 % lower than that of Sc_1.

With Sc_2, two remanufactured circuit breakers in addition to the first new circuit breaker are supplied to the customer. One remanufactured circuit breaker in addition to the first new circuit breaker is supplied with Sc_1. Based on the price of one new and one remanufactured circuit breaker, Sc_2 revenues are around 40 % higher than Sc_1 and 20 % higher than Sc_0 for both applications. It is assumed that customers perceive the value of circularity and are willing to spend more on an environmentally-friendly circuit breaker. Fig. 12 shows that Sc_2 has less TLCC than Sc_1, more than Sc_0 and more margin, profit and revenue than Sc_0 and Sc_1.

Margin of Sc_2 is 2 % higher than that of Sc_0 and 5 % higher than that of Sc_1. Sc_2 is therefore more profitable than Sc_0 and Sc_1. The benefit of Sc_2 is 22 % higher than that of Sc_0 and 47 % higher than that of Sc_1 in both applications. This result is mainly due to the number of circuit breakers in service in each scenario.

4.3. Sensitivity analysis results

The recommended circular strategies based on the use of the CST demonstrated a benefit of up to 7 % and 5 % in terms of EI for the "climate change" indicator, in Genset and Hospital applications, respectively. In addition, it generates an additional 18 % profit over linear savings, with a TLCC of <1 %. This result is based on certain assumptions for defining the parameters. The CST uses several parameters that may affect the final CS and even the t_{TB}. This subsection presents the sensitivity analysis results on the different parameters subjects to uncertainties. These results have been organized in two groups as follow.

(1) – Sensitivity of the parameters of SoH thresholds

The first group is for the parameters of SoH thresholds. Setting SoH thresholds as a condition for the reuse, remanufacture or recycling of a component or product is highly complex and depends significantly on the type of product. Therefore, applying the proposed methodology to another product may require redefining the thresholds to suit the product in question. The main method for defining thresholds is based on expert opinion on the product, experiments and the circular processes concerned. This brings a high degree of uncertainty to the results. In the case of the circuit breaker, the results are likely to change if the SoH thresholds are changed. For example, changing the SoH threshold may change the position of the vertical lines in Fig. 8. Lowering the upper State of Health (SoH) threshold from 70 % to 50 % reduces the take-back interval for remanufacturing in the Genset application. The take-back interval, indicated by the years between the second and third orange lines in Fig. 8, currently spans 4 to 10 years. By implementing the new threshold, this interval may narrow to 7 to 10 years, effectively shifting the second orange line in Fig. 8 from year 4 to year 7. To assess the variability of results according to SoH thresholds, the dependency ratio was applied to the AR and TLCC results, as described in subsection 3.8.

The annual dependency rates obtained following variations in SoH thresholds (*in subsection 3.8*) are illustrated on the heatmap in Fig. 13. It shows four heatmaps, organized in two rows and two columns, representing the deviations of EI ("climate change" indicator) values and TLCC based on SoH thresholds mentioned above. In Fig. 13(a), the bottom-left area shows positive deviations (up to 6 %), indicating an increase in EI with an increase of SoH thresholds (up to +20 %). Negative deviations (up to −5 %) are concentrated in the top-right, signalling a reduction in EI with a decrease of SoH thresholds (up to −20 %). Fig. 13(b) mainly shows slight deviations with little variation. However, certain years and thresholds exhibit positive increases in EI. For these thresholds, EI appears to have slightly increased. In these first two heatmaps, it can be seen that increasing the SoH lower threshold by 20 % (i.e., from 20 %–70 % to 40 %–70 %), leads to an increase in EI values in certain years with a low relative dependency rate of up to 6 %. And conversely, a 20 % reduction in the lower SoH threshold (i.e., from 20 %–70 % to 0 %–70 %), leads to a reduction in EI values in certain years, with a low relative dependency rate of up to 5 %. This means that EI is slightly sensitive to uncertainties in the lower SoH threshold. This is also observed when the upper SoH threshold is varied (i.e., from 20 %–70 % to 20 %–90 % or 20 %–50 %). This testifies to the robustness of the proposed methodology. In contrast, in Fig. 13(c), significant positive deviations in TLCC values are visible for some years with SoH thresholds (up to +31 %). Negative values are also characterised at lower SoH thresholds, with reductions reaching −19 %, meaning that TLCC values decreased in some configurations with low SoH thresholds. In Fig. 13(d), there are significant TLCC reductions in some configurations (up to −15 %) with a decrease in SoH upper threshold (up to +20 %, from 20 %–70 % to 20 %–90 %), which could indicate long-term cost savings. However, certain years show significant increases in costs (up to +19 %). This may represent a weakness in some SoH parameters assumed for the proposed methodology.

An in-depth analysis was conducted to examine the dependence of the identified circular strategies on take-back years, which were

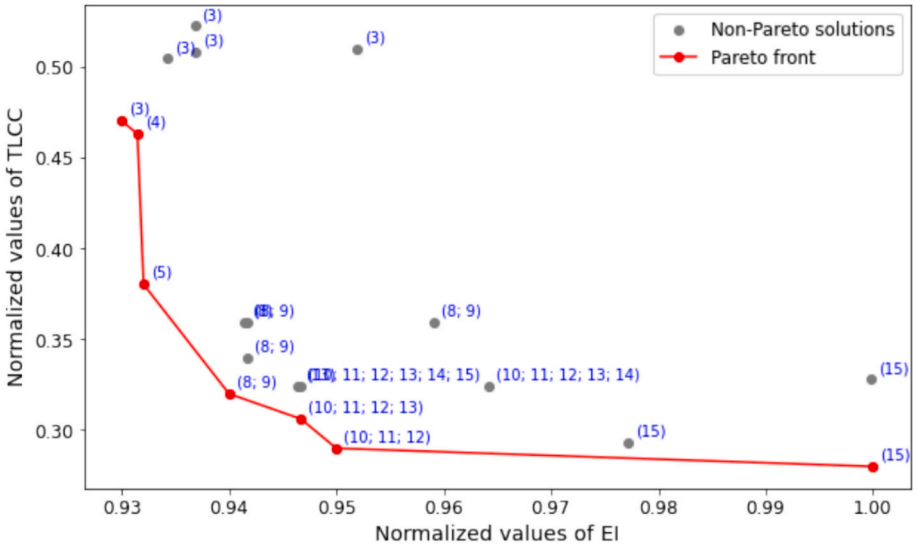

Fig. 14. Sensitivity of the proposed methodology as a function of SoH threshold parameter uncertainty in Hospital application.

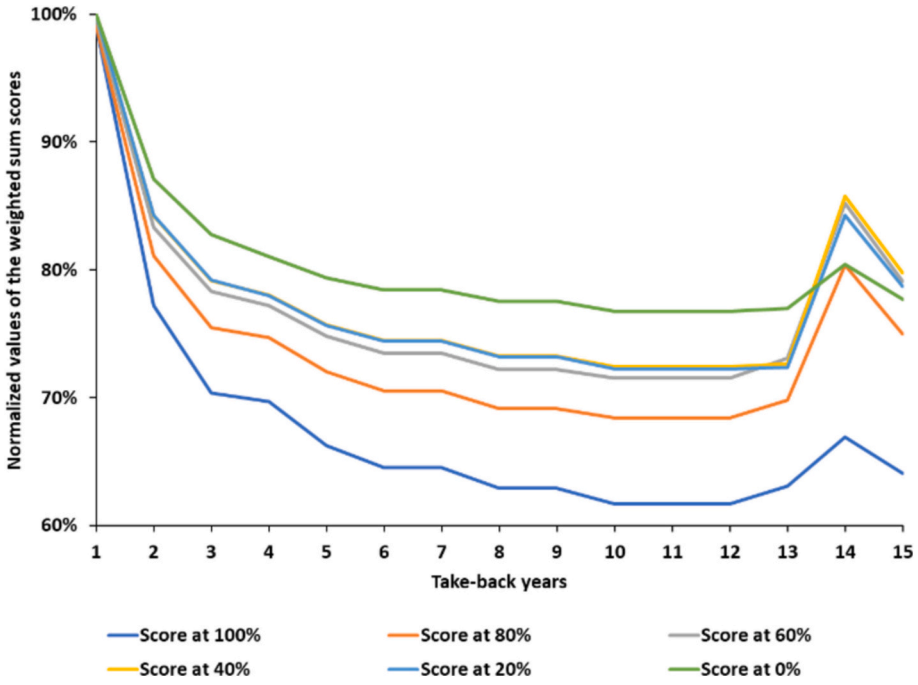

Fig. 15. Sensitivity of the weighted sum score in relation with closed-loop parameters values for Hospital application.

calculated based on the assumptions of the SoH parameter. Basically, the optimal take-back years were calculated using the algorithm, for each SoH threshold variation mentioned above. The results are presented in Pareto front in Fig. 14. This Figure shows all the solutions of the multi-objective model solved as a weighted sum of normalized EI and TLCC values in the algorithm in Fig. 5, as a function of SoH thresholds variations of −20 %, −10 %, +10 %, +20 %. The numbers above each solution point represent the corresponding take-back years. The red line, which is the Pareto front, contains the optimum of all solutions.

For almost all the solutions related to the various values of the SoH thresholds in Fig. 14, years 10, 11, and 12 frequently appear. That said, although EI and TLCC are respectively weakly and strongly dependent on variations in the SoH thresholds, the circular product strategy may not be significantly impacted. The t_{TB} could remain the same, and the proposed strategy for each subassembly as well. Finally, Fig. 14 also confirms that the optimal solution is obtained for a SoH threshold setting of 20 % - 70 % with some point of the SoH threshold setting of 20 % - 50 % and 20 % - 60 %. This reflects the reliability of the model and the robustness of the proposed method.

(2) – Sensitivity of the parameters of the closed-loop process

The second group is for the parameters of the closed-loop process. To illustrate the sensitivity of the proposed method according to these parameters, the values 100 %, 80 %, 60 %, 40 %, 20 % and 0 % were respectively assigned to the parameters ρ, λ, η, δ and ε in the closed-loop process presented in Fig. 4. Fig. 15 shows the weighted scores for each take-back year over the product's entire lifetime. The result in Fig. 15 shows that the score decreases as the parameter values increase. Furthermore, all scores for different parameter values show the lowest score between years 10, 11 and 12. The best case is when parameters are set to 100 %, which gives the lowest scores, and the worst case is when parameters are set to 0 %. This demonstrates the sensitivity of the results in the performance (efficiency) of each stage of the closed-loop process.

The weighted sum score curves exhibit a bathtub shape over the 14-year product take-back year. This results from the progressive reduction in the number of product cycles (n_c) and each subassembly (n_{c_i}), associated with the product's take-back year. Consequently, fewer defective subassemblies need to be replaced, transported, and recycled. This reduction is particularly significant during the early years (years 1 to 3, with SoH thresholds of 20 % - 70 %), as sub-assemblies are mostly reused, thereby minimizing replacement needs and reducing manufacturing, transport, and recycling costs. From years 3 to 13, the number of subassemblies to be remanufactured stabilizes as the product enters a more established phase of use (SoH thresholds remain at 20 % to 70 %). However, near the product's EoL (years 14 and 15), nearly all subassemblies are recycled, leading to a sharp rise in manufacturing, transport, and recycling costs. At take-back year 14, n_c reaches 3, since the total simulation period (N) is 30 years. Thus, each subassembly has an n_{c_i} of 3 in the simulation, tripling the associated costs and causing a peak in year 14. By year 15, the product has been fully replaced twice within the 30-year simulation (with n_c of 2), leading to a reduction in costs compared to year 14, though still higher than in year 13. These changes in costs are reflected in the weighted sum score in Fig. 15.

5. Discussion

5.1. Result interpretation and real-world implications

The circuit breaker is considered as a passive device: it remains on standby for most of its life cycle and is activated mainly in response to a fault, such as to protect a system from a short circuit. It is also operated at a defined frequency to conduct functional tests. The operating frequency is contingent upon the level of risk inherent to the application in the event of a circuit breaker failure. In Genset and hospital applications, the operating frequency is on average 1 and 2 times per week, respectively. On one hand, this similar use of the product across these applications explains the low variation in EI results for the “climate change” indicator in Fig. 8. The EI value remains relatively constant in a comparable manner with regard to both applications, in accordance with the product's take-back year throughout its entire life cycle. Similarly, the low variation in EI results is observed for all environmental impact indicators. Nevertheless, it is possible to see an entirely different variation in other applications with higher usage, such as in solar applications, where the circuit breaker operates two to three times per day as a contactor for photovoltaic panels. On the other hand, the variation

observed in the TLCC results presented in Fig. 8 is more pronounced and progressive for each take-back year throughout the product's entire use phase. This can be explained by the fact that at each take-back year, the number of life cycles of the product and its subassemblies decreases. This has an impact on the cost of manufacturing new subassemblies to replace the defective ones, as well as the costs of their transportation and the recycling of the replaced subassembly. In a circular context, when a subassembly is in a degraded SoH that does not facilitate its repair or remanufacturing, it is replaced by a new subassembly. This is the case, for example, with electronic subassemblies such as the trigger unit or coils, which are systematically replaced after 10 and 15 years of use, respectively, in hospital and Genset applications. Subsequently, the costs associated with manufacturing and transportation must be incorporated into the overall costs of the product's circularity. Conversely, costs associated with repair, reuse, or remanufacturing must be considered. Therefore, in all instances, the implementation of a circular economy entails the incurrence of supplementary costs. This raises the question of the most effective ways of optimizing costs in order to enhance the circular value chain. One key aspect of achieving this cost optimization is determining the optimal take-back year (t_{TB}), which plays a pivotal role in balancing both economic and environmental impacts. The results obtained from the Pareto front in Fig. 9, in conjunction with those in Fig. 8, provide justification for t_{TB} where product circularity would result in the lowest EI and TLCC. It is important to note that the results presented are for scenarios in which the circuit breaker does not encounter a short circuit during its operational phase. In such cases, the number of cycles for the subassemblies listed in Table 3 would be approximately 1 or at most 2 for the majority of these subassemblies. To illustrate this, some subassemblies (such as the fixed contact, mobile contact, the arc chamber, and the mechanism) would not be reusable as they could be damaged after a short circuit. Nevertheless, certain subassemblies may still be reused, including the pole shaft, the clusters, sensors and accessories, which are not damaged during a short circuit.

When optimized, product circularity offers significant benefits for industries across multiple dimensions. To illustrate, a comparison between Sc_2 and Sc_0 demonstrates that the implementation of CS can extend the service life of the circuit breaker from 12 to 28 years in Genset applications and from 15 to 30 years in hospital applications. This results in substantial environmental advantages, particularly in the significant reduction of impacts (over 50 %) in categories such as “land use”, “eutrophication, freshwater” and “resource use, minerals and metals,” due to material savings throughout the product's life cycle (as illustrated in Fig. 10). From an economic view, Fig. 12 demonstrates a 22 % gain for Sc_2 in comparison to the linear strategy (Sc_0), with an even more substantial benefit of approximately 47 % when contrasted with a conventional circular strategy (Sc_1). From a social perspective, the transition to a circular economy presents opportunities for the recruitment of additional personnel to manage the circular line. Furthermore, it cultivates a positive work environment, enhancing employee morale and productivity, as workers contribute to a sustainable, forward-thinking company.

Moreover, the optimization of a circular value chain necessitates the integration of additional stakeholders within the product ecosystem. For example, reverse logistics costs are considered to be the most significant in product circularity. The ability to engage a partner capable of collecting the product and delivering it to the OEM's facilities at relatively low cost represents a significant advantage, as illustrated in the circuit breaker case study. Similarly, the involvement of partners capable of remanufacturing or recycling subassemblies in a given condition at low costs is also a crucial aspect in optimizing the circular value chain. This adaptation of the product ecosystem can be simulated in the CST through the defined parameters.

In addition to optimizing the product ecosystem, the economic viability of these circular strategies heavily relies on customer acceptance. This is especially true given that circular products entail an increase in the overall product cost in its entire lifetime for a given customer. Indeed, customers would be required to pay 30 % less for a circular product that they would use for a shorter period of time compared to a new product based on the current linear strategy. In the case of the hospital, the CS indicates that there are three product life cycles, which equates to a price of 70 % of the initial cost multiplied by three cycles. Consequently, the price of a circular product is twice that of a new product for the same total life time. This represents a limitation of the current version of the CST, because it does not yet take into account the acceptance and perspective of the final product user to reduce the user cost as well. The parameters employed in the CST to define CS may also prove a limitation if their values are not adequately defined. The sensitivity analysis results in subsection 4.3 demonstrates a pronounced dependence of TLCC results on considerable variations in SoH thresholds, whereas the dependence on EI results is relatively weak. Moreover, this analysis corroborates the suitability of the selected SoH thresholds in the circuit breaker case study.

The results of the appropriate circular product strategy at t_{TB} also depends on the number of cycles (n_{c_i}) of each subassembly. So far, as the results show, n_{c_i} were set to the maximum value possible considering the technological constraints of each subassembly. However, it is possible to set them manually, a different setting of n_{c_i} may affect the EI and TLCC values at each stage of the product's life cycle. For example, changing n_{c_i} from 3 to 1 for the charging motor subassembly leads to multiply by 3 the cost of manufacturing of the charging motor since for 3 cycles of the product, 3 new ones are required. It also leads to an increase of the distribution, of the assembly, the reverse logistic, and the recycling costs by a factor of 3. Similarly, the EI values at these stages are affected. To avoid a considerable variability in the results, and to obtain an optimal model, this parameter should be carefully defined or automated to the maximum possible value. However, the assumptions made in the calculation of EI for remanufacturing and reuse may result in a different outcome, favouring the linear scenario over the circular one. Therefore, circular processes should be optimized to minimize their EI as much as possible. If the EI of a remanufacturing process is equal or exceeds than that of the manufacturing process, the benefits of circularity diminish. This extreme scenario may also be simulated using the CST.

In the context of a circular economy for an OEM, the feasibility of tracking the number of cycles a subassembly has undergone represents a significant challenge. It can be effectively addressed by integrating technologies such as Product Lifecycle Management (PLM), Enterprise Resource Planning (ERP), and Digital Product Passport (DPP). The PLM system is capable of tracking the full lifecycle of a product, from its initial design phase to its EoL stage. For example, in the case of a circuit breaker, when a subassembly such as a “rear connection” is remanufactured and reused, the PLM updates its lifecycle data to reflect that this subassembly is in its second or third cycle, thereby providing a detailed record of its entire history. In addition, an ERP system could be used to monitor operational data, such as the number of switching cycles completed by the subassembly “mechanism”. This enables the ERP to effectively manage maintenance schedules and inventory, ensuring that the subassembly is remanufactured or replaced at the t_{TB}, typically within a year. Thanks to Radio Frequency Identification (RFID) or Quick Response (QR) code attached to each subassembly of the circuit breaker, a DPP would serve to store all of the critical data, including the number of operational cycles, previous remanufacturing, and any subassembly replacements. This information can be accessed instantaneously by technicians, thereby ensuring efficient and well-informed decision-making when the subassembly is sent for remanufacturing. This traceability will become even more important with the introduction of the new European Ecodesign for Sustainable Products Regulation (ESPR) (Office of the European Union L, P, and Luxembourg, 2024), which promotes the use of DPPs. The DPP will store relevant information on a product's sustainability, circularity and compliance, strengthening the legal framework for OEMs to optimize their circular economy models. Collectively, these systems establish a robust framework of traceability

and transparency, which is indispensable for optimizing product life cycles and supporting sustainable practices in the OEM's circular economy model.

In conclusion, although it presents certain limitations, the CST remains consistent in determining the most appropriate CS for a given product in a specific application. It demonstrates significant progress in terms of economic and environmental gains and in defining the appropriate ecosystem, thereby facilitating the implementation of a circular economy in the industry at the subassembly level.

5.2. Use of the CST

Product circularity offers significant economic, environmental and social benefits to industry. It allows companies to retain control over the material and energy value of their products, which is increasingly critical for industrial sustainability. However, the lack of knowledge and the variety of circular processes create confusion and uncertainty among industrial actors, who clearly need guidance. This is where the CST comes in, helping industry to determine the most appropriate circular strategy for their products, down to the sub-assembly level. In addition, the CST makes it possible to simulate scenarios that optimize the chosen strategy, ensuring that it is both economically and environmentally viable. As the circuit breaker case study shows in section 4, it is possible to define a circular strategy that delivers both economic and environmental benefits. The CST is designed to serve as a decision support tool to help decision-makers make informed choices about the circularity of their products.

While the uncertainties associated with the mentioned parameters (*in subsection 3.8*) are not directly addressed in the CST, the users of the tool can conduct their sensitivity analysis by varying the parameters and observing the results. The CST facilitates this due to its dynamic and easily configurable nature. This flexibility allows for the simulation of several linear and circular scenarios. The repair and repurposing processes can be simulated by adjusting the product's number of cycles. Similarly, an upgrade of a product subassembly can also be simulated by incorporating the updated original EI data and the process's cost available. This process is quite common in industry and poses a significant barrier to circularity due to the obsolescence of certain product subassemblies. In industrial production, this obsolescence is often driven by the introduction of new technologies, rendering some subassemblies incompatible with circular systems due to evolving quality standards. However, upgraded subassemblies can replace them if they remain compatible in terms of hardware, software, and firmware. The importance of the upgraded subassemblies' compatibility is often overlooked, and its impact on circularity is poorly understood. Simulating these scenarios using the CST offers a major advantage in promoting eco-innovation and enhancing circularity in industry.

The CST also allows the simulation of the product use in several applications, which can be an advantage for its circularity. As products do not age in the same way, certain subassemblies can be reused across different applications, either to manufacture new products or as part of maintenance by the field service. Although this approach is not covered in this article, it is currently being explored. The CST can be used for a wide range of products, provided that all the required data, including the structural configuration of the product, the subassemblies SoH, EI and TLCC data, as well as the values of parameters are available. Once these data are uploaded in the CST, the simulation of CS can begin. However, the simulation for a product with a lifetime lower than one year can be a limitation for the application of this methodology. Because in that case, the service life is not long enough to observe the evolution of the EI and the cost. Comparison between scenarios is fixed in the CST, meaning that it is not possible to generate results for configurations beyond Sc0, Sc1, and Sc2. However, users can still manually compare other scenarios using the results from CST.

5.3. Future work

Since the aim of this study is to assist decision-makers in advancing toward circularity, it is essential to incorporate the legislative frameworks that currently serve as key drivers into the simulation of CS (Chelly et al., 2022). Among these frameworks are various progressive carbon taxation strategies implemented by governments, which impose carbon taxes on OEMs based on the volume of emissions they generate. These taxation strategies can significantly affect the TLCC of a circular product strategy and conduct to EI reduction. They can even help to decide where, in terms of countries with an advantageous taxation strategy, to implement the circular products strategy for multinational companies. Therefore, integrating taxation strategies into the CST is highly relevant to assess their potential impact on TLCC and how they might influence the final decision on selecting an optimal circular strategy. Although this aspect has not been covered in the present article, it will be addressed in future research.

The circuit breaker is a safety product. For the OEM, safety is the top priority. There are therefore other constraints to be taken into account, such as certification of the quality of the reconditioned product, the upgradability of such a product and programmed obsolescence. Standardisation of the CST is a work in progress. At present, it has only been tested for circuit breakers. It will soon be tested with other types of products. In addition, a multiple user profile is being integrated to make it easier to be understood and used by decision-makers with various skills and objectives such as business managers, Ecodesign engineers, LCA engineers, maintenance technician and so on. A business manager can use the tool to simulate different business case and get simplified EI and TLCC results for marketing. Ecodesign and LCA engineers can conduct ecodesign guidelines in the tool, such as changing a component or upgrading it to observe the impact in EI and Cost at the same time.

The CST enables the simulation of an appropriate circular strategy for an individual product. While the strategy may be profitable at the single-product level, its profitability may decrease when scaled to mass production. Considering both the volume of products manufactured and the proportion that will be taken back is crucial when designing a circular strategy at the company level. This aspect can also be integrated into the tool, providing valuable insights for business managers in OEMs to optimize their circular strategies on a larger scale.

The simulation tool will also incorporate the perspective of product users, taking into account factors such as willingness to pay, total cost of ownership, demand flow, the impact of value-added tax (VAT) on price reductions, and the design of circular strategies at each stage of the take-back process.

Furthermore, the current CST does not account for the possibility that a subassembly may undergo different circular processes across multiple life cycles. For instance, a subassembly might be reused in its first cycle, remanufactured in the second and third cycles due to some degradation of its SoH, and then reused again in the fourth cycle before finally being recycled at the end of its life. The forthcoming version of CST will incorporate a simulation of the circular strategy of subassemblies at the life-cycle level.

In addition, given the importance of traceability in a circular economy, future enhancements to the CST are planned, including the integration of a product digital twin in its next version. This integration will enable real-time monitoring and simulation of each product's lifecycle, providing accurate data on subassembly usage, wear and maintenance requirements. This future upgrade aims to further optimize the circular economy model by enabling a higher level of transparency and control over the product lifecycle.

The simulation tool includes many parameters for the P-LCA and P-LCC proposed. This may lead to errors when defining the strategy. A verification stage should therefore help to limit errors.

Finally, a circular service business model such as subscription, sharing, leasing, pay-per-use or pay-per-performance (Brissaud et al., 2022), will also be implemented using the take-back year method to

assess its potential for further promoting circularity and enhancing decision-making support.

6. Conclusion

This article presents a methodology for assessing circular product strategies and scenarios in terms of their environmental and economic benefits, based on the optimum product's take-back year (t_{TB}) with a view to its circularity. The specificity of this methodology is to achieve an overview approach to the problem to define the appropriate Circular Strategy (CS) for a given product. It takes into account the product's multiple subassemblies and applications, including in particular their State of Health (SoH). It is implemented in a dynamic circular simulation tool (CST).

The CST depends on input data and parameter setting for the simulation. Input data could be the structural composition of the product, the SoH of the product and its subassemblies, the environmental and cost data over the lifecycle of the product. The parameters are SoH thresholds, the closed-loop process parameters, and the LCA and LCC parameters.

It has been used for the case of industrial circuit breakers within two applications: Genset and Hospital applications. In both applications, CS defined using CST significantly extends the service life of circuit breakers by remanufacturing subassemblies over multiple life cycles. For the Genset application, the circuit breaker is taken back every 9 years, with most subassemblies remanufactured over three cycles, except for three that are replaced after the second cycle. This extends the total service life from 12 to 28 years. In the Hospital application, the circuit breaker is taken back every 10 years, with one subassembly replaced after the second cycle and two others replaced at each cycle, extending the service life from 15 to 30 years. Both strategies optimize the product's service life by combining remanufacturing and selective replacement, though with different intervals and subassembly treatments. The proactive CS defined for the circuit breaker revealed environmental and economic benefits of up to 7 % and 18 % respectively in both applications with a narrow confidence interval for a confidence level of 95 %. The t_{TB} is obtained using the weighted sum as an objectives function to minimize EI and TLCC.

A sensitivity analysis has been achieved to assess the variability of results with respect to the parameters. It shows that TLCC results are strongly dependent on the SoH thresholds in contrast to the EI results. Furthermore, the EI and TLCC results decrease as the performance parameter values of the circular process increase. Despite the observed variations in results, the CS proposed by the CST remains largely consistent.

To further improve the CST, future enhancements could integrate additional decision-makers' requirements. The next phase of development will see the integration of carbon taxation strategies and user profiles. The tool will also be enhanced to align with the specific needs of different user roles. Business managers, for instance, prioritize cost and business strategy, while ecodesign engineers focus on ecodesign recommendations to reduce EI in circular production systems. Furthermore, the circular product strategy could be extended to the company level by considering product fleets and leveraging economies of scale as a circular strategy. This approach could be reinforced by integrating simulations of circular service business models, such as subscription, leasing, pay-per-use models into the CST.

CRediT authorship contribution statement

Christian Wandji: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andreas Riel:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Helmi Ben Rejeb:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Conceptualization. **Mohammad Kanso:** Software. **Florent Pitis:** Writing – review & editing, Validation, Supervision.

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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7.2. Article 2: A Stakeholder-Centered Repairability Index Supporting Circular Product Design

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A stakeholder-centered repairability index supporting circular product design

Christian Wandji [a,*], Helmi Ben Rejeb [a], Andreas Riel [a], Cyrille Dalla Zuanna [b]

[a] Grenoble Alpes University, CNRS, Grenoble INP, G-SCOP, 46 Avenue Félix Viallet, 38000, Grenoble, France
[b] Technical Center for Mechanical Industries (CETIM), 7 rue de la presse, 42952, Saint Etienne, France

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ABSTRACT

In response to increasing environmental concerns and regulatory pressure, repairability has become a central focus of circular product design. European legislation, such as the Ecodesign Directive 2009/125/EC and the French AGEC law (Anti-Waste for a Circular Economy), now require products to be designed to facilitate repair. However, existing methods for assessing repairability often fail to account for heterogeneous stakeholder expectations, ranging from individual consumers to maintenance professionals and design teams. Moreover, most available approaches remain product-specific and lack applicability across different product categories. To address these limitations, this paper introduces the RIUP method (Repairability Index according to User Profiles), a novel approach for evaluating repairability that integrates multiple user perspectives. The method is grounded in the EN 45554 standard and relies on a criterion-based assessment framework combining a scoring system with a customizable, stakeholder-specific weighting system as its core contribution. The RIUP method is applied to an illustrative case study of a heat-sealing machine to demonstrate its stakeholder-centered assessment capabilities. The results show that repairability outcomes vary depending on the stakeholder perspective considered. While the overall repairability of the machine is satisfactory, the design team's perspective yields a higher repairability index than those of consumers or maintenance teams. These findings highlight the importance of explicitly considering maintenance-related constraints alongside design objectives when developing circular products, particularly in service-oriented business models. Future work will extend the method to incorporate product-specific criteria and support the development of a dynamic repairability index.

1. Introduction

The Circular Economy (CE) is one of the key elements for achieving the European objective of net-zero carbon by 2050. Among the 10 R-principles of CE, repair is a particularly relevant strategy as it aims to extend the life of products and components by keeping them in operating condition, as well as contributing to waste reduction. Repair is typically the first action when a product breaks down (Morseletto, 2020). Repair has been a key maintenance objective for several years. In maintenance, the concept of "maintainability" reflects a product's capacity to be maintained and returned to its functional state during its operational life (Piller et al., 2015). The "maintainability" is regarded as an operational enabler of repairability, focusing on the efficiency of repair actions and system availability, while repairability is framed within a CE perspective as a broader capability aimed at extending product lifetime and preserving the value embedded in products (Roskladka et al., 2025). Even if a product or a component cannot fulfill its function, it might be used for other purposes (Wandji et al., 2025). According to the European norm and standard EN 45554: 2020, the ability of a given product to be repaired is expressed in the form of the repairability index (RI) or score.

The RI is an essential indicator for designing a circular product (Roskladka et al., 2023). It allows companies to save energy, materials, and value, and at the same time to reduce waste, which has been growing by 2–5% per year according to the OECD report (OECD, 2015). Furthermore, the RI is a purchasing criterion in today's market (Jourdain, 2025). According to the French Agency for Ecological Transition (ADEME) and Samsung France survey (OpinionWay), 55% of participants systematically include the reparability index among their purchasing criteria, and 35% are probably planning to do so. Based on this, the reparability index has risen to number 4 among the main purchasing criteria for French consumers, behind price, reliability, and

* Corresponding author.
E-mail address: christian-berenger.wandji-wouapi@grenoble-inp.fr (C. Wandji).

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performance.

Regarding the fact that the RI is a considerable purchasing criterion, many companies in several fields, such as mechanical, mechatronic, electrical, and electronic, intend to assess the RI of their product through an ecodesign deployment strategy. According to ADEME, 75% of companies in France have included ecodesign within their strategy. These companies are limited when it comes to assessing the repairability of their product because almost all the existing tools are Energy-related Product (ErP) specific (Ruiz-Pastor and Mesa, 2023). Moreover, all existing tools have been designed with the consumer perspective for a product in the Business-to-Consumer (B2C) context. However, companies in Business to Business (B2B) contexts, such as those that need to know the repairability of a machine or equipment for their production lines, are not adequately considered. There is a need for a general assessment tool that is applicable across product categories and is adaptable to different evaluator perspectives.

The novelty in the paper relies on the consideration of several user's perspectives in the assessment of the RI applicable to any type of product. The research presented in this paper aims to design a universal and comprehensive RI tool, consistent with the EN 45554 standard, and applicable to all types of products in both B2B and B2C contexts. It can be used by designers as a "Design for Repair" tool for electronic, electrical, mechanical, and mechatronic products, as well as by a company's maintenance or production team as a decision-support tool for purchasing new equipment, ensuring that repairability is systematically considered throughout the product lifecycle. As such, the "Design for Repair" constitutes a key ecodesign strategy for the development of circular products (Roskladka et al., 2025).

1.1. Identification of research gap

A systematic literature review of the RI was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to identify existing repairability index assessment methods. The review was performed using the Web of Science database with a structured query, followed by successive screening steps based on publication period, subject area and relevance to repairability assessment. Titles, abstracts and full texts were screened to retain only relevant contributions. The detailed search strategy, selection criteria and PRISMA flow diagram are provided in the Supplementary Material (see Text S1 and Fig. S1). The relevant papers found using the PRISMA method can be grouped into two main application-based categories. These categories are shown in Fig. 1 as a synthesis of the literature review analysis.

The first category concerns documents that propose the repairability assessment method for ErP or EEE (Electronic and Electrical Equipment) products in B2C. This is the case of the French RI (FRI) method supported by the AGEC law in France (Anti-waste law and circular economy), which requires certain manufacturers to use the FRI assessment sheet to assess the reparability index of certain products, and to display the result to raise consumer awareness (Ministry of Ecological Transition, 2022). This FRI method mainly concerns 7 categories of mass-market products, such as smartphones, laptops, lawnmowers, washing machines, dishwashers, vacuum cleaners, and high-pressure cleaners. The criteria used to assess the reparability index may vary depending on the category. There is an assessment sheet for each consumer product (French repairability assessment sheet). In this case, the index is displayed between 0 and 10, with 0 meaning that the product is not repairable at all, and 10 meaning that it is 100% repairable. The FRI method does not include a weighting system; all criteria and priority parts are assigned a default weight of 1. Blanco-Espeleta et al. (2024) proposed an alternative repair matrix based on EN 45554, tailored specifically for capsule coffee machines. This limitation is addressed by other methods in the research field, such as the Assessment Matrix for ease of Repair (AsMeR) method developed by Bracquené et al. (Bracquené et al., 2018; Bracquene et al., 2019). The AsMeR method differs from the FRI method not only in terms of the list of criteria, but also in its general approach, which enables it to be used for a wider range of products. The method is focused on the repair and reuse from the consumer perspective. Consumers may include self-repairers, repair café's, etc. The AsMeR method is also applied to ErP, and it is intended to be used by stakeholders of the repair value chain of a product, such as manufacturers, retailers, independent repairers, etc. In the same way, the Repair Scoring System (RSS) method developed by Cordella et al. (2018, 2019) also presented a general approach. Compared with previous methods, it includes a weighting system for priority parts and

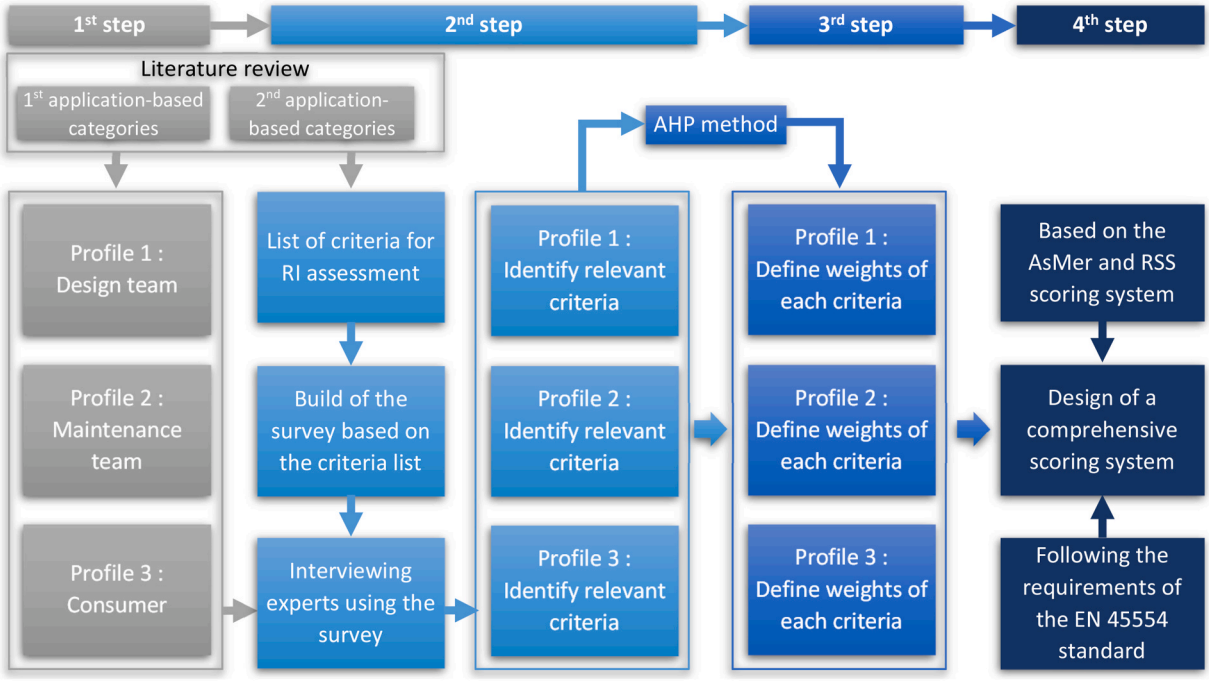

Fig. 1. Research methodology.

criteria. Like the AsMer method, it can be applied to a wider range of mass-market products, considering the end-user perspective. A comparative study was performed by Bracquené et al. (2020) to highlight the coherence of the RI from both methods applied to the case study of a washing machine. Following a similar approach, there is also the ONR 192102 method that proposes a RI assessment method based on criteria and weights reflecting consumer perspectives (ONR, 192102, 2014). To improve the efficiency of repairability index assessment, Liao et al. (2024) proposed an artificial intelligence–based approach aimed at automating the evaluation and rating of product repairability. Their method comprises two complementary approaches: a supervised learning model based on product teardown images to quantify repairability, and an unsupervised learning model used to identify design features and cluster products with similar design characteristics. This method was applied in the case of a smartphone. Finally, Alkouh et al. (2023) proposed a novel approach for assessing the Index of Repairability (IOR) of industrial EEE in the oil and gas sector using a mathematical modeling framework. Their method employs the Analytic Hierarchy Process (AHP) to derive criterion weights, covering design, documentation, software, and spare parts, based on and adapted from existing repairability assessment methods.

There are other methods from commercial companies such as i-Fixit (i-Fixit, 2003; Flipsen et al., 2016) from the company i-Fixit. Its assessment principle is quite similar to the one developed in research, in terms of scoring and the weighting system. A comparison between the i-Fixit and the FRI methods was performed by Barros and Dimla (2023) on the case study of a smartphone to highlight that a high RI does not always mean that the product is easy to repair. It can mean, for example, that the service of repair is a high quality and affordable. The industrial design features play an important role in the RI assessment. In “Design for Repair”, the objective is to improve the product design based on criteria from the repairability assessment method. These criteria are used as design guidelines for repair (Roskladka et al., 2025). From this perspective, Dangal et al. (2022) proposed a design aspect of the six major repairability scoring systems mentioned above in the first group of relevant papers with applications to ErP or EEE products in the B2C context. They compared the objectivity and completeness of the six major repairability scoring systems with those of the latest study in the literature based on the criteria that drive product repairability. It was established that the design features guidelines are strongly linked to repairability. De Fazio et al. (De Fazio et al., 2021) proposed a disassembly map to improve the “Design for Repair” of a product. This study has also been conducted for the EEE or ErP product. Complementing this design-oriented perspective, Fakhredin et al. (Fakhredin and Campean, 2026) applied a product ethnography approach on five smartwatches to highlight how product “Design for Repair” affects practical repairability assessment beyond what theoretical metrics can reveal. This approach consists to observe professional repairer to harvest and replace high-wear product's parts in a repair process. To contribute to this approach, Wandji et al. (2023) proposed a non-exhaustive list of criteria that can be used to support the development of a comprehensive assessment of product repairability within a CE context. This set of criteria conceptualizes repairability as a multidimensional product–system property, encompassing design, support and service-related aspects across the repair process. It was derived from a comparative analysis of the six main repairability rating systems reported in the literature, synthesizing their common and complementary dimensions. Due to this generic and adaptable structure, the criteria are applicable to different product types and user profiles and can therefore be used as an operational basis by multiple repairability index evaluation methods.

The second category concerns papers that proposed a repairability assessment method for other types of products. This is the case of Rodrıguez and Favi (2024) who proposed a design methodology based on the EN 45554 standard to generate and implement ecodesign rules to improve the RI of a mechatronic product. The methodology was applied to the case study of an electro-mechanical oven. Few papers were found in the assessment of the RI of buildings. Bavandi et al. (2022) proposed a new method for assessing the RI of steel structures equipped with post-tensioned self-centering connections after an earthquake. Their method implements an incremental dynamic analysis on different buildings using various seismic recordings. Using a regression approach, the authors established an equation relating the RI to the spectral acceleration of the first mode and the number of floors. This index is expressed as the ratio between the maximum rotation observed in the connection and a predefined rotation limit corresponding to the “Immediate Occupancy” performance level. A ratio of less than 1 indicates that the structure is considered repairable, as damage is limited to replaceable elements (mainly corners) without affecting the overall integrity of the building. Following this, Ke et al. (2024) proposed a repairable multiple elasticity steel slot damper to mitigate the seismic effects of engineering structures. The goal was to reduce the damage from earthquake events to buildings. In this context, the RI refers to the ability of a building to recover, after repair, hysteretic behavior and energy performance comparable to those of a new building.

We noticed based on this literature review, that the methods developed to assess the RI in this second category are not based on the same criteria as the methods in the first category. They are also too product-specific. In general, the existing methods for assessing reparability clearly show that the index is applied to the mass-market ErP and EEE, calculated by companies and intended for the end consumer. This assumes that consumer perception is taken into account when calculating the reparability index produced by the company. The reality, however, is quite different. Torca-Adell et al. (2025) highlighted a misalignment between the consumer's perceptions and of the RI displayed for appliances. This proves that the criteria used to assess repairability do not correlate perfectly with the consumer's point of view. Following this approach, a RI should also be customized according to the user's objective, as it is customized according to the product type. The user is a stakeholder or an actor in the product value chain, such as manufacturers, retailers, independent repairers, B2B, and B2C consumers. As far as the literature was investigated, none of the existing methods has addressed the calculation of the RI score according to the different types of user objectives to support a more repairable product design. All methods are generic and independent of specific user objectives. This is the main gap in existing RI evaluation methods that explains the 53% of the French customers do not well perceive it, according to the ADEME (OpinionWay). On this basic, repairability is considered in this paper as the ability of a product to be restored to a functional state after failure, under real operating conditions, in line with user objectives, in order to extend its useful life and preserve the value embedded in the product. This ability does not rely solely on intrinsic technical design features, but also on the conditions that effectively enable repair, such as access to information, tools, spare parts and support services. Furthermore, no dedicated repairability assessment method specifically targeting purely mechanical products was identified from the literature review. This highlights a clear second gap in the current literature regarding the assessment of repairability for mechanical products.

1.2. Research question

Based on these two gaps, the research question underlying the work presented here is as follows: *How can a stakeholder-centered repairability index be structured to reflect heterogeneous user objectives, while being designed to be applicable across different product types?*

The proposed method for assessing the RI by user objectives aligns with the European standard EN 45554 requirements. The method is based on a list of criteria grouped into categories. Each criterion and category has an assigned weight according to the user's objectives. These weights are derived using the Analytical Hierarchical Process (AHP) method (Saaty, 2005), which involves the input of experts from very specific user profiles. The index encompasses three primary user profiles: the design team, the maintenance team, and the handyman. Each

user profile has its objectives or purpose for product use.

2. Materials and methods

The existing methods used to assess the RI of an ErP are supported by the European standard. This standard provides a non-exhaustive list of criteria for assessing the RI of an ErP. The RI of a product is an aggregation of the repairability indices of its priority parts. Priority parts are defined as parts that are directly or indirectly related to the product's current failure during its use phase and parts that are linked to the product's primary and secondary functions. EN 45554 also allows users to define their own scoring and weighting system. This paper, therefore, proposes a new assessment method called the RI Per User/Stakeholder Profile (RIUP) method. This section presents the methodology used and the RIUP method.

2.1. Research methodology

The RIUP method proposed in this paper is based on the list of criteria provided by Wandji et al. (2023). The list was selected because of its adaptability to various product categories and its ability to consider different stakeholder perspectives. It aligns well with the objective of RIUP as it is adaptable to both product type and user profile. This list was used as a basis to build a survey to assess the relevance of each criterion for assessing the RI of a given product. Based on that, a first hypothesis is that a survey and interviews can help to characterize the relevant criteria to use for assessing the RI according to the objective of the user. However, before assessing this hypothesis, it was necessary to identify the different user profiles and their objective of use of the RI. The complete methodology to developed the RIUP method is summarized in Fig. 1.

The first step of the methodology is to identify the user profiles and their objectives. To this end, the stakeholders in the product repair value chain were identified based on the literature. According to Bracquené et al. (2018), repair activities can be conducted by various stakeholders in the repair value chain, including manufacturers, retailers, independent repairers in B2C and industrial repairers in B2B, as well as consumers. Based on these stakeholders, three categories of user profiles were defined: the first category refers to the design team in a manufacturing company, the second is the maintenance team in an industry that is a B2B consumer, and the third is a B2C consumer who may be an independent repairer or a handyman.

In the second step, industrial experts from each of the selected user profiles were interviewed to validate the initial hypothesis. Only industrial experts were interviewed to ensure reliable input for selecting relevant criteria for each profile. Three industrial product experts with design profiles and three industrial maintenance experts were interviewed. The expert panel was intentionally limited and used for methodological demonstration purposes, consistent with exploratory applications of multi-criteria decision analysis, rather than for statistical inference. The interviews were semi-structured to ensure consistency across expert assessments while allowing clarification of complex criteria. During the interviews, the participants were asked to rate the criteria on a scale of 1–5. For the consumer profile, a repairability workshop was organized with five participants identified as handymen. At the end of the workshop, all participants completed the same paper-based survey. During the interviews, the difference in levels, even between the relevant criteria, was highlighted several times. This was also confirmed during analysis of the survey results. This means that stakeholders perceive the criteria differently, which can make assessment difficult.

In total, 11 experts/users were interviewed. Although the sample size is limited, it remains appropriate with *ad-hoc* exploratory applications of multi-criteria decision analysis, that focus at methodological validation rather than statistical generalization. This observation led to the formulation of a second hypothesis: the use of a multi-decision aid method to assess the weight of each criterion per user profile. To validate this approach, interviews were conducted with academic experts in each profile to assign reasonable and accurate weights to each criterion and user profile using the AHP method. This was the third step of the methodology.

The fourth step was to design a comprehensive scoring system for evaluating the reparability index, following the requirements of EN 45554 and drawing inspiration from the AsMer (Bracquené et al., 2018) and RSS (Cordella et al., 2019) scoring systems. Finally, the RIUP method was implemented in Excel.

2.2. Method for assessing the repairability index according to stakeholder profiles

This subsection presents the RIUP method, which is organized into five parts, as shown in Fig. 2.

1 Identification of stakeholder profiles;
2 Selection of relevant criteria for each profile;
3 Definition of a weighting system;
4 Development of a scoring system;
5 Construction of the comprehensive assessment matrix for the reparability index.

Together, these steps constitute the RIUP method. The specificity of this method lies in the specific weighting given to stakeholders. Due to its comprehensive approach, it can be applied to any type of product.

2.2.1. The identification of stakeholder profiles

The existing methods for assessing the RI were designed to align with the consumer perspective. However, consumers interact with the same product in different ways depending on their environment and personal or professional objectives. For instance, a handyman may prioritize ease of repair when choosing a device, whereas an industrial maintenance team may prioritize quick repair and minimal downtime. Consequently, the RI should not be a one-size-fits-all metric; its meaning may vary according to the user's objectives during the repair phase, influencing the product's design strategy. Within this framework, three key stakeholder profiles in the repair value chain have been identified:

- The end-users or handymen (denoted as "consumer" in Fig. 1): This stakeholder profile values products that are easy to repair for personal satisfaction and uninterrupted use (Sabbaghi et al., 2016). Detailed repair documentation is critical to them, even if repair speed is not a critical factor.
- Maintenance/Production managers (denoted as "maintenance team" in Fig. 1): In industrial environments, decision-makers in production and maintenance departments prioritize long-term operability when acquiring new machinery or equipment. They prioritize equipment that is straightforward to disassemble and reassemble, with readily available spare parts and a rapid repair process to minimize downtime and total maintenance costs. Robustness and repair costs, and times are essential criteria for reliability and availability, as shown by the study on the impact of maintenance costs and the efficiency of machine acquisitions carried out by Hagström et al. (2020).
- Design teams (denoted as “design team” in Fig. 1): These professionals must balance customer requirements, internal and external policies, and technical constraints. They assess repairability by taking into account the diverse needs of customers and operational efficiency, resulting in clear repairability goals during the design phase. Depending on the business type, customers can be end users or part of another company's maintenance team. As their objectives are different, the RI calculation during the product's design phase might not be the same. During the design phase, the “Design for Repair” features serve to improve the repairability of a product by taking user objectives into account.

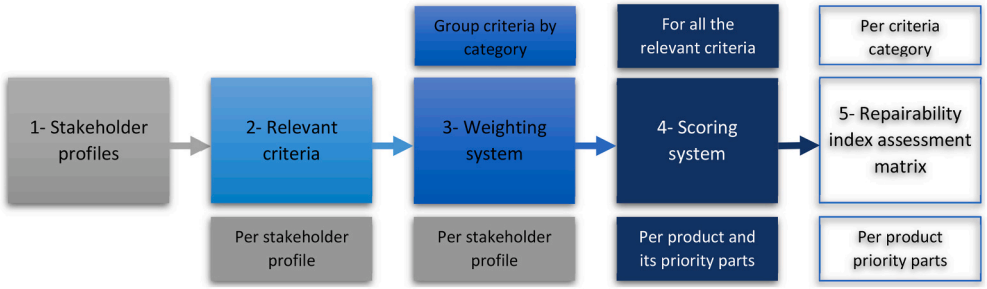

Fig. 2. Method RIUP for assessing the repairability index per stakeholder profile.

These three stakeholder profiles were selected to represent the main actors directly involved in repair actions along the product lifecycle, covering upstream design decisions, professional maintenance activities in industrial contexts, and non-professional repair practices addressed by consumer-oriented repairability policies.

The usage objectives of the three stakeholder profiles presented above demonstrate that their perception of the RI differs. Therefore, the evaluation of the RI must be adapted to meet the expectations of each profile. In addition to these profiles, the RIUP method considers a "generalist" reference profile for comparison purposes to highlight the impact of weights when assessing the RI. It does not represent a specific stakeholder group, but serves as a neutral reference scenario in which all repairability criteria are considered of equal importance, therefore all criteria and category weights set to 1. This baseline allows comparison with stakeholder-specific profiles and helps identify how weighting schemes reflecting particular objectives influence repairability outcomes.

Since the proposed method is based on the EN 45554 standard, the assessment uses a rating system combined with a weighting system. To ensure relevance for different stakeholder groups, the RI assessment was adapted by selecting appropriate criteria for each profile. EN 45554 provides a generic framework that describes the technical characteristics relevant to assessing the repairability of a product. It must be adapted to the studied product typologies and the perspectives of the stakeholders involved. The RIUP method fulfils these requirements.

2.2.2. *Selection of the relevant criteria by stakeholder profile*

The initial set of 39 criteria used to assess the RI was derived from the framework proposed by Wandji et al. (2023), which synthesizes the criteria identified in the existing literature. To determine the relevant criteria for each stakeholder profile, a structured questionnaire was developed to evaluate the influence of each criterion on the repair process of a given product on a scale from 0 to 5. A rating of 0 indicates that the criterion has no influence, while ratings of 1, 2, 3, 4, and 5 correspond to insignificant, low, moderate, acceptable, and strong influences, respectively. An additional response option, "I do not know", was also provided. The details of the preparation and the leading of the workshop are provided in the supplementary material in Text S2. The profiles of the industrial experts who participated in the workshop are presented in Table S2. The experts came from various companies in different fields to provide a clearer view of the selection of relevant criteria. Although the number of industrial experts is limited, this qualitative, expert-based approach serves as exploratory validation of the RIUP method, verifying that the selected criteria correspond to real industrial practices. The synthesis of responses to the questionnaire is presented in Table S6.

In light of the responses obtained from the completed questionnaires, a two-stage analytical procedure was implemented to identify the most relevant criteria for each stakeholder profile.

Stage 1: The initial set of 39 criteria was subsequently extended to 41 criteria through the inclusion of additional criteria proposed by industrial experts during the semi-structured interviews. Semi-structured interviews were employed to ensure comparability across expert assessments while allowing clarification of complex criteria. The selection targeted 41 criteria that had been rated 3, 4, or 5 by each interviewee. This process yielded three distinct lists of criteria for the "maintenance team" and "design team" profiles, each corresponding to the three experts interviewed for each profile. Five separate lists were generated for the "consumer" profile.

Stage 2: The lists generated for each profile were then consolidated into a single comprehensive list. For the "maintenance team" and "design team" profiles, only those criteria endorsed by at least two of the three industrial experts were retained. For the "consumer" profile, the criteria selected by at least two out of the five workshop participants were retained. The participants were people who were used to doing handyman work. They were included to ensure the applicability of the RIUP method beyond strictly professional or industrial repair contexts.

This analytical procedure yielded selections of 20, 35, and 26 criteria for the "design team", "maintenance team," and "consumer" profiles, respectively. Notably, only 10 criteria were common to all profiles. This variation in criteria selection among the different stakeholder profiles provides initial evidence that the RI of a product is perceived differently by various stakeholders within the repair value chain. The "generalist" profile considers all criteria and categories when assessing the RI. Table 1 summarizes the criteria selected for each stakeholder profile, as well as their weights.

2.2.3. *Definition of the weighting system*

During the selection of the most relevant criteria for each stakeholder profile, differences in their relative importance were explicitly highlighted. Some criteria were considered to have a moderate influence, while others were assessed to have a strong or critical influence on repairability, and these assessments varied depending on the stakeholder perspective. To systematically capture and formalize these differences, the AHP was employed, as it is widely recognized as a robust multi-criteria decision-making method for structuring complex problems and deriving relative weights (Saaty, 1980). In this study, AHP was used to determine and validate the weights assigned to the selected repairability criteria for each stakeholder profile introduced in Section 2.2.2. The method enables the explicit comparison of criteria importance within and across categories, ensuring internal coherence of the weighting system. For the "generalist" profile, equal importance was assumed and all criteria weights were therefore set to 1.

The application of the AHP method was conducted through a structured three-stage process, including criteria categorization, hierarchical structuring, and pairwise comparison with consistency verification. It was completed with the support of one academic expert per stakeholder profile. These experts were selected based on their expertise in design, maintenance, handyman work; and their role was to ensure consistency in criteria interpretation and validation of AHP consistency ratios. The profiles of the academic experts, who completed the pairwise

Table 1
Relevant criteria and their weights per stakeholder profile.

N°	Categories	Criteria	Weights					
			Designer Team		Maintenance Team		Consumer	
			Categories	Criteria	Categories	Criteria	Categories	Criteria
1	Disassembly &	Disassembly depth/sequence	0.066	0.455	0.036	0.188	0.171	0.111
2	Reassembly	Disassembly time		0.091		0.081		0.111
3		Tools		0.455		NA		0.667
4		Fasteners		NA		0.731		0.111
5	Supports	Availability of diagnostic support and interfaces	0.119	NA	0.150	NA	0.023	0.093
6		Accessibility of diagnostic support and interfaces		NA		0.478		0.057
7		Availability of identification support		0.114		0.037		0.323
8		Accessibility of identification support		0.093		0.062		NA
9		Availability of technical support for disassembly and reassembly		0.503		0.116		0.526
10		Accessibility of technical support for disassembly and reassembly		0.290		0.306		NA
11	Working conditions	Working environment	NA	NA	0.024	0.800	0.107	NA
12		Skill level		NA		0.200		1.000
13	Spare parts	Availability of spare parts by target groups	0.325	0.078	0.073	0.232	0.072	0.473
14		Duration of spare parts availability		0.232		0.128		0.253
15		Delivery time of spare parts		0.208		0.176		NA
16		Spare parts connection interfaces		0.036		0.027		0.071
17		Supply of spare parts - content		0.063		0.020		0.047
18		Spare parts compatibility		0.383		0.342		NA
19		Price of spare parts		NA		0.076		0.156
20	Product design	Modular design of the product	0.174	0.072	0.308	0.042	0.226	1.000
21		Standardized design		0.185		0.059		1.000
22		Product designed for easy failure detection		0.593		0.449		NA
23		Product designed for ease of restoring to working condition after repair		0.150		0.449		NA
24	Product reconditioning	Technical support for reconditioning - accessibility	0.055	NA	0.247	0.171	0.307	0.038
25		Ease of restoring the product to working condition after repair		NA		0.040		0.238
26		Environmental issues at the end of life		NA		0.029		0.171
27		Availability of OEM (Original Equipment Manufacturer) qualified service engineers		0.200		0.062		0.033
28		Estimated Reliability (R) - state of health		NA		0.252		NA
29		Password reset and restoration of factory settings		NA		NA		NA
30		Software and firmware		0.800		0.101		0.066
31		Data transfer and deletion		*NA*		*NA*		*NA*
32		Risk of injury		NA		0.345		0.455
33	Documentation or	Type of information/documentation	0.111	1.000	0.093	0.637	0.044	1.000
34	information	Availability of information or documentation by target groups		NA		0.258		1.000
35		Duration of time of information or documentation availability		NA		0.105		NA
36	After-sales strategy	return options	0.080	*NA*	0.051	*NA*	NA	*NA*
37		Guarantee management		0.333		0.800		NA
38		Remote after-sales assistance		0.667		0.200		NA
39	Product identification	Ease of identification	0.071	1.000	0.017	0.800	0.050	NA
40		Accessibility of identification		1.000		NA		1.000
41		Robustness of identification		NA		0.200		1.000

NA (Not Applicable): this means that the criterion or the category has not been selected for the stakeholder profile.

comparison, are presented in Table S2. A detailed description of each stage of the AHP implementation is provided in Text S3.

2.2.4. Development of a scoring system

The scoring system is the fourth part of the RIUP method, as illustrated in Fig. 2. This part converts each criterion into a numerical value scaled to the [0, 1] interval for each stakeholder profile. It uses a class-based scoring approach derived from EN 45554, which assigns an alphanumeric class from A to E to express how strongly a criterion is addressed during repair activities:

- A – criterion is given full and explicit consideration (best performance).
- E – criterion is ignored or receives only negligible attention (worst performance).

As repairability criteria differ in their intrinsic nature and discriminative capacity, the number of rating classes "n" is adapted on a criterion-by-criterion basis and may vary between two and five. Criteria evaluated using two classes correspond to binary situations (e.g., presence or absence of a repair-enabling feature), where additional intermediate levels would not provide meaningful information. Conversely, criteria that can be partially or progressively fulfilled require a higher number of classes to capture intermediate performance levels.

Each class is mapped to the interval [0; 1] using linear spacing as shown in equation (1):

$$Score = 1 - \frac{k}{n-1}, k = 0, 1, \ldots, n-1 \quad (1)$$

where k is the position of the class from best (k = 0, class A) to worst. Table S3 gives the resulting discrete scores for the mapping of two to five alphanumeric classes to numerical scores. The selection of the number of classes for each criterion is detailed in the Text S4, together with the associated justification. The complete scoring system is presented in Table S4.

2.2.5. The repairability index assessment matrix

The RI assessment matrix represents the fifth step of the RIUP method (see Fig. 2) and is presented in Table 2. This matrix summarizes the scores assigned to each pair composed of criterion "***j***"; priority part "***i***", denoted as $x_{i,j}$. These $x_{i,j}$ values numerically correspond to the alphabetical classes established in the scoring system (Table S4).

Furthermore, the matrix provides aggregated scores at both the cri-

Table 2
Repairability index assessment matrix.

Categories	Category weights	Criteria	Criteria weights	Priority part 1	Priority part i	Priority part n		Category's score
Disassembly & Reassembly	W_1	Disassembly depth/sequence	ω_1	$x_{1,1}$	$x_{i,1}$	$x_{n,1}$	$s_1 = \frac{\sum x_{i,1}}{n}$	$\mathcal{S}_1 = \frac{\sum s_j \times \omega_j}{\sum \omega_j}$
		Disassembly time	ω_2	$x_{1,2}$	$x_{i,2}$	$x_{n,2}$	$s_2 = \frac{\sum x_{i,2}}{n}$	
		Tools	ω_3	$x_{1,3}$	$x_{i,3}$	$x_{n,3}$	$s_3 = \frac{\sum x_{i,3}}{n}$	
		Fasteners	ω_4	$x_{1,4}$	$x_{i,4}$	$x_{n,4}$	$s_4 = \frac{\sum x_{i,4}}{n}$	
				$\Delta_{1,k} = \frac{\sum \omega_j \times x_{1,j}}{\sum \omega_j}$	$\Delta_{i,k} = \frac{\sum \omega_j \times x_{i,j}}{\sum \omega_j}$	$\Delta_{n,k} = \frac{\sum \omega_j \times x_{n,j}}{\sum \omega_j}$		
Supports	W_2	Availability of diagnostic support and interfaces	ω_5	x_5			$s_5 = x_5$	$\mathcal{S}_2 = \frac{\sum s_j \times \omega_j}{\sum \omega_j}$
		Accessibility of diagnostic support and interfaces	ω_6	x_6			$s_6 = x_6$	
		Availability of technical support for disassembly and reassembly	ω_7	x_7			$s_7 = x_7$	
		Accessibility of technical support for disassembly and reassembly	ω_8	x_8			$s_8 = x_8$	
		Availability of identification support	ω_9	x_9			$s_9 = x_9$	
		Accessibility of identification support	ω_{10}	x_{10}			$s_{10} = x_{10}$	
				$\Delta_{i,k} = \frac{\sum \omega_j \times x_j}{\sum \omega_j}$				
Spare parts	W_3	Availability of spare parts by target groups	ω_{11}	$x_{1,11}$	$x_{i,11}$	$x_{n,11}$	$s_{11} = \frac{\sum x_{i,11}}{n}$	$\mathcal{S}_3 = \frac{\sum s_j \times \omega_j}{\sum \omega_j}$
		Duration time of spare parts availability	ω_{12}	$x_{1,12}$	$x_{i,12}$	$x_{n,12}$	$s_{12} = \frac{\sum x_{i,12}}{n}$	
		Delivery time of spare parts	ω_{13}	$x_{1,13}$	$x_{i,13}$	$x_{n,13}$	$s_{13} = \frac{\sum x_{i,13}}{n}$	
		Spare parts connection interfaces	ω_{14}	$x_{1,14}$	$x_{i,14}$	$x_{n,14}$	$s_{14} = \frac{\sum x_{i,14}}{n}$	
		Supply of spare parts - content	ω_{15}	x_{15}			$s_{15} = x_{15}$	
		Spare parts compatibility	ω_{16}	$x_{1,16}$	$x_{i,16}$	$x_{n,16}$	$s_{16} = \frac{\sum x_{i,16}}{n}$	
		Price of spare parts	ω_{17}	$x_{1,17}$	$x_{i,17}$	$x_{n,17}$	$s_{17} = \frac{\sum x_{i,17}}{n}$	
				$\Delta_{1,k} = \frac{\sum \omega_j \times x_{1,j}}{\sum \omega_j}$	$\Delta_{i,k} = \frac{\sum \omega_j \times x_{i,j}}{\sum \omega_j}$	$\Delta_{n,k} = \frac{\sum \omega_j \times x_{n,j}}{\sum \omega_j}$		
Working conditions	W_4	working environment	ω_{18}	x_{18}			$s_{18} = x_{18}$	$\mathcal{S}_4 = \frac{\sum s_j \times \omega_j}{\sum \omega_j}$
		Skill level	ω_{19}	x_{19}			$s_{19} = x_{19}$	
				$\Delta_{i,k} = \frac{\sum \omega_j \times x_j}{\sum \omega_j}$				
Product design	W_5	Modular design of the product	ω_{20}	x_{20}			$s_{20} = x_{20}$	$\mathcal{S}_5 = \frac{\sum s_j \times \omega_j}{\sum \omega_j}$
		Standardized design	ω_{21}	x_{21}			$s_{21} = x_{21}$	
		Product designed for easy failure detection	ω_{22}	x_{22}			$s_{22} = x_{22}$	
		Product designed for ease of restoring to working condition after repair	ω_{23}	x_{23}			$s_{23} = x_{23}$	
				$\Delta_{i,k} = \frac{\sum \omega_j \times x_j}{\sum \omega_j}$				
Product reconditioning	W_6	Technical support for reconditioning - accessibility	ω_{24}	x_{24}			$s_{24} = x_{24}$	$\mathcal{S}_6 = \frac{\sum s_j \times \omega_j}{\sum \omega_j}$
		Ease of restoring product to working condition after repair	ω_{25}	x_{25}			$s_{25} = x_{25}$	
		Environmental issues at end of life	ω_{26}	$x_{1,26}$	$x_{i,26}$	$x_{n,26}$	$s_{26} = \frac{\sum x_{i,26}}{n}$	
		Availability of OEM qualified service engineers	ω_{27}	x_{27}			$s_{27} = x_{27}$	
		Estimated Reliability (R) - state of health	ω_{28}	$x_{1,28}$	$x_{i,28}$	$x_{n,28}$	$s_{28} = \frac{\sum x_{i,28}}{n}$	
		Software and firmware	ω_{29}	x_{29}			$s_{29} = x_{29}$	

		Risk of injury	ω_{30}	x_{30}			$s_{30} = x_{30}$	
				$\Delta_{1,k} = \frac{\sum \omega_j \times x_{1,j}}{\sum \omega_j}$	$\Delta_{i,k} = \frac{\sum \omega_j \times x_{i,j}}{\sum \omega_j}$	$\Delta_{n,k} = \frac{\sum \omega_j \times x_{n,j}}{\sum \omega_j}$		
Documentation / Information	W_7	Type of information or documentation available	ω_{31}	x_{31}			$s_{31} = x_{31}$	$S_7 = \frac{\sum s_j \times \omega_j}{\sum \omega_j}$
		Availability of information by target groups	ω_{32}	x_{32}			$s_{32} = x_{32}$	
		Duration time of availability of information or documentation	ω_{33}	x_{33}			$s_{33} = x_{33}$	
				$\Delta_{i,k} = \frac{\sum \omega_j \times x_j}{\sum \omega_j}$				
After-sales strategy	W_8	Guarantee management	ω_{34}	x_{34}			$s_{34} = x_{34}$	$S_8 = \frac{\sum s_j \times \omega_j}{\sum \omega_j}$
		Remote after-sales assistance	ω_{35}	x_{35}			$s_{35} = x_{35}$	
				$\Delta_{i,k} = \frac{\sum \omega_j \times x_j}{\sum \omega_j}$				
Product identification	W_9	Ease of identification	ω_{36}	$x_{1,36}$	$x_{i,36}$	$x_{n,36}$	$s_{36} = x_{36}$	$S_9 = \frac{\sum s_j \times \omega_j}{\sum \omega_j}$
		Accessibility of identification	ω_{37}	$x_{1,37}$	$x_{i,37}$	$x_{n,37}$	$s_{37} = x_{37}$	
		Robustness of identification	ω_{38}	$x_{1,38}$	$x_{i,38}$	$x_{n,38}$	$s_{38} = x_{38}$	
				$\Delta_{1,k} = \frac{\sum \omega_j \times x_{1,j}}{\sum \omega_j}$	$\Delta_{i,k} = \frac{\sum \omega_j \times x_{i,j}}{\sum \omega_j}$	$\Delta_{n,k} = \frac{\sum \omega_j \times x_{n,j}}{\sum \omega_j}$		
Priority part scores (∇_i) & Final Repairability Index ($\mathcal{R}$)				$\nabla_1 = \frac{\sum W_k \times \Delta_{1,k}}{\sum W_k}$	$\nabla_i = \frac{\sum W_k \times \Delta_{i,k}}{\sum W_k}$	$\nabla_n = \frac{\sum W_k \times \Delta_{n,k}}{\sum W_k}$	$\mathcal{R} = \frac{\sum \nabla_i}{n} = \frac{\sum S_9 \times W_k}{\sum W_k}$	

terion and priority part levels within each category "k". At the criterion level, the aggregate score s_j at each criterion "j" level is calculated as the arithmetic average of the $x_{i,j}$ values associated with all relevant priority parts "i". At the category level, the category score $\mathcal{S}_k$ is calculated as a weighted sum of the criterion-level scores s_j, using criterion-specific weights ω_j.

Similarly, for each priority part "i", an aggregate score $\Delta_{i,k}$ is computed as a weighted sum of the criterion values $x_{i,j}$, using the criterion weights ω_j. Each priority part score ∇_i is subsequently obtained by aggregating these $\Delta_{i,k}$ scores across categories, weighted by their respective category weights W_k.

Ultimately, the RI is calculated using two alternative approaches: (i) as the weighted sum of category scores $\mathcal{S}_k$, or (ii) as the arithmetic average of all priority part scores ∇_i. The detailed mathematical formulations for these calculations are provided in Table 2.

To enhance interpretability, the original scoring system values, initially ranging between 0 and 1, are scaled up to a range of 0–10 by multiplying by a factor of 10. Consequently, all scores, including $x_{i,j}$, s_j, $\Delta_{i,k}$, ∇_i, and $\mathcal{S}_k$ comply with these 0 to 10 scales. This standardized scaling system enables stakeholder profiles to easily interpret the RI, where a score of 10 represents maximum satisfaction regarding their product RI perspectives.

The scaling aligns directly with the color-coding scheme and symbols proposed by the French Ministry of Ecological Transition. As illustrated in Fig. S2, the FRI representations are employed to demonstrate the level and color thresholds employed in the RIUP method. A proposed design for the RIUP method will be presented in the future. This scheme utilizes a color-coding system to denote the repairability of products. Products with a score strictly below 2 are shown in bright red, indicating very low repairability, i.e., they are not repairable or are very difficult to repair. Products rated in the range [2, 4[are shown in orange, indicating low repairability. Products with a score in the range [4, 6[are shown in yellow, indicating average repairability. Products with a score between [6, 8[are shown in light green, indicating good repairability, while those with a score greater than 8 are shown in dark green, indicating excellent repairability (Barros and Dimla, 2023).

3. Results

To illustrate the capability of the RIUP method to integrate different RI perspectives across stakeholder's profiles, a heat-sealing machine was selected as case study. This case study is intended as an illustrative application to demonstrate the feasibility, internal consistency, and discriminative capacity of the method, rather than as a statistical validation across product categories. This machine is designed, manufactured and sold by an SME in B2B context. A description of the heat-sealing machine can be found in Text S5. Among all the heat-sealing components, those delivering the technical functions listed in Table S5 were identified as priority parts for assessing the RI. This assessment was carried out in collaboration with a member of the SME's design team with the aim of redesigning the machine to improve its repairability.

3.1. Scoring system results

The heat-sealing machine comprises tightly integrated mechanical, electrical and electronic modules. Although the evaluation workshop was conducted from the perspective of the OEM's design team, each RIUP criterion was scored so that the results can be reweighted for any stakeholder at a later stage. Table 3 presents the RI calculated using a generalist profile, in which all criteria and categories carry an equal weighting of 1. The matrix can be read in two ways: Vertically, it shows how each priority part performs across the criteria; and horizontally, it reveals the contribution of every criterion and its category to the overall RI.

A color-coding system is used to highlight important information for the results interpretation. Color coding is used to visually support the interpretation of repairability indices and stakeholder-specific scores, based on predefined threshold values. Numerical values remain the primary source of information. Bright red cells indicate that specific priority parts perform very poorly against the corresponding criteria, which has a significant impact on the overall RI. For instance, critical deficiencies were identified in the product-level criteria such as "Availability of diagnostic support and interfaces", "Accessibility of diagnostic support and interfaces", "Technical support for reconditioning - accessibility". Similarly, low scores were observed for the criterion "Environmental issues at end of life" in relation to the "PID thermo

regulator" and "Thermo dwell timer" priority parts, as well as for the criteria "Ease of identification", "Accessibility of identification" and "Robustness of identification" concerning the "Miniature linear guides". In addition to these critical red cells, orange and yellow scores indicate areas with moderate performance that should also be targeted for improvement to further enhance the RI. Light green scores reflect satisfactory performance and demonstrate a positive contribution to the product's repairability. However, depending on the company's design or maintenance objectives, even these aspects may be optimized.

As the industrial partner also provides a maintenance service for their machines, the "maintenance team" perspective was considered. Finally, clients who cannot pay for the maintenance service are assumed to have either a "maintenance team" or "consumer" perspective. The RI results from the "generalist", "design team", "maintenance team" and "consumer" perspectives are shown in Fig. 3. It can be seen that the RI from the "design team" and "consumer" perspectives are 14% and 11% higher than that from the "generalist" perspective, respectively. These stakeholders' perspectives seem to favor a product's RI with respect to the generalist perspective. Conversely, the RI from the "maintenance team" perspective is 2% lower than that from the "generalist" perspective. The maintenance team perspective seems to be less favorable to the RI of the product than the generalist perspective.

The RIUP matrix breaks down the global repairability index (RI) according to priority part, criterion and category, enabling designers to identify areas where improvements will be most effective. As each stakeholder applies different weights, these partial scores shift accordingly. The shift was measured as the relative deviation (RD) between each weighted score and the unweighted generalist profile (baseline), with the results visualized in Fig. 4 (priority parts) and Fig. 5 (criterion categories).

As illustrated in Fig. 4, most parts only move slightly from the baseline. Design team weights raise scores by +11 to –15%, consumer weights by +7 to –12%, whereas maintenance team weights lower them by −1 to −4%. The "Miniature linear guides" exhibits the largest negative swing and therefore represents the part with the greatest potential for raising the machine's RI.

As shown in Fig. 5, the relative deviation of the most significant criteria categories contributing to the product's RI is highlighted. From the design team's perspective, the categories "Supports", "Documentation/Information" and "After-sales strategy" appear to favor the RI by 50%, 33% and 15% respectively. It is notable that the categories "Product reconditioning", "Product design" and "Product identification" compromise the RI by −25%, −11% and −7%, respectively. The remaining categories have been found to have an insignificant influence, with an estimated margin of error of approximately 1%. From the standpoint of the "maintenance Team", the categories predominantly result in a reduction of the heat-sealing machine's RI. The categories "Supports", "After-sales strategy", and "Product identification" have a negative impact on the RI, with respective contributions of −22%, −27% and −25%. Conversely, the "Product reconditioning" and the "Documentation/Information" categories have a positive impact, with respective contributions of 9% and 8%. From the standpoint of the "Consumer", the categories "Supports", "Product reconditioning", and "Product identification" are the most significant, contributing to an

Table 3
Result of the repairability index from a generalist profile (with all weights equal to 1 and the color-coding system).

		Priority parts										
Categories	**Criteria**	**Miniature linear guides**	**Heating block**	**Contactors**	**Mano-pressure regulator**	**Pneumatic cylinder**	**Tooling plate**	**PID thermo regulator**	**Thermo dwell timer**	**Cartridge heater**		**Category score**
Disassembly & Reassembly	Disassembly depth/sequence	9.11	9.11	9.11	9.56	8.89	9.56	9.11	9.11	9.11	9.19	9.76
	Disassembly time	9.72	9.86	9.86	9.94	9.81	9.94	9.86	9.86	9.86	9.86	
	Tools	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10	
	Fasteners	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10	
		9.71	**9.74**	**9.74**	**9.88**	**9.67**	**9.88**	**9.74**	**9.74**	**9.74**		
Supports	Availability of diagnostic support and interfaces	0.00									0	6.67
	Accessibility of diagnostic support and interfaces	0.00									0	
	Availability of technical support for disassembly and reassembly	10.00									10	
	Accessibility of technical support for disassembly and reassembly	10.00									10	
	Availability of identification support	10.00									10	
	Accessibility of identification support	10.00									10	
		6.67										
Spare parts	Availability of spare parts by target groups	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10	9.59
	Duration time of spare parts availability	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10	
	Delivery time of spare parts	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.5	
	Spare parts connection interfaces	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10	
	Supply of spare parts - content	10.00									10	
	Spare parts compatibility	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10	
	Price of spare parts	10.00	10.00	10.00	10.00	10.00	10.00	6.60	10.00	10.00	9.62	
		9.64	**9.64**	**9.64**	**9.64**	**9.64**	**9.64**	**9.16**	**9.64**	**9.64**		
Working conditions	working environment	6.60									6.6	7.05
	Skill level	7.50									7.5	
		7.05										

Product design	Modular design of the product	10.00								10	7.90
	Standardized design	5.00								5	
	Product designed for easy failure detection	6.60								6.6	
	Product designed for ease of restoring to working condition after repair	10.00								10	
		7.9									
Product reconditioning	Technical support for reconditioning - accessibility	0.00								0	6.16
	Ease of restoring product to working condition after repair	6.60								6.6	
	Environmental issues at end of life	7.50	10.00	5.00	7.50	10.00	10.00	0.00	0.00	2.50	5.83
	Availability of OEM qualified service engineers	10.00								10	
	Estimated Reliability (R) - state of health	6.60	10.00	6.60	6.60	10.00	10.00	6.60	6.60	3.30	7.37
	Software and firmware	3.30								3.3	
	Risk of injury	10.00								10	
		6.29	**7.13**	**5.93**	**6.29**	**7.13**	**7.13**	**5.21**	**5.21**	**5.10**	
Documentation / Information	Type of information or documentation available	10.00								10	7.50
	Availability of information by target groups	2.50								2.5	
	Duration time of availability of information or documentation	10.00								10	
		7.5									
After-sales strategy	Guarantee management	2.50								2.5	4.55
	Remote after-sales assistance	6.60								6.6	
		4.55									
Product identification	Ease of identification	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	4.44	6.85
	Accessibility of identification	0.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	5.00	8.33	
	Robustness of identification	0.00	10.00	10.00	5.00	5.00	10.00	10.00	10.00	10.00	7.78	
		0.00	**8.33**	**8.33**	**6.67**	**6.67**	**8.33**	**8.33**	**8.33**	**6.67**	
Final repairability index		**6,59**	**7.61**	**7.48**	**7.35**	**7.42**	**7.63**	**7.35**	**7.40**	**7.20**	**7.34**

increase in the RI by 27%, 24% and 18% respectively. Conversely, the "Documentation/Information" category exhibits a 17% decrease in favor of the index.

In general, from the priority parts point of view, they favor the RI in the "Design team" and "Consumer" perspectives, while disfavoring it in the "Maintenance team" perspectives in comparison to the generalist perspective. However, from a categorization point of view, their contribution to the RI is highly diverse. Nevertheless, the categories "Supports", "Product design", "Product reconditioning", "Documentation/Information", "After-sales strategy" and "Product identification" were the most significant contributors for the three stakeholder perspectives.

3.2. Sensitivity analysis

The differences in repairability scores across stakeholder views arise from the criteria that each view selects or omits, and the weight assigned to each selected criterion. To isolate the second factor, a univariate sensitivity analysis was performed, varying one criterion while holding all others in the same category constant. Category weights were always required to sum to 1. Tests were performed on a single priority part, as preliminary checks showed that the pattern remains unchanged when several parts are evaluated together.

Fig. 6 plots the resulting RI for each stakeholder profile against every varied criterion, making it easy to identify the most influential factors.

This analysis shows that:

- For the generalist profile, the RI shifts by less than 5%, confirming that equal weighting yields a uniformly stable score.
- The design team profile shows that most criteria again move the RI by less than 5%. Larger shifts (down to 9.5) stem from "Accessibility of technical support for disassembly and reassembly", "Duration time of spare parts availability", "Delivery time of spare parts", "Spare parts compatibility", "Product designed for easy failure detection", "Type of information or documentation available" and "Ease of identification". The "Spare parts" category alone accounts for 43% of the RI variance.
- For the maintenance team profile, the pattern is similarly flat, except for six criteria such as "Accessibility of diagnostic support and interfaces", "Product designed for easy failure detection", "Product designed for ease of restoring to working condition after repair", "Estimated Reliability (R) - state of health", "Risk of injury" and "Type of information or documentation available", each of which can lower the RI score below 9.5.
- For the consumer profile, most criteria still vary RI by less than 5%, yet "Tools", "Skills level", "Modular design of the product", "Standardized design", and "Risk of injury" can lower the score to below 9.0. Here, the product design category accounts for up to 40% of the variance.

In summary, modifying any single criterion changes the RI by 5%, but in isolated cases, the effect can reach 15%. These results pinpoint which levers deserve priority when tailoring repairability improvements

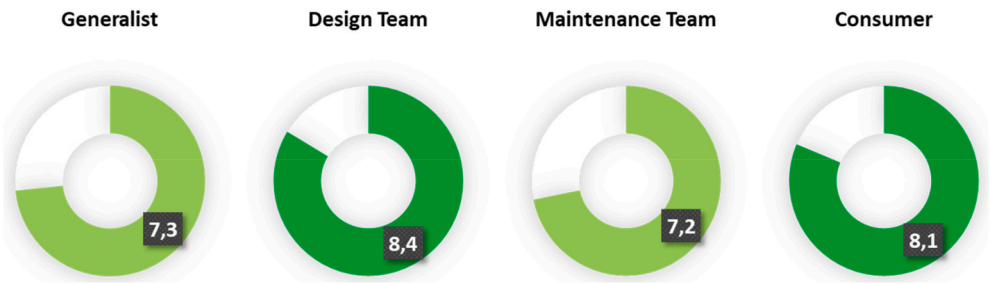

Fig. 3. Repairability index from several stakeholders' perspectives.

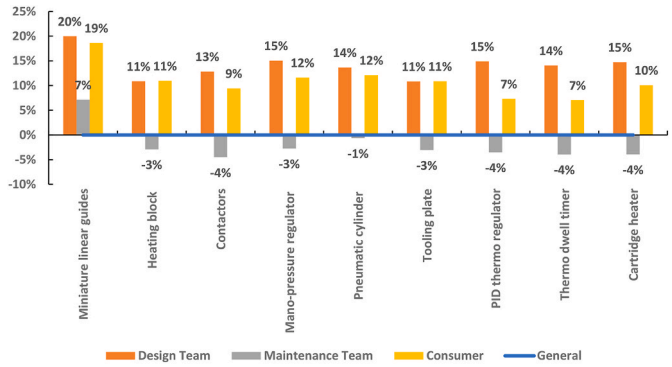

Fig. 4. Relative deviation of the repairability score based on the priority parts.

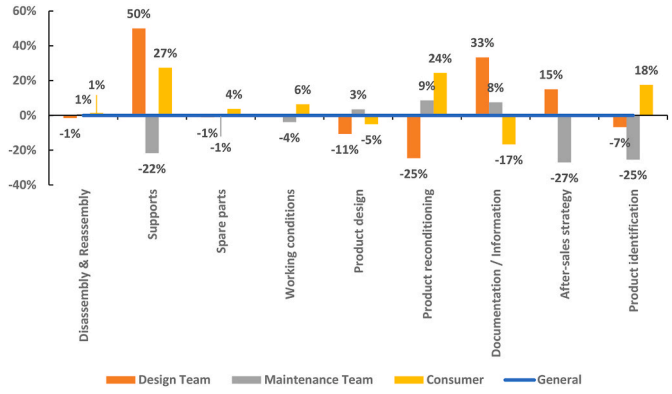

Fig. 5. Relative deviation of the repairability scores based on the criteria's categories.

for each stakeholder.

4. Discussions

The RIUP method, which allows the RI of products to be assessed based on stakeholder profiles, provides important information to product design teams, maintenance teams, and consumers. Consumers may be individuals (B2C) or professionals (B2B). On this basis, the RIUP method can be used for various purposes.

4.1. The applications of the method for repairability assessment

The RIUP method was piloted on a heat-sealing machine developed by an OEM in B2B context, that combines mechanical, electrical, and electronic modules. Using the generalist weighting, the machine achieved a satisfactory RI across all stakeholder profiles. Matrix analysis then guided the design team towards high-impact upgrades, such as richer diagnostic support, clearer service documentation, and an extended commercial warranty.

As the OEM is shifting to a leasing model, repairability is becoming a source of profit. RIUP showed that substituting standardized, easily identifiable components would reduce service time and increase asset longevity, directly supporting a lease-and-service business model. These recommendations are in line with the goal of the EU Circular Economy Action Plan (CEAP) of keeping products in use for longer (CEAP, 2020).

Beyond this industrial case, RIUP can be deployed throughout the product's life cycle. In the early stages of design, when data is limited, the index can be computed incrementally and refined as more information becomes available, providing teams with a dynamic tool to guide repairability decisions. An essential feature of the RIUP method is its incorporation of the end-user perception, whether from industrial maintenance teams, professional customers, or private consumers, into the weighting scheme. This produces an RI that predicts real-world acceptance, offering manufacturers a market advantage.

The RI is also gaining traction within industrial maintenance services. In maintenance, the concept of “maintainability” reflects a product's capacity to be repaired and returned to its functional state during its operational life. The criteria for maintainability are closely aligned with those of the RIUP method. Interviews with industry maintenance experts revealed that many of these criteria are already used to guide purchasing decisions for machinery on production lines. Criteria such as disassembly depth and time, fasteners and product design type (modular, standard), spare parts price, availability and accessibility, product reconditioning, accessibility and availability of technical support (for diagnosis, disassembly and reassembly, identification) and product reliability are integral both to maintainability assessments and the RI.

Interviews with plant maintenance specialists confirmed that the RIUP criteria mirror the classic factors of maintainability: disassembly depth/time, fastener type, modularity, spare part logistics, diagnostic access, and reliability. Most of the criteria (except physical teardown) can be scored in under 30 min; a confirmatory strip-down typically takes between one and three hours, depending on the complexity of the product and the experience of the operator (e.g., via eDIM (ease of Disassembly) (Peeters et al.) or FRI methods). Therefore, RIUP can serve as a rapid decision-making tool for equipment procurement.

OEMs that are new to repairability may find the full RIUP grid challenging, particularly the design team weighting, which often results in lower scores than the unweighted baseline (see Fig. 6). We recommend that first-time users start with the generalist profile or an even simpler binary rubric (0 or 1 with uniform weights), before graduating to stakeholder-specific weights as familiarity grows.

From a methodological standpoint, the RIUP criteria are underpinned by complementary metric types. Most criteria rely on qualitative or semi-quantitative class-based metrics derived from EN 45554, capturing the degree to which repair-enabling features (e.g., documentation availability, diagnostic support, spare-part accessibility) are implemented. These metrics are designed to be rapidly assessed and interpretable by different stakeholders. In contrast, criteria directly related to physical repair actions, such as disassembly depth and disassembly time, are evaluated using continuous quantitative metrics,

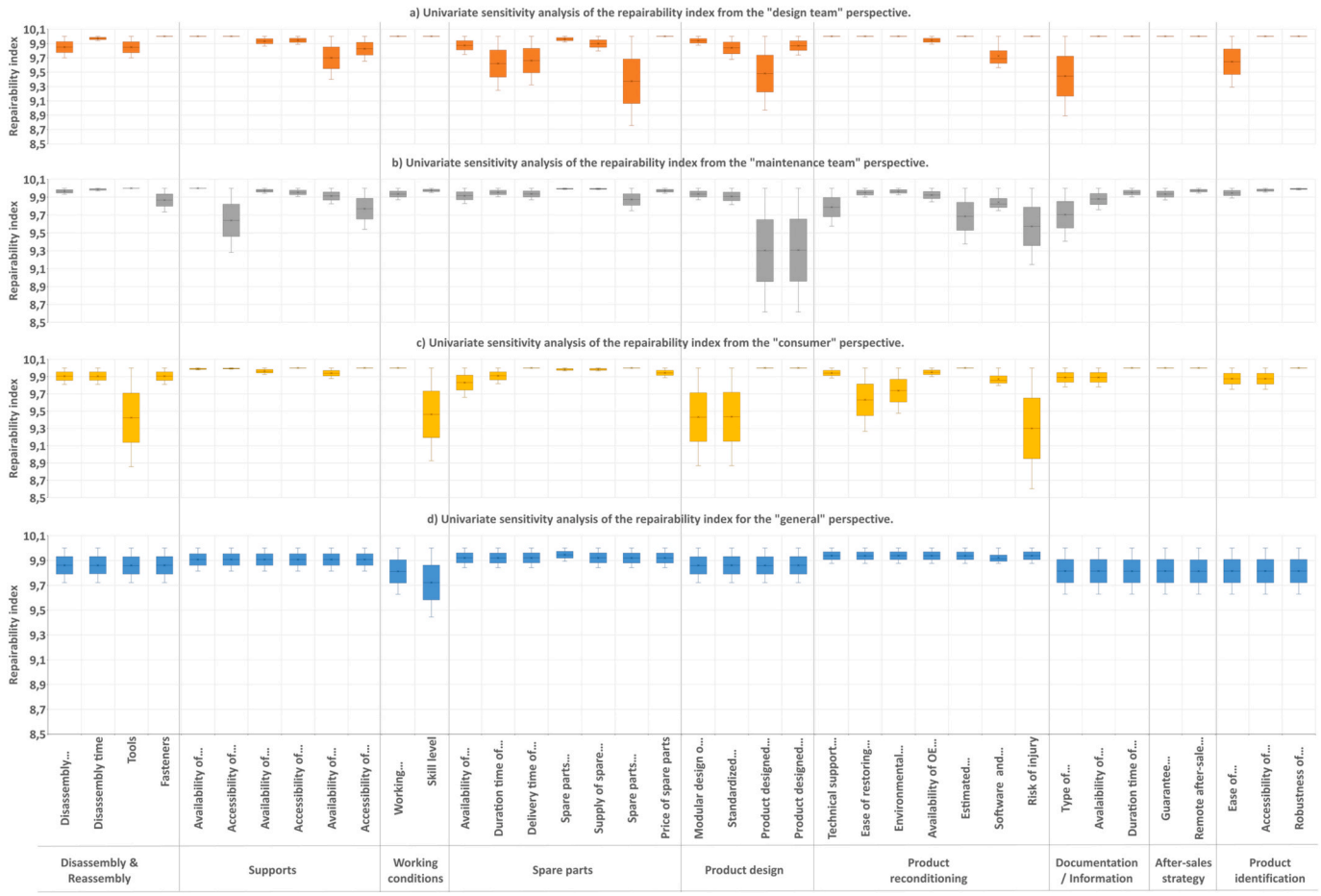

Fig. 6. Univariate sensitivity analysis of the RI by stakeholders' perspectives.

allowing a more precise characterization of mechanical effort during repair. The combination of class-based and continuous metrics ensures both usability and technical robustness of the repairability index.

4.2. *Limitations of the RIUP method and future works*

The RIUP method is inherently based on stakeholder-specific interpretations of repairability, reflecting the different objectives and constraints of design teams, maintenance teams, and non-professional users, as described in Section 2.2.1. Consequently, repairability outcomes are profile-dependent and should not be interpreted as a single, universal metric applicable to all usage contexts. This profile-based approach improves decision relevance for each stakeholder but implies that repairability scores should be interpreted within their specific context rather than directly compared across B2B and B2C use cases.

Despite the advantages demonstrated by the RIUP method, certain limitations that are inherent to its development process may introduce uncertainties in the results and raise questions about its robustness in diverse industrial contexts.

Firstly, although the scope of the literature review includes both B2C and B2B contexts, the results reveal a clear dominance of B2C-oriented repairability assessment methods, mainly applied to EEE and ErP products. This reflects the current regulatory and market-driven focus on consumer information rather than a comprehensive coverage of industrial B2B contexts. Notably, the review did not identify any repairability assessment method specifically developed for purely mechanical products, as most existing approaches address mechanical components only when embedded within EEE or ErP systems. As a result, the direct applicability of existing criteria to mechanical products and industrial settings remains limited and requires careful adaptation. This limitation is partially addressed in the present study through the involvement of industrial experts from B2B contexts in the selection and weighting of repairability criteria of the RIUP method. Their input ensures that industrial constraints such as availability requirements, downtime costs and maintenance organization are explicitly considered. Nevertheless, further validation on a broader range of mechanical products and B2B case studies remains necessary.

Secondly, stakeholder-specific criteria were largely chosen through industrial expert elicitation, especially for the “design team” and “maintenance team” profiles. The use of semi-structured interviews may introduce subjective biases. However, several mitigation measures were implemented. They include a standardized interview guide, neutral question framing, and the use of predefined criteria derived from the literature, as illustrated by the questionnaire presented in Table S6. While this approach ensures technical relevance and consistency across interviews, it inherently involves industrial expert judgment and therefore introduces a degree of subjectivity. This subjectivity may influence the prioritization of criteria and weighting schemes. Broader surveys involving a larger number of organizations with contrasting business models (e.g., service-oriented versus product-sales-oriented) could lead to different prioritizations or the identification of additional criteria. Notably, the rankings obtained for the “maintenance team” and “consumer” profiles were relatively consistent across respondents, suggesting a certain robustness of these perspectives. Nevertheless, extending the expert panel would further strengthen the external validity of the results.

Thirdly, criterion weights are derived using the AHP and thus reflect academic expert judgement. Sensitivity tests show that adjusting any

single weighting has a negligible impact on the overall RI, indicating acceptable robustness. However, alternative weighting techniques should be explored to confirm this, as sensitivity analysis has indicated that modifying the weight of a single criterion results in variation of less than 5% in the final RI for most assessed criteria. This suggests that, while some variability is inevitable, the method produces outcomes that are satisfactory in terms of stability and reliability. While class-based metrics enable consistent comparison across diverse criteria, they inevitably simplify complex technical realities; this trade-off between precision and usability is inherent to repairability assessment methods intended for multi-stakeholder decision support. The selection of academic experts may introduce bias related to disciplinary background or sectoral expertise. However, this limitation is acknowledged, and future work should consider this for methodological improvement.

Fourthly, while the overall sensitivity analysis indicates limited variation in the global repairability index, discrepancies observed at the criterion and category levels can be explained by several factors. First, stakeholder-specific weighting schemes concentrate importance on different subsets of criteria, amplifying the influence of categories such as spare-parts logistics, product design, documentation, and support services depending on the profile considered. Second, criteria that are structurally central to the repair process (such as spare-part availability and delivery, diagnostic access, failure detection, modularity, and disassembly-related characteristics) affect multiple downstream repair steps, which explains their higher sensitivity compared to more peripheral criteria. Finally, discrepancies may also arise from the cumulative effect of several moderately weighted criteria acting in the same direction. These hypotheses suggest that sensitivity patterns are not random but reflect meaningful differences in stakeholder priorities and repair process structure.

Fifthly, the current scale distributes maximum points evenly across classes, mirroring EN 45554 and related schemes. More punitive or reward-rich scales, e.g., binary penalties for unavailable spares or high bonuses for exemplary modularity, could improve discrimination, but could also lead to user frustration and greater variance in the results. Future work must balance precision with usability.

Finally, using one framework for diverse product families introduces some inequity, but sensitivity analysis shows that the resulting uncertainty is usually less than 5%. Accuracy can be improved by adding product-specific technical parameters to the user-centric matrix. The (Joint Research Centre) JRC's exploratory method (Joint Research Centre et al., 2025) for prioritizing environmentally significant product groups under the Ecodesign and Energy-Labelling Work Plan (European Commission, 2022) offers a way to achieve this refinement.

Repairability undergoes an evolution in accordance with wear, usage, and state of health. The development of a dynamic RI, incorporating real-time condition data, is therefore planned in order to provide age-adjusted scores. Concurrently, the extension of RIUP into a composite circularity Index (Sustainability index 2023, 2023), integrating repairability with durability, recyclability, resource efficiency, and full life-cycle impact, would ensure alignment with emerging regulations (e.g., the Ecodesign for Sustainable Products Regulation (Ecodesign for Sustainable Products Regulation, 2024) and the increasing industrial demand for multidimensional ecodesign metrics. The evolution of the RIUP method into a circularity index has the potential to address the discrepancy between technical design requirements, regulatory compliance, and societal expectations for more durable, resource-efficient products.

5. Conclusion

This paper introduces the RIUP method, a novel approach for assessing a product's RI whose originality lies in incorporating the perspectives of key stakeholders across the product value chain. This method can be applied to any type of product. These stakeholders include the design and maintenance teams and end users, such as individual consumers in B2C contexts and professionals in B2B settings. Each stakeholder group has distinct objectives throughout the product's life cycle. The design team aims to develop products that meet professional standards and are easy to manufacture, cost-effective, and environmentally efficient. The maintenance team seeks equipment with high availability and minimal downtime to ensure optimal productivity. Consumers, in turn, prioritize the ability to repair products themselves or through independent repair services. To tailor the repairability assessment to each stakeholder profile, relevant criteria were identified through interviews with industry professionals. These criteria were then weighted using the AHP in collaboration with academic experts. A rating system was subsequently defined that emphasizes fairness and balance.

The RIUP method was applied to a heat-sealing machine case study in a B2B context. The results yielded RI scores of 8.4/10 from the design perspective, 7.2/10 from the perspective of maintenance team of a company considering the purchase of the machine, and 8.1/10 from the consumer, both individual and professional users. These indices indicate a generally good level of repairability. Furthermore, the findings informed the industrial partner's strategic decisions, including targeted design improvements and transitioning to a rental-based business model for the machine.

Beyond this case study, the RIUP method has versatile applications. It can serve as a design aid at the beginning of product development or during post-design evaluation to create more repairable products. In maintenance, it provides a tool to support decisions about selecting equipment to purchase based on repairability performance. Future developments may further enhance the method by integrating criteria specific to product types, alongside stakeholder profiles. Additionally, a dynamic RI that evolves with the product's condition over time, is under development to offer more precise guidance aligned with circular economy principles.

CRediT authorship contribution statement

Christian Wandji: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Helmi Ben Rejeb:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Andreas Riel:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Cyrille Dalla Zuanna:** Writing – review & editing, Validation, Methodology, Funding acquisition.

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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. ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2026.100419.

Data availability

The tool will be made available on request.

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7.3. Article 3: Circularity assessment of power electronic converters: manual disassembly, bill of material, circularity indicators and actionable guidelines.

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Circularity assessment of power electronic converters: manual disassembly, bill of material, circularity indicators and actionable guidelines

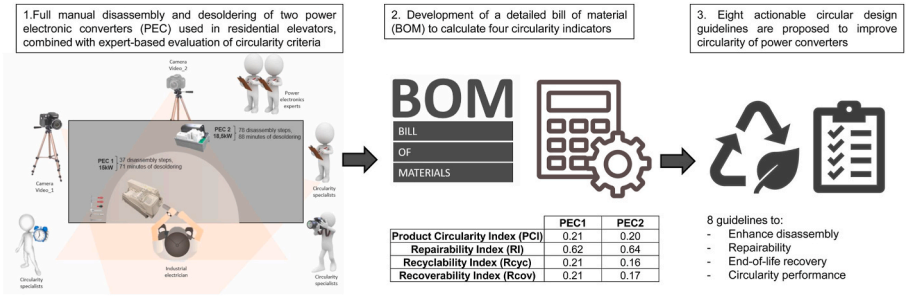
Irati Ruiz de Azua Lahidalga [a,*], Christian Wandji [b], Aitor Picatoste [a], Daniel Justel [a], Iosu Aizpuru [a], Andreas Riel [b], Helmi Ben Rejeb [b], Joan Manuel F. Mendoza [a,c,**]

[a] Mondragon Unibertsitatea, Faculty of Engineering, Mechanics and Industrial Production, Loramendi 4, Mondragon, 20500, Gipuzkoa, Spain
[b] Univ. Grenoble Alpes, CNRS, Grenoble INP, G-SCOP, 46 Avenue Félix Viallet, 38000, Grenoble, France
[c] IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009, Bilbao, Spain

HIGHLIGHTS

- Integrated circularity assessment performed on two real power electronic converters.
- Manual disassembly and desoldering revealed major circularity barriers.
- Circularity performance of power converters remains very limited.
- Eight actionable circular design guidelines are proposed to improve sustainability.

GRAPHICAL ABSTRACT



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ABSTRACT

Power electronics are essential for the energy transition, supporting renewable integration, electrified transport, and efficient industrial systems. However, their growing deployment raises environmental concerns linked to the use of scarce materials, difficult-to-disassemble product architectures, and insufficient end-of-life strategies, factors which contribute to the global increase in electronic waste. As the core functional units of power electronic systems, power electronic converters (PECs) play a central role in determining these environmental outcomes. This study evaluates the circularity of two PECs. The methodology combined complete disassembly and desoldering, bill of material development, and the calculation of four indicators: Product Circularity Index (PCI), Reparability Index (RI), Recyclability (Rcyc), and Recoverability (Rcov). The results indicate that disassembly and desoldering of the two PECs, 37 and 78 steps, 71 and 88 min, respectively, require a high degree of manual effort, representing a significant barrier to practical and economically viable end-of-life recovery. Circularity was consistently low for PCI (0.21 and 0.20), Rcyc (0.21 and 0.16), and Rcov (0.21 and 0.17), while

* Corresponding author.
** Corresponding author. Mondragon Unibertsitatea, Faculty of Engineering, Mechanics and Industrial Production, Loramendi 4, Mondragon, 20500, Gipuzkoa, Spain.
E-mail addresses: iruizdeazua@mondragon.edu (I. Ruiz de Azua Lahidalga), jmfernandez@mondragon.edu (J.M.F. Mendoza).

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RI values were moderate (0.62 and 0.64), suggesting some potential for life extension through repair. Based on these findings, eight design guidelines are proposed to improve disassembly, reparability, and recovery. This study underscores how product design directly affects circularity outcomes in PECs, reinforcing the need to integrate circular economy principles in the development and management of PECs.

1. Introduction

The global energy demand is expected to continue to grow, driven by increasing industrialisation and digitalisation (Mahmood et al., 2024). In 2024, fossil fuels accounted for approximately 60% of global primary energy, despite the accelerated deployment of renewable energy technologies (IEA, 2025). In the same year, the emissions from the energy sector reached a record 37.8 gigatons of CO_2, accounting for about 70% of all anthropogenic emissions (IEA, 2025). A large share of this growth stems from the electricity system, which is expanding as economies electricity consumption is projected to rise by about 3% per year this decade, increasing its current share from 20% to up to 36% by 2035 (IEA, 2024). These trends highlight the urgency of accelerating the decarbonisation of the global energy system.

In an effort to address climate and resource challenges the (United Nations, 2015) has called for urgent climate action (Goal 13). Similarly, the European Climate Law (European Commission, 2021) has mandated a 55% reduction in European Union (EU) greenhouse gas emissions by 2030 relative to 1990 levels. Within this framework, the Circular Economy Action Plan (CEAP) (European Commission, 2020) promotes strategies such as repair, reuse, and recycling to minimise resource extraction and waste. Complementary initiatives, including the Circular Electronics Initiative (European Commission, 2020b) and the Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2024), aim to extend energy-related product longevity, enhance reparability, and foster sustainable material use across product life cycles (Spiliotopoulos and Beltran, 2025). In support of these ambitions, the Joint Research Centre (JRC) has provided an exploratory assessment highlighting the importance of electronic product categories for future reparability evaluation (Spiliotopoulos and Beltran, 2025). Taken together, these policy developments position energy-related electronic systems as priority targets for improving durability, reparability and circularity.

Among energy-related products, power electronic (PE) systems have emerged as critical enablers of the energy transition (Idoko et al., 2024). By efficiently controlling and converting electrical energy, these technologies facilitate the integration of renewable energy sources. They also improve energy conversion in electric vehicles, and reduce losses in power transmission and distribution systems (Blaabjerg et al., 2017). As demand for these functions grows, global PE deployment is projected to reach 100 TW (TW) per year by 2050, significantly contributing to net-zero targets by reducing system-level energy losses (Sangwongwanich et al., 2024).

Although PE devices contribute to greater energy efficiency, their production presents significant environmental and circularity challenges that impact EU CO2 neutrality targets. Their manufacture is highly resource- and energy-intensive, particularly in semiconductor fabrication, which requires 1.15 kW h per cm^2 wafer, substantially more than other electronic components such as printed circuit boards (PCB) (Wang et al., 2023). PE systems also incorporate critical materials, such as neodymium or dysprosium, and hazardous substances, such as lead or cadmium (Baudais et al., 2023) regulated under European laws, including RoHS (European Commission, 2011) and REACH (European Commission, 2006). Moreover, the PE sector predominantly follows a linear economy model, contributing to significant e-waste which is projected to reach 120 million tonnes annually by 2050 (Sangwongwanich et al., 2024).

Power electronic converters (PECs) are central to PE systems. They convert and control electrical energy by adapting voltage, current, or frequency to suit applications such as renewable energy integration and industrial automation (Blaabjerg et al., 2017). Their complex manufacturing and material composition reflect the broader environmental challenges linked to PEs. Enhancing PEC circularity could contribute to minimising the environmental footprint and improving resource efficiency. This requires the integration of life cycle thinking into the early stages of product design and development (Romano et al., 2023; Mendoza et al., 2017).

Despite the importance of PECs in the energy transition, the scientific literature on the circularity and environmental sustainability of PECs remains limited and fragmented. Most studies have focused on improving energy efficiency (Marati et al., 2022; Ristić, 2024; Tang et al., 2022), with little attention paid to other life cycle stages, such as material sourcing or end-of-life (EoL) management (Fang et al., 2023). This narrow focus has also been reflected in life cycle assessment (LCA) studies, which, although increasingly applied to PECs (Baudais et al., 2023; Musil et al., 2023; Vauche et al., 2024; Zimmermann, 2013) tend to concentrate mainly on energy performance or CO_2 emissions. As a result, other environmental impact categories across the full product life cycle remain understudied and the scarcity of high-quality primary life cycle inventory (LCI) data continues to constrain the development of more comprehensive and robust sustainability assessments (Fang et al., 2023). Together, these issues contribute to the fragmented understanding of the overall environmental sustainability of PECs.

Other studies have analysed circularity indicators in a broader electrical and electronic equipment (EEE), context. For example, Vanegas et al. (2018) examined the ease of disassembly of liquid crystal display (LCD) monitors to support circular strategies. Bracquené et al. (2020) proposed a framework to assess circular performance in complex supply chains, particularly relevant for electronic systems, by integrating quantitative indicators with strategic decision-making tools. Herrmann et al. (2023) reviewed recent research on measuring EEE durability but did not apply the methods to specific products. Ardente and Mathieux (2014) examined measures to improve resource efficiency in energy-consuming products such as LCD-TVs.

Despite these advances none of these studies have focused on PECs, nor have they addressed their combined environmental, functional, and material challenges. This gap is further underscored by the fact that, to the best of our knowledge, only one study has applied a circularity indicator directly to a PEC. Evaluating the ease of Disassembly Metric (eDIM) indicator (Vanegas et al., 2018), Romano et al. (2024) revealed critical limitations in the availability of disassembly data and a lack of standardised procedures. However, the scope of the study was limited to disassembly complexity and did not consider broader circularity strategies.

Taken together, these limitations demonstrate the need for comprehensive and multidimensional circularity assessments of PECs that integrate product disassembly data, bill of material (BOM), multiple indicators and design-orientated insights. While several circularity metrics have been proposed in recent years, most studies remain limited either to simplified teardown approaches or to single-indicator analyses focused on isolated life cycle stages. This restricts their ability to capture product-specific design constraints and generate actionable recommendations.

This study applies a detailed empirical methodology to assess the circularity of two real PECs. Unlike previous works based on datasheets or partial assessments, this approach combines complete manual disassembly and desoldering, material-level characterisation through primary BOM reconstruction, and the simultaneous calculation of four

complementary indicators: the Product Circularity Index (PCI), Reparability Index (RI), Recyclability (Rcyc), and Recoverability (Rcov). Although these indicators have been previously defined, they are seldom applied in practice, especially in complex products like PECs, where circularity challenges are tightly linked to integration, joining techniques, and recovery feasibility.

The analysis generates a multidimensional profile of circularity performance and identifies specific design limitations that hinder recovery and reuse. Based on these insights, the paper proposes design and life cycle management (LCM) guidelines tailored to the functional and structural characteristics of PECs. The specific objectives of this study are:

- Analyse the PEC disassembly sequence process, identifying bottlenecks, critical steps, and design-related barriers to circularity.
- Characterise the material composition of two PECs and develop a BOM to allow calculation of circularity indicators.
- Assess the circularity of the PECs using quantitative indicators, including the Product Circularity Index (PCI), Reparability index (RI), Recyclability (Rcyc) and Recoverability (Rcov) rates, to generate a multidimensional circularity profile for each product.
- Define design and LCM guidelines to improve circularity in future generations of PECs.

2. Methodology

This study examines two industrial PECs used in elevators (rated at 15 kW and 18.5 kW) from Nidec Control Techniques (Nidec Corporation, 2025). The first converter (PEC1) belongs to the older Unidrive SP series (Control Techniques, 2011), and the second (PEC2) from the newer Unidrive M700 range (Control Techniques, 2014). Both feature a modular architecture, including PCBs, insulated-gate bipolar transistors (IGBTs), aluminium heatsinks, electrolytic capacitors, plastic housings, and integrated cooling fans. Both units were retired due to communication board failure, with other components remaining functional, and showed no external damage or visible ageing during disassembly.

These PECs were selected to comparatively assess design criteria and circularity indicators, including disassembly, reparability, recyclability, and material circularity. The comparative analysis of two commercial converters of 15 kW and 18.5 kW, manufactured in different years, makes it possible to examine how technological and architectural variability influences circularity performance and to identify potential design improvements across product generations for the same application. Although the units analysed were originally used in elevator systems, this type of medium-power converter is widely employed across industrial sectors due to its primary role in controlling three-phase alternating current (AC) motors. Approximately 380 million electric motors operate within the EU (European Commission, 2025), highlighting both the scale of the motor stock and the prevalence of the associated PECs. In this context, the units under study can be considered representative of industrial converters commonly deployed in the European market. Table 1 summarises the main technical characteristics and operational information of the two PEC.

A structured two-step methodology was applied to evaluate circularity performance (Fig. 1). First, the converters were manually disassembled and desoldered, and experts reviewed their circularity and environmental sustainability criteria (Section 2.1). Second, a detailed BOM was compiled to support the calculation of the selected circularity indicators (Section 2.2). The qualitative and quantitative information from these two stages supported an integrated interpretation of the circular design of the converters. This consolidated analysis revealed critical design limitations and circularity enablers, which in turn informed the design guidelines discussed in Section 3.3.

Table 1
Technical specifications and operational data of the analysed PECs.

Parameter	PEC 1	PEC 2
Manufacturer	Control Techniques (Emerson)	Control Techniques (Emerson)
Series	Unidrive SP	Unidrive M700
Model	SP2403	M701-064 00350 A
Production year	2011	2014
Rated power	11 kW/15 kW	15 kW/18.5 kW
Input Voltage	380–480 V AC, 3-phase	3/PE AC 380–480 V
Input Frequency	48–62 Hz	50–60 Hz
Operating Temperature	0 °C to 40 °C without derating	0 °C to 40 °C without derating
Cooling Method	Forced air cooling (internal fan)	Forced air cooling (internal fan + heatsink)
Dimensions (HxWxD)	540 × 270 × 265 mm	540 × 270 × 265 mm
Weight	8.5 kg	11.8 kg
Installation Method	Panel mounting (IP20)	Panel mounting (IP20)
Communication Options	Modbus RTU, CANopen, PROFIBUS, EtherCAT, CTNet, etc.	Modbus RTU, EtherCAT, PROFINET, Ethernet/IP (via modules)
End-of-life Condition	Failure of communication board	Failure of communication board
Estimated Years in Operation	~10–13 years (prior to disassembly)	~10 years prior to disassembly

2.1. PECs disassembly and design assessment

2.1.1. Manual disassembly and desoldering

This process was performed to both physically separate the components, and collect detailed design and operational data necessary for calculating four key circularity indicators (Section 2.2.2). The disassembly and desoldering were carried out by an industrial electrician, supported by two PE experts who ensured technical accuracy and architectural integrity. Furthermore, a team of three circularity specialists documented the process through video recordings, technical notes, and real-time logging, while gathering insights on component condition and potential for circular strategies.

The disassembly protocol was adapted from two existing methodologies: one proposed by Vanegas et al. (2018) and the other a protocol developed by the French Ministry for Ecological Transition (AGEC) (Ministry of Ecological Transition, 2022). These were combined with further operations to develop the disassembly protocol for circularity purposes. The resulting procedure was structured into sequential phases each outlining essential tasks to achieve the intended outcomes. Full details are provided in S1 of the supplementary file (SF).

The first stage of manual PEC disassembly took place in September 2024 in a controlled workshop environment. The industrial electrician followed the protocol, starting from the external casing and progressing inward. Only manual tools were used, including flat and star-tip screwdrivers, Torx (T10 and T20), Allen keys, and socket wrenches. For each component removed, the team documented the part name, type and number of fasteners, number of disassembly steps, and time required for each operation. Fig. 2 illustrates the disassembly sequence, numbered in chronological along with dismantling times, tool changes, fastener types per operation and material heterogeneity.

The second stage focused on desoldering the electronic components. Completed in March 2025 this operation aimed to recover and characterise the electronic components mounted on the PCBs for subsequent integration into BOM. The same industrial electrician who performed the disassembly conducted the desoldering process in a dedicated electronics workshop, under supervision of the research team and in consultation with PE experts.

To minimise damage and protect component integrity, desoldering was executed using specialised thermal techniques and protective measures. The workflow followed three steps: (i) preheating of all PCBs in a reflow oven to homogenise internal temperatures and reduce thermal shock; (ii) localised heating of solder joints with a hot air gun to

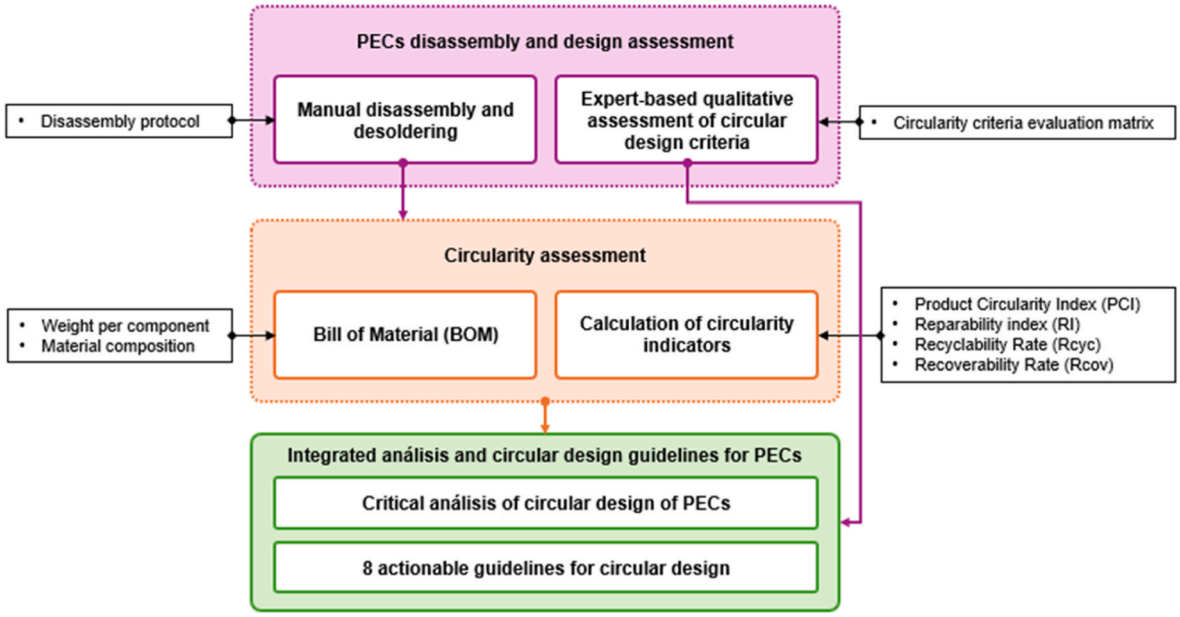

Fig. 1. Methodological steps.

allow targeted heating while preserving both board and component integrity; and (iii) manual removal of components with tweezers and controlled mechanical actions. More delicate elements, such as integrated circuits, were handled with particular care to prevent deformation or breakage.

The tools employed included a hot air gun, solder preheating station, reflow oven, and a fume extractor to reduce operator exposure to solder fumes. The operator also wore thermal gloves and safety footwear as a precautionary measure. Full details about both processes are provided in S2 of the SF. The key findings of the disassembly and desoldering process are presented in Section 3.1.

2.1.2. *Expert-based qualitative assessment of circular design criteria*

The qualitative analysis of circularity criteria was conducted during disassembly and desoldering. These hands-on sessions provided a real-world context for collaborative reflection with PEC experts and the industrial electrician. During the disassembly, technical discussions addressed component accessibility, repairability, and recyclability, as well as identifying critical components, failure-prone parts, and functional design weaknesses.

During the desoldering phase, the discussion was structured around the circularity criteria proposed by Ruiz de Azua Lahidalga et al. (2025), which served as a guiding framework for expert reflection. Rather than applying a formal scoring method, the evaluation was conducted qualitatively through open dialogue and joint interpretation among the participating experts. This process generated contextual insights into how circularity aspects were (or were not) considered in the PECs' design, and identified key barriers and opportunities for improvement. The criteria used and associated observations are presented in Table S3 of the Excel SF. The resulting insights, along with the circularity performance (Section 2.2) directly informed the design guidelines proposed in Section 3.3.

2.2. *Circularity assessment*

In this phase, each PEC component was inventoried, documenting weight, material composition, type of joints, and the presence of labels facilitating material identification, traceability, and sorting. This information supported the calculation of the four circularity indicators considered in the study (see Section 3.2).

2.2.1. *Bill of material (BOM)*

The total weight was 8.5 kg for PEC1 and 11.8 kg for PEC2. Although both share the same material categories, their mass distribution and structural configuration differ significantly. Metals dominate in both cases (84.7% PEC1, 74.7% PEC2), with aluminium, copper, and steel as the primary constituents. Aluminium was extensively used in external structures and heatsinks, particularly in PEC2 (up to 3.5 kg). Copper, present in windings, PCBs, and interconnections, was more prevalent in PEC1 relative to total weight (24.7% vs. 19.5%). Steel, used in fasteners, shielding, and transformer cores, was notably higher in PEC2 (2.9 kg vs. 1.5 kg), contributing to its greater mass.

Plastic components accounted for 10.3% of PEC1 and 16.1% of PEC2, with PEC2 more than doubling the polymer mass (1.9 kg vs. 0.9 kg) due to extended use of housing and insulation. Both devices included polycarbonate, nylon, polypropylene, and ABS. Glass fibre and composites were also higher in PEC2 (0.4 kg vs. 0.2 kg), consistent with a larger number of PCBs and double-sided configurations. Additionally, PEC2 contained more epoxy resin and mineral compounds (1.0 kg vs. 0.2 kg) used for encapsulation, coating, and potting. The BOM for the two PECs is detailed in Fig. 3, and the complete mass breakdown per material, component, and subcomponent are provided Tables S4 and S5 of the Excel SF.

2.2.2. *Calculation of circularity indicators*

The selection of the four circularity indicators was based on a two-stage literature review combining academic and normative sources. The process followed the PRISMA guidelines, as illustrated in Fig. 4.

Two structured searches were conducted in SCOPUS in February 2025, using three combined keyword streams: (i) power electronics or electrical and electronic equipment (EEE), (ii) circular economy and eco-design, and (iii) indicators and metrics (Table 2) (see Fig. 4). The first search targeted circularity and environmental sustainability indicators specifically applied to power electronics (PE), while the second search adopted a broader scope by covering EEE in general. Only peer-reviewed journal articles and reviews written in English between 2015 and 2025 were included. This period was selected because the launch of the EU Circular Economy Package in 2015 marked a turning point in research, regulation, and industrial interest in circularity (Alcalde-Calonge et al., 2022)

The two searches yielded 91 records. Studies related to circularity and environmental sustainability indicators applied to PE and/or EEE

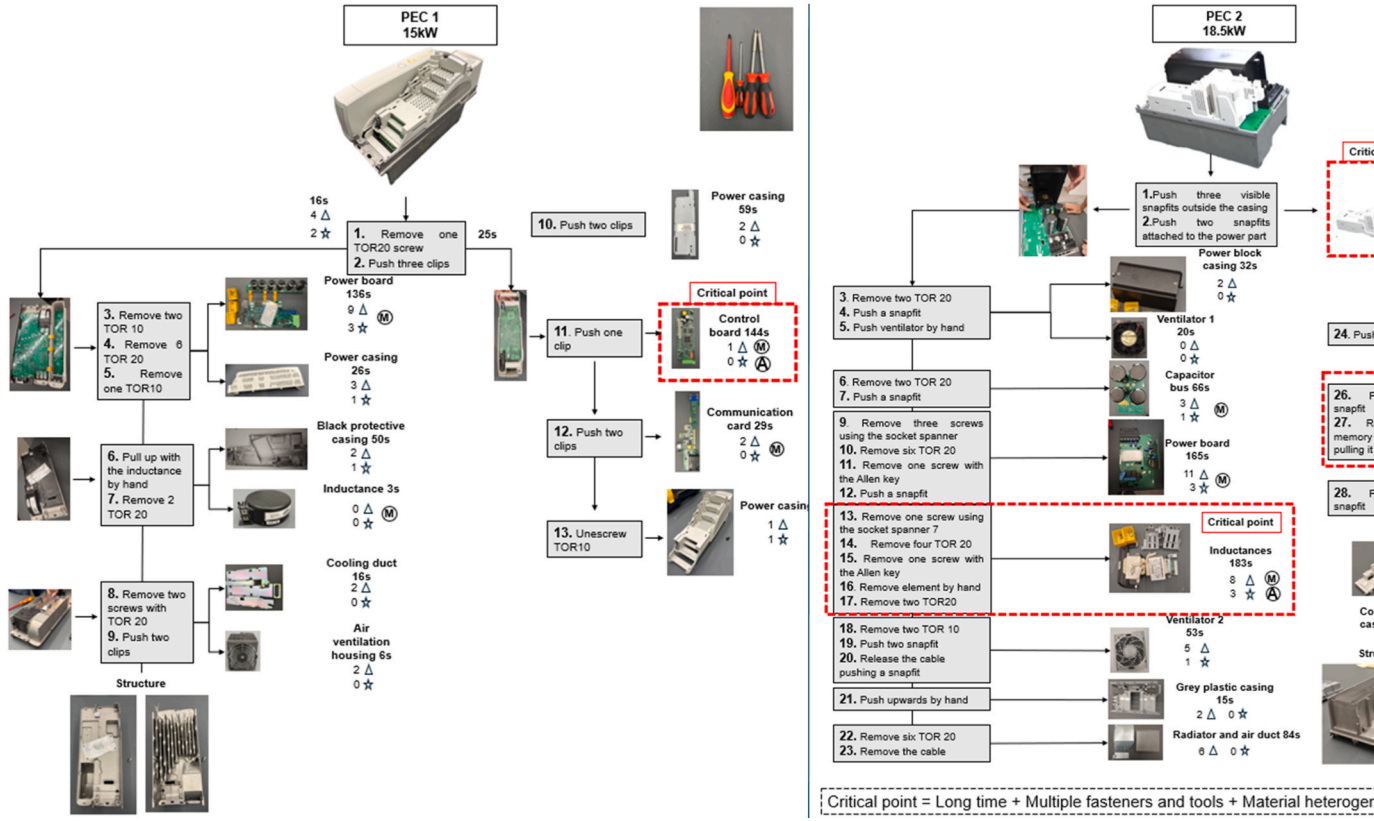

Fig. 2. Step-by-step visual workflow of both PEC disassembly process with critical point highlighted in red dotted squares. (For interpretation of the references to colour in t
Web version of this article.)

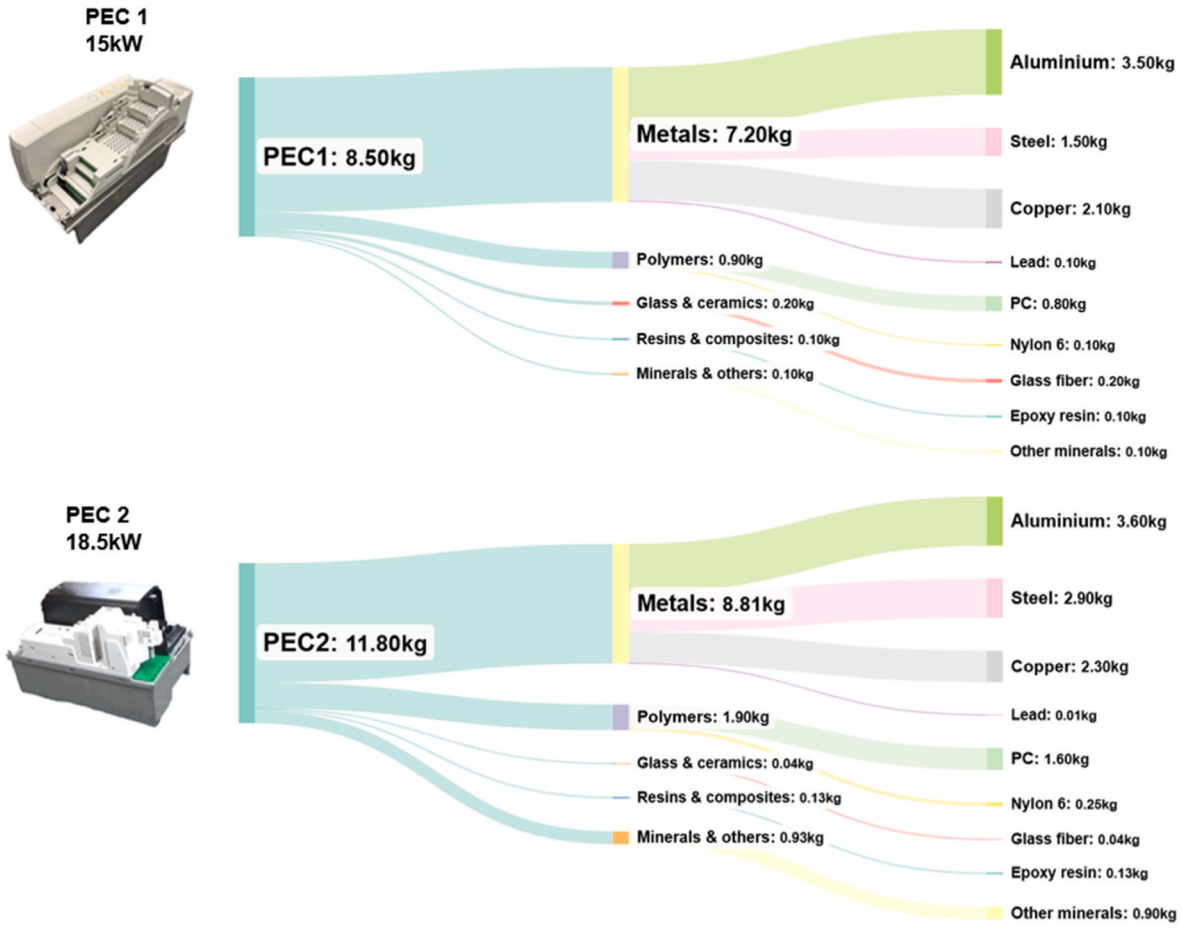

Fig. 3. Bill of Materials for the PECs. Acronyms: PEC (power electronic converter).

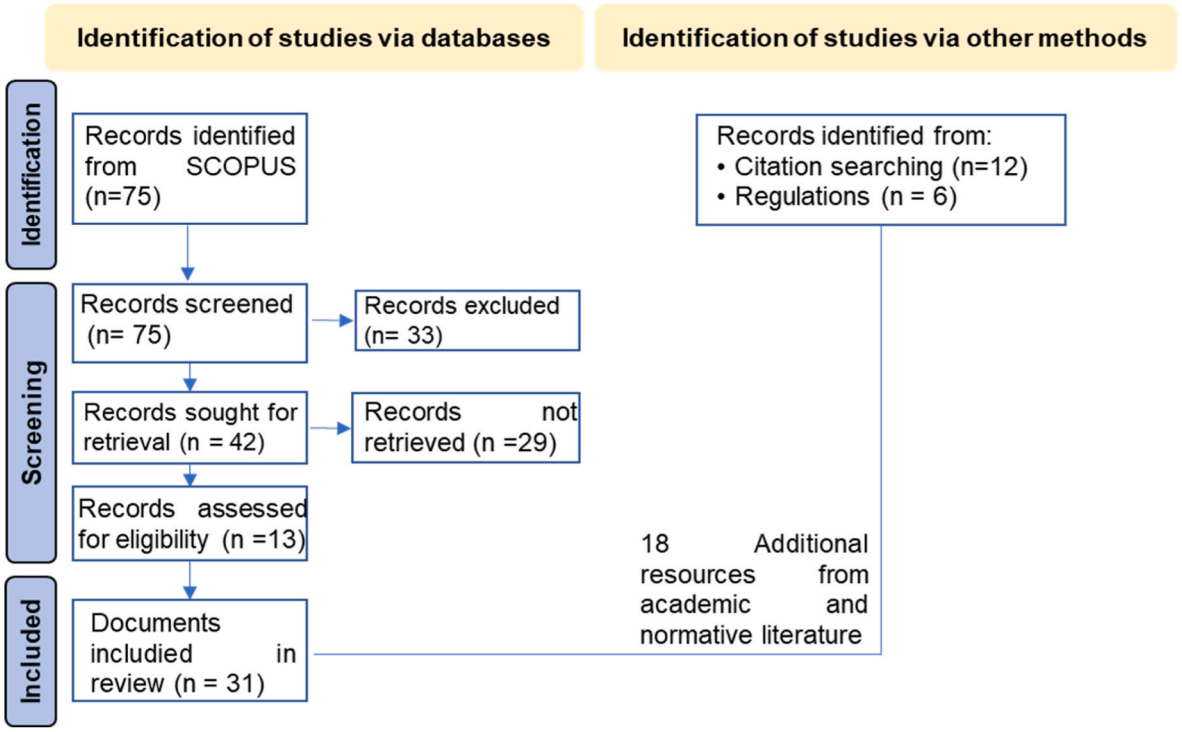

Fig. 4. Systematic literature review, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram (Page et al., 2021).

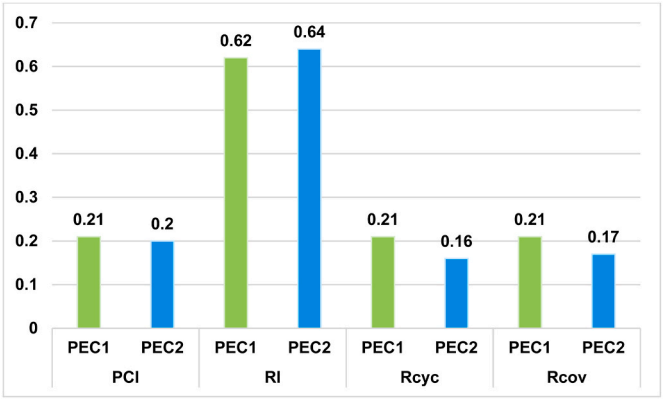

Fig. 5. Circularity performance of PEC1 and PEC2 against four indicators. Acronyms: PEC (Power Electronic Converter), PCI (Product Circularity Index), RI (Reparability Index), Rcyc (Recyclability Index), Rcov (Recoverability Index).

Table 2
Literature searches to identify relevant journal papers. Acronyms: CE – circular economy, EEE – electric and electronic equipment.

Literature searches	Search streams	Keywords	Hits
1	Stream 1	"Power electronic*" OR "Power converter" OR "electronic power switch*" OR Semiconductor*	18
	Stream 2	"Circular economy" OR CE OR circularity OR "circular design" OR eco-design OR ecodesign OR "design for environment" OR "design for sustainability" OR "sustainable design" OR circularity-by-design OR "circularity by design	
	Stream 3	indicator OR index OR metric* OR scor*	
2	Stream 1	"Electrical equipment" OR "Electronic equipment" OR "Electronics product*" OR "Electric appliance*" OR "electrical and electronics industry" OR "electric and electronic equipment" OR "electric and electronic sector" OR EEE OR "Power electronic*" OR "Power converter" OR "electronic power switch*" OR Semiconductor*	75
	Stream 2	Same as above	
	Stream 3	Same as above	

were considered. To this end, the pertinence of the title, keywords, and abstracts of the articles to the research topic was examined. Applying the aforementioned cut-off criteria, the sample of articles for the exhaustive evaluation was reduced to 14 papers in relation to the circularity indicators for EEE. In addition, the search for indicators was supplemented by a further 11 papers identified by snowballing, giving a total of 25 papers.

The academic review was complemented with relevant European regulations, the analysis of which is fundamental for comprehending research in the fast-growing sector of energy-related products, in particular PEs (Fang et al., 2024). Policy sources reviewed included the Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2024), UNE EN 45552 (AENOR, 2021), and UNE EN 45558 (AENOR, 2019). Six references from regulatory and industry literature were reviewed.

In total, 31 documents (25 academic and six normative) formed the basis for identifying the circularity and environmental sustainability indicators considered in this study. The complete list of included works is provided in Table S6 of the Excel SF. From this review, indicators were selected based on three criteria:

i) Proven applicability to EEE products, validated through case studies and prior scientific literature (Saidani et al., 2019);
ii) Methodological robustness and institutional endorsement, particularly by the European Commission and its Joint Research Centre (JRC) (Joint Research Centre, 2025), which guarantees alignment with regulatory frameworks such as the ESPR (European Commission, 2024) and CEAP objectives (European Commission, 2020a);
iii) Coverage of the three core CE strategies: Narrowing (reducing resource use), Slowing (extending product life), and Closing (reincorporating materials into the economic cycle) (Mendoza et al., 2022). By combining resource efficiency, durability, and EoL valorisation perspectives, the selected indicators ensure a holistic assessment of circular performance.

Finally, the following four indicators were considered:

- Product Circularity Indicator (PCI) (Bracquené et al., 2020): Measures the overall circularity of a product by quantifying the share of circular versus virgin material flows throughout its life cycle. It integrates three key variables: (i) the proportion of secondary materials used, (ii) the potential for component reuse, and (iii) the recoverability of materials at EoL. The PCI formulation combines these variables into a single linear flow index (LFI), which is subsequently adjusted by a utility factor that reflects product lifetime relative to sectoral use patterns. This yields a dimensionless value between 0 and 1, where higher scores indicate lower dependence on virgin resources and greater capacity to retain material value throughout the product life cycle. These aspects correspond to the circular economy strategies of narrowing, slowing, and closing loops. The final expression applied in this study is given in Eq. (1).

$$PCI = 1 - \frac{LFI}{X} \tag{1}$$

- Reparability Index (RI): Measures the level of repairability of a product based on the specifications of Wandji et al. (2023) and the recommendations of standard EN 45554 (AENOR, 2020a). It combines qualitative and quantitative criteria, organised into nine analytical blocks: i) disassembly, ii) support, iii) spare parts, iv) working condition, v) product design, vi) product reconditioning, vii) documentation, vii) after-sales strategy, and ix) product identification.

Each block includes specific evaluation parameters, such as fastener type and accessibility, availability of repair guides, or provision of spare parts. The calculation of the final score follows a hierarchical weighted-aggregation structure. First, a partial score S_k is obtained for each category k as the weighted average of its criterion-level scores, as expressed in Eq. (2):

$$S_k = \frac{\sum (S_i \cdot \omega_i)}{\sum \omega_i} \tag{2}$$

where S_i represents the score of criterion i within category k, and ω_i is the weight assigned to that criterion. The overall Reparability Index is then computed as a weighted combination of the category-level scores following Eq. (3):

$$RI = \frac{\sum S_K \, W_K}{\sum W_K} \tag{3}$$

with W_k denoting the weight of each category k. This formulation makes explicit that the RI is a weighted average across all analytical blocks, integrating both the hierarchical structure of the method and the relative importance of its components. The indicator reflects the circular-economy strategy of slowing resource loops, as it supports product

lifetime extension through repair-oriented design.

- Recoverability and Recoverability Rates (Rcyc and Rcov): Measures the proportion (by weight) of a product that can be technically recycled (Rcyc) or valorised (Rcov) through either material recycling or energy recovery, based on established industrial processes. While Rcyc reflects the material fraction compatible with current recycling technologies, Rcov accounts for additional non-recyclable but energetically recoverable fractions, offering a more comprehensive measure of EoL valorisation potential (AENOR, 2020b). Both indicators are calculated by weighting each material stream according to its mass (m_k) and its recyclability or recoverability factor ($Rcyc_k$ or $Rcov_k$), relative to the total product mass (m_{tot}), as shown in Eq. (4) and Eq. (5). These factors represent the proportion of each material that can be recycled or recovered under current industrial treatment conditions. Both indicators are aligned with the closing strategy of the circular economy and are defined under the EN 45555 standard (AENOR, 2020b).

$$Rcyc = \frac{\sum_{k=1}^{n} m_k \cdot Rcyc_k}{m_{tot}} \text{ x } 100 \quad (4)$$

$$Rcov = \frac{\sum_{k=1}^{n} m_k \cdot Rcov_k}{m_{tot}} \text{ x } 100 \quad (5)$$

Together, these indicators provide a multidimensional evaluation of the product circularity performance: PCI offers an integrated perspective, RI focuses on life extension, and Rcyc and Rcov quantify the material recirculation at EoL.

The calculations drew from primary data obtained from the physical disassembly and BOM of each PEC (Section 2.2.1), and secondary data from academic sources. Each indicator was calculated using a custom Excel-based tool developed for this study, which integrates official methodologies and formulas. The tool, input data, and calculation sheets are available in S3 of the SF.

Table 3
Summary of disassembly and component-related parameters for PEC1 and PEC2. Acronyms: PEC (Power Electronic Converter), PCB (printed circuit board).

Parameter	PEC1 (15 kW)	PEC2 (18.5 kW)
Disassembly process		
Disassembly time	10min 36s	22min 35s
N° disassembly steps	37	78
N° fasteners	19 screw and 10 clips	47 screw and 17 clips
N° of different fastener types	3 (TOR (10,20), clips)	4 (TOR (10,20), Allen, clips)
N° tools	4	5
N° distinct elements (modules)	13	15
N° distinct components	29	67
N° PCB	4	5
Desoldering process		
Desoldering time	71min	88min
N° different electronic component	17	17
N° electrolytic capacitors	19	14
N° capacitors	221	490
N° resistors	335	926
N° transistors	127	91
N° diodes	50	51
N° inductors	6	12
N° sensors	2	3
N° relays	4	4
N° varistors	6	1
N° integrated circuit	77	190
N° connectors	14	16
N° power modules	1	1

3. Results and discussion

3.1. PECs structural configuration and disassembly process

Key quantitative metrics collected during the manual disassembly and desoldering of both PECs are presented in Table 3. The values include total operation times, number and types of fasteners, tools employed, components extracted, and electronic components identified. Full procedural details are provided in S2 of the SF.

Disassembly performance varied significantly between the devices. The modular architecture and intuitive layout of PEC1 allowed disassembly in 10 min and 37 steps, involving 29 fasteners and 4 tools. Snap fits dominated, with minimal tool variation and straightforward access to key components. In contrast, PEC2 required 78 steps, 22 min, 64 fasteners, and 5 separate tools, reflecting a denser internal configuration and greater mechanical complexity.

The disassembly sequence in Fig. 2 (Section 2.1) reveals that PEC1 followed a relatively linear and intuitive dismantling sequence, with minimal obstruction between modules. In contrast, there were several critical points in PEC2 (highlighted in red), where component extraction was delayed by dense architecture and complex fastening strategies. For instance, the control block required over 220 s (s) and five snapfit interactions; the inductance block involved socket, Torx, and Allen tools across a multi-step sequence totalling more than 180 s; and the communication board zone included tightly packed, interconnected PCBs with hidden snapfits that required two operators for safe removal. These factors (time, fasteners, tool diversity, material composition, and accessibility) emerged as the principal dimensions conditioning dismantlability, providing concrete guidelines for improving circular design.

These structural differences were also reflected in desoldering times: 71 min for PEC1 versus 88 min for PEC2. PEC2 contained more identified components (67 vs. 29), more distinct modules (15 vs. 13), and higher electronic density. This was evident in the desoldering metrics: PEC2 included 490 capacitors, 926 resistors, and 190 integrated circuits, nearly triple the number in PEC1, all of which increase processing time and hinder manual recovery. Although both PECs featured high-value elements such as inductors and power modules, their accessibility and separability differed considerably. The higher density of components, use of double-sided PCBs, and presence of high thermal mass areas made PEC2 more demanding to process. These barriers hinder not only recycling operations but also repair and upgrade interventions during the use phase, limiting circular strategies.

In addition, material heterogeneity, particularly in PEC2, further limited circular potential. Multi-material joints, such as encapsulated inductors or resin-sealed power modules, extended processing time and complicated EoL separation. These design choices compromise recyclability and hinder interventions for repair or reuse during the use phase.

These disassembly patterns are consistent with findings reported in recent literature. Vanegas et al. (2018) show that disassembly time in electronic products is often dominated by tasks such as identification, positioning and tool changes—rather than by the detachment itself—particularly when accessibility is limited or fasteners are heterogeneous. This behaviour mirrors the critical points observed in PEC2, where hidden snap-fits, obstructed access and multiple tool changes substantially extended operation times. Similar constraints are reported by Romano et al., 2024, who demonstrate that power electronic systems combine dense PCB integration, encapsulated components and diverse fastening strategies that hinder both disassembly and desoldering operations. Finally, Fang et al. (2023) highlight that design decisions in PECs are frequently driven by functional compactness rather than circularity, which results in architectures that challenge EoL interventions.

Moreover, the critical disassembly bottlenecks identified in this analysis have direct economic implications that help explain current

end-of-life treatment practices for PECs. In most industrial recycling schemes, complex and highly integrated electronic products are not manually dismantled, but instead processed through shredding-based routes, as manual disassembly is generally constrained by high labour costs and limited economic viability (Choux et al., 2024). This is particularly the case for power electronic equipment, where resin encapsulation, dense component integration and irreversible joining techniques substantially increase disassembly effort while reducing the recoverable value of individual components.

As a result, prevailing recycling practices prioritise bulk material recovery over component-level reuse, often leading to losses in material quality and functional value (Goyal and Gupta, 2024). In this context, the disassembly times and bottlenecks identified in this study should be interpreted not only as technical indicators of dismantlability, but also as proxies for the economic barriers that currently limit the implementation of higher-value circular strategies for PECs.

3.2. PECs circularity performance

Fig. 4 summarises the circularity results, enabling a comparative interpretation of the PECs in terms of material circularity, reparability, and recovery potential (Section 2.2.2). Results are presented normalized on a scale from 0 to 1. Full disaggregated results for each indicator are provided in S3 of the SF.

3.2.1. Product circularity index

Both PECs reported similarly low PCI values: 0.21 (PEC1) and 0.2 (PEC2). This indicates that less than a quarter of the material value is retained throughout the product lifecycle. These values are far from the ideal performance (PCI = 1). As a recirculation-related indicator, they fall significantly below the minimum material recovery (55%) and overall recovery (75%) rates required by the WEEE Directive (European Commission, 2012) for small electronic equipment, specifically for those classified as equipment for the generation of electric currents. This clearly reflects the low circularity of the products.

In both cases, the proportion of materials flowing circularly in the product system is limited, resulting in high dependence on virgin resources and restricted EoL material recovery capability. The root causes of this limited circularity can be better understood by analysing the three key variables that define the PCI, as described in Section 2.2.2.

The first PCI variable concerns the use of secondary materials. Both devices incorporate recycled materials, such as aluminium and copper, used in structural components like chassis, heatsinks, and inductors. However, the proportion of recycled content is moderate (32% in PEC1, 40% in PEC2), and their integration limits recovery. For example, the copper in inductors is coated, encapsulated, and bonded to the core, while aluminium heatsinks are mechanically integrated with other parts. Without design strategies for recovery, these recycled materials contribute little to the PCI.

The second variable, component reuse, scored near zero for both devices. Although passive components could theoretically be reused, the lack of modularity, standard connectors, and accessible interfaces prevents their extraction without damage. This effectively eliminates reuse opportunities, significantly penalising the PCI score.

The third variable, material recoverability at EoL, is also severely restricted by the design. Valuable materials like copper can only be accessed through destructive processes such as cutting or shredding, which are inefficient and unfeasible at scale. This limitation mirrors broader issues in e-waste management, where high theoretical recyclability is rarely realised under real operating and industrial recovery conditions (European Commission, 2012).

Hence, the low PCI values reflect a significant dependence on virgin materials and architectures that hinder circularity. These findings reinforce the need for ecodesign strategies that prioritise both the use of quality secondary materials and their incorporation into easily disassembled and recoverable configurations. These PCI results are consistent with previous studies on product-level circularity. Bracquené et al. (2020) emphasise that the PCI is particularly sensitive to component reuse and to the ability of a product system to return high-quality materials to the supply chain, two conditions that rarely hold in complex electronic equipment. Their analysis shows that even when recycled metals are present, their contribution to circularity remains limited if recovery requires destructive processes or if materials are embedded in multi-material assemblies. This was precisely the case for inductors and aluminium heatsinks in the PECs analysed in the present paper. Furthermore, the restricted recoverability observed here mirrors the broader gap between theoretical recyclability and real material recovery documented for WEEE systems, where only a fraction of valuable metals is actually recovered due to material losses during separation and recycling inefficiencies (European Commission, 2012). These findings confirm that low PCI values in PECs arise from both limited secondary material content and design configurations that hinder reuse and prevent effective end-of-life valorisation.

Furthermore, these results show that the low PCI values are mainly driven by limitations in upstream material sourcing and reuse potential, rather than by improvements in end-of-life recycling efficiencies. A scenario-based sensitivity analysis (SA) confirmed this trend: increasing the recycled content of the main structural metals raised the PCI to 0.61 and 0.55, while improving the potential for component reuse led to a PCI of 0.43 and 0.40. In contrast, enhancing the end-of-life recycling efficiency produced only a marginal increase (PCI = 0.25 and 0.23). These findings reinforce the importance of prioritising design strategies that facilitate material reuse and integration of high-quality secondary materials as the most effective levers for improving product circularity. Table 4 summarises the PCI sensitivity results; detailed scenario calculations are available in S3 of the SF.

3.2.2. Reparability Index

The results show a score of 0.62 for PEC1 and 0.64 for PEC2, both falling within the “good” repairability range [0.61–0.8], as defined by the AGEC (Ministry of Ecological Transition, 2022). These scores reflect the capacity of the two PECs to be repaired at the assembly level, replacing entire PCBs, rather than at the level of individual PCB components.

In PEC1, the components with the longest disassembly times, the power board and the horizontal control PCB, also exhibited the lowest repairability scores (5.95 and 6.07). This stems from poor performance in the “disassembly & reassembly”, “spare parts” and “product reconditioning” criteria. Together, these components account for nearly half of the total disassembly time, mainly because of obstructive fasteners, limited accessibility, and component fragility. This correlation between disassembly complexity and repair challenges supports the RI score obtained for PEC1.

In contrast, PEC2 presented a more nuanced situation. As shown in Fig. 3, the control block (228s), communication board 2 (197s), and inductances (183s) required the most time to disassemble. However, these were not the main contributors to the RI score. Instead, the capacitor bus (5.96) and the electronic power board (6.07) were the most penalising components. Their mechanical and functional interdependence means that one must be disassembled to repair or replace the other, preventing selective interventions and increasing the likelihood of unnecessary part replacements.

These results indicate that the RI captures several product-level

Table 4
Scenario-based sensitivity analysis of the PCI for PEC1 and PEC2.

PCI Scenario	PEC 1	PEC 2
Baseline	0.21	0.20
SA1: Higher recycled content in structural metals	0.61	0.55
SA2: Higher reuse fraction of key components	0.43	0.40
SA3: Improved recycling efficiency at EoL	0.25	0.23

criteria beyond disassembly alone. In both PECs, several categories scored in the moderate-to-low range, highlighting systemic areas for improvement. Notably, the "product reconditioning" category scored the lowest in both cases (0.4), indicating limited potential to reuse or improve internal components. Similarly, the "product design" and "after-sales strategy" categories revealed design flaws such as the use of non-standard fasteners, lack of repair documentation, or limited availability of spare parts. These limitations were more pronounced in PEC1, contributing to its lower overall score.

These RI outcomes are in agreement with broader repairability patterns described in recent research. Current studies emphasise that repair potential in electronic equipment is primarily limited by architectural complexity, internal interdependencies and insufficient diagnostic or repair information, rather than by isolated component features (Ruiz-Pastor and Mesa, 2023; Romano et al., 2023; Formentini et al., 2025). This aligns with the multi-criteria perspective adopted in emerging EU frameworks such as the ESPR (European Commission, 2024) and the recent JRC proposal (Spiliotopoulos and Beltran, 2025), which highlight that repairability depends on how product architecture enables (or restricts) selective interventions throughout the lifecycle. Both PECs achieved "good" repairability scores, yet they still exhibit several structural barriers. This illustrates a wider trend identified in the literature: products can be repairable in principle at the subsystem level but remain constrained by design choices that limit modular upgrades, component-level access and the availability of technical support.

3.2.3. Recycling and recoverability index

The results obtained reveal modest differences in the EoL circularity potential between the two PECs. The PEC1 achieved 0.21 in both indicators, while PEC2 scored lower: 0.16 and 0.17, respectively.

These results show limited potential to close the material cycle in both products, although PEC1 performs comparatively better. This gap stems partly from the differences observed during disassembly. PEC1 presents a simpler, more accessible architecture, with modular connections and a higher proportion of easily separable metals. These features allowed a higher fraction of its total mass to be recovered through conventional recycling or energy recovery routes.

In contrast, PEC2 prioritises compactness of design, incorporating for example double-sided printed circuit boards, which complicates the separation of components and materials and increases the complexity of material streams. As a result, both the effective input of recycled materials and the possibility of recovering their EoL value are reduced.

Ultimately, these findings show that maximising recoverable circular value requires not only technically recyclable materials but also product architecture that allows access, separation, and sorting without loss of quality or functionality. Hence, the complementarity between robust initial design and effective EoL measures is key to improving levels of real circularity (Romano et al., 2023).

These low Rcyc values and only moderate Rcov levels reflect recent evidence on the technical recyclability of EEE. Hämmer and Wambach (2024) show that, at each treatment stage, products with high electronic density and complex architectures tend to generate substantial "lost" fractions, even when they contain high-value materials such as copper or aluminium. This occurs because separation without degradation or dispersion is often impossible. Similarly, Charles et al. (2020) demonstrate that, although many electronic components contain valuable metals such as gold, their real recovery potential is limited. Existing industrial infrastructure can efficiently recover only a small share of these materials, while the remainder is either permanently dissipated in pyrometallurgical processes or diluted into heterogeneous low-value fractions. This evidence aligns closely with the behaviour observed in both converters, where dense PCBs, encapsulated inductors and multi-material joints restrict both recyclability (Rcyc) and the potential to retain value at end-of-life (Rcov), despite the presence of recoverable metals.

3.3. Integrated analysis and circular design guidelines for PECs

Neither PEC1 nor PEC2 was conceived with circularity as a design priority. The marginal differences between their circularity indicators suggest no substantial evolution in design strategy between generations. This continuity reflects a design logic driven by functionality and performance, with little consideration of resource efficiency or EoL strategies (Fang et al., 2023).

This misalignment exemplifies a broader disconnection between product functionality and resource recovery potential, a recurring issue in PEs (Ruiz de Azua Lahidalga et al., 2025). This gap contributes to the environmental impacts of EEE, notably through the irreversible loss of critical materials (Köpman and Majava, 2024)

The disassembly and desoldering processes confirmed that current design practices, such as resin encapsulation, permanent bonding, and complex material assemblies, limit component reuse and material recovery, while also compromising the quality of secondary raw materials.

Furthermore, the applied circularity indicators capture only partial dimensions: PCI quantifies material circular flows, Rcyc and Rcov address EoL recovery potential, and RI reflects reparability. Yet none offers a systemic view of circularity (Picatoste et al., 2024). This highlights the need for integrated assessment frameworks that connect life cycle stages with value retention, a gap particularly evident in PE.

Advancing the circularity of PECs therefore requires a systemic rethinking of design logic, embedding circular principles from product architecture and material selection through to EoL strategies. When the design limitations identified at product level are extrapolated to the scale of the European PEC market, the urgency of this shift becomes evident. This is especially urgent considering the European PEC market reached 17.535 billion dollar in 2024 (over 30% of global revenues) and is projected to grow at 7.3% annually until 2031 (Kalyani Raje, 2025). Without a shift towards circular design approaches, the environmental footprint of this sector will continue to escalate.

Although the limited number of case studies represents a constraint in terms of statistical generalisation, the challenges identified in the analysed power electronic converters extend beyond these specific products and reflect broader limitations affecting complex EEE. In particular, the high material density and architecture observed in the analysed PECs highlight the systemic relevance of certain critical materials. PECs and other complex EEE rely on material-intensive designs that combine power semiconductors, printed circuit boards, passive components, and metallic structural elements, resulting in high material density and complex assembly configurations. Among these materials, copper plays a fundamental role in power tracks and planes, windings, transformers, and busbars, making it one of the main contributors to both the material footprint and the end-of-life value of such equipment. Current projections indicate that final copper demand could increase by a factor of 2.5 between 2015 and 2050, reaching approximately 62 million tonnes, while life-cycle-related copper emissions could rise from 0.3% to 2.7% of the global carbon budget by 2050 (Watari et al., 2022). These trends highlight that improving material efficiency, recoverability, and circularity in electrical and electronic equipment (including PECs) is not a marginal design optimisation, but a systemic requirement. Consequently, the circularity-related design challenges identified in this study are not only relevant for the PECs, but are also significant for other categories of high-power and material-intensive EEE, reinforcing the relevance and transferability of the results beyond the specific case studies considered.

The qualitative analysis conducted with experts is directly corroborated by the results of the quantitative indicators. During the disassembly and desoldering processes, experts identified structural barriers that hinder circularity, such as the absence of secondary materials, high material heterogeneity, irreversible joining techniques, extreme design compactness, and limited accessibility to critical components. These issues were consistently reflected in the PCI, RI, Rcyc and Rcov values. As explained by the experts, the wide variety of materials and the use of

double-sided PCBs complicate separation and sorting operations, which aligns with the low recyclability and recoverability scores. Likewise, the lack of modularity, the high component density, and the presence of hidden fasteners penalise practical repairability, as also captured in the RI results. The PCI further confirms the near-absence of component reuse and the minimal incorporation of secondary materials. This was consistent with the expert assessments, indicating that in semiconductors, magnetics and capacitors, current design practices do not allow meaningful recovery or reuse. Hence, the alignment between qualitative observations and quantitative results both validates the diagnostic and clearly indicates which design dimensions must be transformed to achieve higher levels of circularity.

Building on this convergence, the study proposes a set of eight circular design guidelines specifically tailored to PECs. These guidelines directly address the design limitations identified through our integrated analysis and are grounded in expert knowledge gathered during the disassembly and desoldering processes, following the criteria established by Ruiz de Azua Lahidalga et al. (2025). They offer operational, evidence-based recommendations aimed at embedding circularity principles from the earliest stages of product development.

To operationalise these guidelines, it is essential first to define the circular strategies to be prioritised, such as extending product lifespan, enhancing reparability, or improving material recovery. Clear specifications must then be established to translate these strategies into concrete design requirements, ensuring that circularity is integrated holistically throughout the product life cycle.

1. Facilitate selective and non-destructive disassembly:
   a. Avoid irreversible joining techniques such as potting with silicone or adhesives.
   b. Ensure that fixing points are clearly visible and marked on the internal structure.
   c. Relocate failure-prone components, such as capacitors and power modules, to peripheral areas or easily removable subassemblies to facilitate access and replacement
2. Enhance modularity and standardisation to enhance repairability
   a. Separate control and power boards with detachable, testable interfaces.
   b. Design control units with standard protocols and voltages for reuse across PEC power classes.
3. Enable reuse and refurbishment of durable components
   a. Design inductors and heatsinks with mounting systems for safe extraction and reconditioning.
   b. Avoid tight integration of components (e.g. fused SMDs on both PCB sides) that hinders testing and reuse.
4. Prioritise thermomechanical compatibility in material selection
   a. Use materials with similar coefficients of thermal expansion in multilayer assemblies.
   b. Apply sintering and advanced interconnections to reduce failures and enhance durability.
5. Improve component traceability and monitoring
   a. Embed identification codes or digital twins on priority components for lifecycle monitoring.
   b. Use sensorised fuses, solid-state relays, or thermal monitors to support preventive maintenance.
6. Reduce functional over-integration to enable recovery
   a. Minimise double-sided PCBs or isolate recoverable materials in accessible zones.
   b. Avoid full-function integration (e.g., AC/DC + DC/AC stages in a single silicon module).
7. Reduce material heterogeneity and enhance recoverability
   a. Use metals with higher proportion of recycled content in structural parts; avoid mixed-material.
   b. Replace low-value resins or plastics with recyclable polymers.
8. Integrate circularity indicators and expert feedback into design
   a. Apply tools such as PCI, RI, Rcyc, Rcov, at the design stage to guide improvements.
   b. Validate circularity design via disassembly trials and expert reviews, incorporating feedback loops.

The analysis confirms that the limited circularity of PECs stems from a functionality-driven design approach that overlooks resource efficiency and EoL strategies. Addressing this challenge requires a systemic approach encompassing the full product lifecycle, from material sourcing and architectural design to reparability, recyclability, recoverability, and reintegration. The guidelines proposed in this study target these gaps by enhancing modularity, disassemblability, traceability, and material recoverability. Implementing such strategies will be key to aligning PEC development with CE principles, especially in a market poised for rapid growth.

4. Limitations and future lines

Five major limitations were identified: first, the disassembly and desoldering times may be overestimated, since the operators were not previously familiar with the optimal sequence for intervening in each converter. Therefore, these values should not be interpreted as standardised operational times but rather as empirical references useful for identifying bottlenecks and design-related barriers. Second, both the measured times and weights exhibit the variability inherent to experimental processes based on manual operations and the handling of complex subassemblies. Third, although the BOM was based on primary data extracted directly from the units, some assumptions were needed to calculate the circularity indicators, as no manufacturer-specific information or consolidated sectoral data were available. The fourth limitation concerns the indicators themselves: the circularity metrics applied in this study were not conceived specifically for power electronic converters, which could lead to a lack of completeness in the analysis. However, this limitation was partially overcome with the use of 4 different circularity indicators in the analysis. Finally, the indicators applied capture relevant dimensions of circularity but do not constitute a comprehensive environmental assessment of the converters, as trade-offs involving energy efficiency, manufacturing impacts, or use-phase emissions are not addressed.

These limitations highlight four complementary research directions that should guide future work. First, the development of a sector-specific circularity indicator for the PE industry, capable of addressing the unique design and end-of-life challenges associated with this type of product.

Second, advancing the integration of circularity indicators with LCA is essential to capture the environmental trade-offs associated with design changes, material flows and energy efficiency. While CE–LCA integration has been explored in other sectors (Khadim et al., 2025), no equivalent methodological development exists for PECs. Establishing such a framework would establish a more holistic evaluation of circular design interventions.

Third, developing decision-support tools tailored to the PEC sector that integrate design-for-circularity principles, circularity metrics, and LCA outcomes. These tools will be essential to guide sustainable innovation, helping PECs align with EU sustainability objectives and reach the circularity maturity already seen in sectors like rail and wind power. Without this progress, the PEC market risks regulatory penalties and resource inefficiencies that threaten the industrial resilience of Europe.

Finally, future research should extend this empirical approach to new generations of PECs, including converters explicitly developed with circularity principles or more recent architectures. Applying the same disassembly-based analytical framework to these products will be crucial to assess whether emerging circular design practices effectively overcome the structural barriers identified in current mainstream PECs.

5. Conclusions

This study addressed a critical gap in circularity assessment approaches applied to PECs, namely the lack of integrated, multidimensional evaluations based on real products. Through the complete disassembly and desoldering of two PECs, a detailed BOM was developed, enabling precise material characterisation and the calculation of four quantitative indicators (PCI, RI, Rcyc, Rcov). Combined with a qualitative, expert-informed analysis, this approach identified design practices that hinder circularity in PECs and proposed specific design and LCM strategies for improvement.

Disassembly revealed critical barriers, including irreversible joints, tight component interdependencies, and compact layouts. These aspects contradict key CE principles, such as design for disassembly and material separability, and limit environmental sustainability goals like reducing hazardous material dispersion or enabling component reuse. The circularity assessment confirmed these limitations: both PECs scored low in PCI (<0.21), recyclability and recoverability rates (<0.21), and moderate reparability (~0.63). These findings align with broader challenges in the EEE sector, where circularity assessments are often limited to theoretical approaches, with fewer studies validating these insights through comprehensive physical product analysis. While sectors like consumer electronics have made progress, empirical studies on complex products such as PECs remain notably scarce.

However, these constraints are not intrinsic to PE but stem from historical design choices. Our results highlight pathways to reconcile functional performance with circularity: enhanced modularity and material standardisation. Such strategies align with ongoing European efforts to standardise reparability and circularity metrics under the ESPR framework.

CRediT authorship contribution statement

Irati Ruiz de Azua Lahidalga: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Christian Wandji:** Writing – original draft, Investigation, Formal analysis. **Aitor Picatoste:** Supervision, Formal analysis, Conceptualization. **Daniel Justel:** Validation, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Iosu Aizpuru:** Validation, Formal analysis. **Andreas Riel:** Writing – review & editing, Validation, Supervision. **Helmi Ben Rejeb:** Writing – review & editing, Validation, Supervision. **Joan Manuel F. Mendoza:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition, Conceptualization.

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

During the preparation of this work the author(s) used ChatGPT (OpenAI) in order to improve language and readability. After using this tool, the author(s) reviewed and edited the content as needed and take (s) full responsibility for the content of the publication.

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.jclepro.2026.147774.

Data availability

Data will be made available on request.

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7.4. Article 4: Design methodology for analysing the feasibility of Product-Service Systems models: The case of the pay-per-unit model

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Design methodology for analysing the feasibility of Product-Service Systems models: The case of the pay-per-unit model

Andreas Riel[a] (2), Christian Wandji[a], Helmi Ben Rejeb[a]

[a] *Univ. Grenoble Alpes, CNRS, Grenoble INP, G-SCOP, 46 Avenue Félix Viallet, 38000 Grenoble, France*

The design and implementation of Product-Service Systems (PSS) is challenging due to the shift from product-centric to service-oriented business models. This paper presents a methodology for analysing the feasibility of the value-delivery-oriented Pay-Per-Unit (PPU) model and deriving design requirements using integrated design concepts and morphological analysis. It has been validated with a company considering the introduction of a PPU model for water pumps. Results demonstrate that feasibility analyses in early concept design identify specific challenges, guiding decision-making and systemic requirements specification. While supporting design teams and decision makers, the methodology's reliance on expert consensus is a limitation.

design method; decision making; product-service systems

1. Introduction

The Pay-Per-Unit (PPU) model is a result-oriented archetype of the Product-Service-System (PSS) proposed by Tukker [1]. This model implies selling a service based on the function of a product rather than selling the product itself. Its design and implementation leverage the transition of companies' activities toward the Circular Economy (CE) according to Brissaud et al. [2]. Yet, transitioning towards this model poses numerous challenges, of which the lack of internal competencies and knowledge, company organization and culture, customer habits, and financial constraints are the most frequent reasons for failing this transition [3], in particular in small and medium-sized companies [4]. Hence, to assess risk and derive requirements, organisations need a method to analyse the technical and economic feasibility of transitioning to a PPU model in early concept design phases.

Several tools have been proposed to guide strategy design for this transition. Bocken et al. reviewed different frameworks, such as the Value Hill and the Circular Business Model (CBM) Canvas, which guide practitioners through strategies like product-life extension, platform sharing and service-oriented offerings [5]. Building on this work, Rexfelt et al. listed 65 circular design tools, grouping them into the five families: activators, enrichers, prompters, analysts/advisors, and flow visualizers [6]. Similarly, Guzzo et al. operationalized circular Product-Service Systems (PSS), including PPU, through a Circular Innovation Framework comprising 21 strategies and 77 practices [7]. Its application was later demonstrated by Pollard et al. in the electrical and electronic sector, confirming the tools' practical value [8]. More generally, transitioning from ideation to implementation necessitates clear strategies for transition and organizational alignment. Geissdoerfer et al. emphasized that circular business model innovation demands a fundamental rethinking of value creation and delivery, potentially reshaping customer relationships and production processes [9]. Building on this, Bocken proposed a design innovation tool consisting of four key transition strategies: slowing, closing, narrowing, and regenerating loops [10].

While these contributions proposed interesting support for innovation and design of PSS, fewer studies addressed the challenge of analysing the feasibility of PSS models in the early design phases. Ludeke-Freund et al. presented a typology of 18 CBM patterns, including PPU, that can serve as generic strategies adaptable by different organizations [11]. Han et al. analysed eight multinational firms deploying Circular Service Business Models in diverse regulatory and cultural environments [12]. Yet, these studies remain largely descriptive and do not provide methods and operational tools for evaluating PSS model feasibility in early concept design phases. A specific analysis method for PPU for machine components has been published by Alaluss et al. [13].

This paper proposes a methodology for analysing the technical and economic feasibility of transitioning to a PPU model based on integrated design principles as of Tichkiewitch et al. [14]. Its key originality lies, first, in its capability to leverage the systemic feasibility analysis of transforming a product-ownership oriented value system to a value-in-use-oriented one. Second, it facilitates the integration of stakeholders with diverse domain expertise and points of view on the product in this analysis. The need for such a method and tool has been clearly highlighted in Brissaud et al. [2]. To achieve this, the methodology relies on a morphological analysis carried out by a design team of stakeholders with diverse expertise and roles within an organisation [15]. It links a company's value features (*value proposition, value capture, value delivery, and value creation*) with the features characteristic of a PPU as a CBM model. It has been validated in a medium-sized company operating in the water and air equipment sector, which traditionally sells pumping systems, and aims to transition toward service-based, PPU offerings.

The remainder of the paper is structured as follows: Section 2 presents the methodology. Section 3 presents the application of the proposed methodology in the said company. Section 4 presents and explains the results of the feasibility analysis. Section 5 critically discusses the insights gained from the method application in terms of originality, added value, and limitations. Finally, Section 6 concludes and provides perspectives.

2. Methodology for PPU model transition feasibility analysis

The feasibility analysis of a PPU model requires the systematic association of the characterisation of a company's current product offer with the characterisation of a specific target PPU model design. The resulting relationships shall provide a structured basis for a design team to systematically evaluate the relevance and feasibility of PPU model design options, much like a morphological analysis in creative problem-solving [15].

2.1. Design method for the feasibility analysis matrix

The proposed method assumes that the CBM design provides an adequate basis for the characterization of the current company state and product offer. As illustrated by the nine blocks of the Business Model Canvas (BMC) [16], business model design captures all aspects that are required to make a value proposition successful in the market. These building blocks can be grouped into four value operations: value proposition, value delivery, value capture, and value creation [11]. Based on a review of the literature, a non-exhaustive list of 23 characteristic features of CBM was identified and related to the BMC's value operations (Table 1, column *BMC Features*). This list is an adaptation and extension of the list provided by Valderrama et al in the context of CBM [17]. Features related to the *Circular product and component, Services, Customer type*, and *Costs* (Table 1, column Characteristic features CBM, top to bottom), were derived from Ludeke-Freund et al. [11]. Additionally, the feature *Resources types* was extracted from the article by Guzzo et al. [7]. The features *Mode of use by the customer* and *Target* were defined based on Tukker's classification of Product-Service Systems [18]. Finally, the features *Customer*

Interaction and *Dynamic Capabilities* were defined based on Pieroni et al. [19].

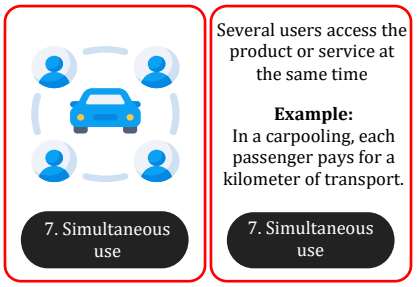
Subsequently, the CBM characteristic features were associated with PPU model design options based on a literature review and analysis of existing PPU models across industrial sectors (*Table 1*, columns *PPU model design options*). For example, the options for the feature *Relationship type* were identified to be either direct or indirect: direct in the case the company directly deals with the end-user of their product or service without any third party, indirect in the opposite situation.

The resulting matrix was reviewed for relevance by four CBM and PSS design experts from academia in a cooperative, participative workshop that fostered in-depth discussion. This led to a refinement of the matrix in terms of the majority of PPU options validated by consensus (*white cells* in Table 1), and some considered to be irrelevant (*grey cells* in Table 1).

Each of the design options is clearly explained and illustrated by a corresponding memo-card showing a pictogram on the front side, and a concise explanation with a practical example on the back side. This format is illustrated in Table 1 using the *Simultaneous Use* card. The complete deck of cards is available in the supplementary material.

Table 1
PPU model feasibility analysis matrix (morphological box)

BMC Features		N°	Characteristic features CBM	PPU model design options						
Value proposition	**Strategy**	**1**	**Circular product and component**	Remanufactured product/ component.	Recycled product/ component	Energy Valorisation	Long Lasting Products (Refuse/ Rethink / Reduce)	Product and Part Reused	Repaired product/ component	Repurposed product/ component
		2	**Services**	Upgrading	Recovering	Auxiliary Services	Take-back Management	Product-Service Based results and Functions	Maintenance, Repair, Control	Waste Handling and Processing
Value delivery	**Customer relationship**	**3**	**Relationship type**	Direct	Indirect					
		4	**Customer interaction**	Short Term	Medium Term	Long Term				
		5	**Customer type**	Quality-conscious Customers	Cost-conscious Customers	Green Customers				
		6	**Property Rights**	Customer	Company					
	Customer segment	**7**	**Customization**	Low / Standard	Moderate	High Flexibility				
		8	**Type of market**	B2B	B2C	B2G				
		9	**Mode of use by the customer**	Individual Use	Sequential Use	Simultaneous Use				
		10	**Customer contracts**	None	Short Term	Medium Term	Long Term			
	Channels	**11**	**Sales channel**	Voice To Voice	Partner Networks	Physical Storefront	Online Platforms	Events And Trade Shows	Referral Programs	
Value capture	**Revenue streams**	**12**	**Revenue model**	Service Fees	Subscription	Pay-Per-Use	Product Sales	Pay-Per-Performance		
		13	**Target**	Availability	Outcome	Product	Agreement / Maintainability			
	Cost Structure	**14**	**Costs**	Supply Risks	Penalties for failure	Labour	Installation, Repair, Maintenance, Control	Waste Handling	Design and Manufacturing	Transportation and Logistics
Value creation	**Key partners**	**15**	**Service delivery**	Company	Outsourcing	Partnership				
		16	**Risk & uncertainties management**	Customer and Company	Company and Third Parties	Customer	Company	Third Parties		
	Key resources	**17**	**Resources types**	Energy	Human	Natural	Technical			
		18	**Dynamic capabilities**	Seizing Capabilities	Reconfiguring Capabilities	Sensing Capabilities				
		19	**Digitalization**	Basic	IT-Based Services	Digital Servitization				
		20	**Risk & uncertainties management**	None	Monitoring Mechanism	Sharing Mechanism	Trust Mechanism			
	Key activities	**21**	**Intangible resources**	None	Cloud Computing	Internet of Things	Big Data and Analytics	Artificial Intelligence	Digital Twin	Information systems
		22	**Tangible resources**	Workshop	Storage Warehouse	Testing Machine	Recycling of Products, Components, Materials	Distribution Centre		
		23	**Data collection**	None	Historical Data	Real-Time Data	Historical And Real-Time Data			



2.2. Application method of the feasibility analysis matrix

The method shall be applied during a workshop with a design team that integrates diverse profiles such as designers, managers, operators, technicians, marketing, and commercial stakeholders. Compliant with the concept of design integration, this diverse involvement aims to integrate various viewpoints in the PPU feasibility evaluation process based on the matrix in Table 1. For each characteristic feature, the design team first rates the PPU model design options related to the company activities they represent between 0% and 100%. 0% means that they do not have that option at this stage, while 100% means that they have no other option. The design team can also distribute percentages across several options of the same feature so that the total adds up to 100%. For example, for the feature *Relationship type*, a company can have a 20% of direct relation with their customers and 80% of indirect relation (relationship with the third party). The design team needs to agree on a percentage value per PPU model option for each characteristic feature. Then, values of relevant options per feature can be summed to obtain a total feasibility percentage rating, which is mapped to five feasibility levels as of Table 2.

Table 2
Pay-per-unit model feasibility rating per characteristic feature

Colours	Intervals	Description
	[80%, 100%]	Perfectly feasible
	[60%, 80%[	Highly feasible
	[40%, 60%[	Moderately feasible
	[20%, 40%[	Fairly feasible
	[0%, 20%[	Not feasible

3. Case study

The proposed method was applied to the case of a company providing PPU-based offers for air compressors, while selling water pumps in a traditional way. Their objective is to introduce a PPU-based offer also for their water pumps. However, they encounter several challenges, such as established traditional market practices, limited relationships with end users, low pump selling prices, and a large variety of pump brands and technologies. Therefore, they were interested in analysing the feasibility of a PPU model for their water pump offer. A workshop was conducted with several employees from the water department, including the department director, a business developer, an operational technician, an after-sales service representative, and an R&D engineer.

During the workshop, and for each feature of the morphological analysis, the design team discussed the options currently available in the department. They also highlighted their internal resources and capabilities limitations, as well as external market constraints. Then, the design team collectively assigned a feasibility percentage rating to each option through a consensus-based approach. The results are presented in the following section.

4. Results

The results are summarized in Table 3, which is an instantiation of the morphological box (the columns BMC features have not been displayed again for space constraints). The feasibility percentage ratings correspond to the design team's consensus ratings with respect to the company's current product-oriented operations. The third column provides the total feasibility score, calculated by summing only the options relevant for the PPU model (i.e., ignoring the values in the grey coloured cells, as explained in Section 3).

For example, the *Circular Product and Component* feature was evaluated based on the company's current circular capabilities. Currently, 75% of a retired pump system is sent to a metal recycling partner. However, because recycling is a standard end-of-life practice rather than a strategy for extending product use, it is marked as irrelevant for the PPU model. In contrast, 10% of the system is repairable (e.g., electrical circuits) and 15% are reusable (e.g., piping). Since the company acts as a service provider rather than as a manufacturer, it does not engage in remanufacturing or repurposing. Consequently, the total feasibility rating for this feature is 25%, which is the sum of the repair and reuse values. This calculation reflects the level of compatibility between the company's current circular strategy and the required one for a successful PPU model.

Table 3
PPU model feasibility analysis result for the case study

N°	Characteristic features CBM	PPU model design options ratings							Total rating
1	Circular product and component	0%	75%	0%	0%	15%	10%	0%	25%
2	Services	0%	0%	15%	5%	0%	70%	10%	75%
3	Relationship type	50%	50%						100%
4	Customer interaction	10%	0%	90%					100%
5	Customer type	80%	0%	20%					100%
6	Property Rights	90%	10%						10%
7	Customization	40%	50%	10%					60%
8	Type of market	40%	30%	30%					100%
9	Mode of use by the customer	100%	0%	0%					100%
10	Customer contracts	0%	10%	10%	80%				100%
11	Sales channel	10%	50%	20%	10%	10%	0%		90%
12	Revenue model	10%	0%	0%	90%	0%			10%
13	Target	0%	0%	100%	0%				0%
14	Costs	0%	0%	15%	65%	5%	5%	10%	100%
15	Service delivery	60%	20%	20%					100%
16	Risk & uncertainties management	0%	45%	10%	45%	0%			45%
17	Resources types	0%	35%	0%	65%				100%
18	Dynamic capabilities	0%	100%	0%					100%
19	Digitalization	0%	100%	0%					100%
20	Risk & uncertainties management	0%	10%	40%	50%				100%
21	Intangible resources	0%	50%	30%	10%	0%	0%	10%	90%
22	Tangible resources	70%	10%	5%	0%	15%			85%
23	Data collection	100%	0%	0%	0%				0%

Table 3 shows a perfect feasibility for 15 features over 23, and a high feasibility for the features *Customization* and *Services*. This means that the company's customers might well perceive the PPU model value for water pumps, provided that the price model is competitive. The customer channels and partner network do not need any change. The company's currently sold pumping system is customized to each customer's needs in terms of clean or dirty water. This can facilitate the establishment of contracts for the period of use. The company has the human and technological resources to maintain and repair its pumps. They can guarantee service continuity thanks to the digital monitoring system sold with the pumping system. These resources and capabilities are well aligned with the required ones for designing and

implementing a PPU model. This means that the *Key Partners* analysis shows moderate feasibility regarding *Risk and Uncertainty Management*. This suggests that while a partner network exists, the current risk-sharing mechanisms must be restructured. To succeed with PPU, the company and its partners must move from a sales-based risk model to one that manages the long-term operational risks of the equipment. This means greater peace of mind for customers and retaining more risk for the company and its partner network.

A fair feasibility for the feature *Circular product or Component*, as well as no feasibility for the features *Property rights, Revenue model, Target,* and *Data collection,* reveals strong barriers to implementing the PPU model. Hence, the company must pay particular attention to these features when designing the PPU model in terms of the need for redefining the value proposition and customer revenue streams. The company lacks feasibility in terms of the features *Property rights,* and *Revenue model* because it follows a product-oriented model where the customer owns the pump. Under PPU, the company must retain ownership and must shift to billing based on consumption (with defined minimum thresholds). While the company does not manufacture the pumps, it can redesign the overall pumping system to improve component circularity and ease of maintenance. This could increase the *Target* feature rating to a feasible level, as it would be results-oriented rather than product-oriented. The Feature *Data collection* is an important barrier for implementing a PPU model. Although the company has the technology to monitor data, many customers (e.g., public sewage treatment plants) treat this data as highly sensitive. For the PPU model to work, the company must either offer robust data cyber security guarantees or focus the PPU offer on private facility customers with lower data sensitivity.

Overall, thanks to this analysis, the company has been alerted early to critical issues and risks associated with implementing the PPU model. This enabled decision makers adjust their strategies, and designers derive adequate PSS design requirements that explicitly addressed the identified challenges.

5. Discussion

The case study showed that the proposed methodology and tool implementation were effective with the constituted design team of diverse expertise. The morphological analysis had its desired effect of inspiring the experts through the systemic, systematic, and universally understandable visualization of all the aspects to consider when transforming an offer (i.e., a value proposition and value provision) to a PPU model. Most notably, it enabled a systemic and holistic view of all the characteristic features and their design choices for a PPU model. This facilitated discussion focus, due to the effect of visualizing all agreements achieved so far in one table, as well as the consistency of ratings and choices.

Having related the CBM characteristic features to the BMC, which is easy to interpret by practitioners and managers, has helped the diverse design team understand the purpose and challenge of each of those features, as well as their related PPU model design options. It also fostered their capability of thinking holistically in terms of both technical and economic aspects.

Both the design team and the company's higher-level decision makers, receiving the team's results, showed a high satisfaction level. They confirmed that these results provided them with key upfront insights before investing in the detailed planning of the design project.

The chosen approach has similarities with Brunnenkant et al. [20], who combined morphological and techno-economic analysis for evaluating the impact of battery pack design on recycling. Both approaches rely on a morphological analysis to help design teams evaluate and select design options. Their economic analysis is limited to the cost/revenue model for the purpose of analyzing the economic feasibility and profitability of technical design options for the product only. Instead, the method presented leverages the systemic and systematic analysis of the entire value proposition, delivery, capture, and creation cycle. This is an essential prerequisite for a holistic, integrated design of a sustainable PSS proposed in a PPU model from a technical, environmental, economic, and social perspective.

With this, the proposed methodology can be considered a contribution to what Brissaud et al. [2] identified as a lack of design methods and tools specialized in PSS. In the PSS design process, the proposed methodology is positioned in the early concept design phases, where the key elements to be considered are feasibility, risks, opportunities, barriers, and uncertainties. Identifying and quantifying these elements is essential for PSS design requirements elicitation and prioritization. In addition to guidance on requirements, the method could even provide design guidelines for circularity based on Hidalgo-Crespo et al. [21].

Experts in the design team of the case study were more or less confident in their judgments, and the method does not support uncertainty and disagreement yet. It is envisaged for the future to support uncertainty by confidence levels or fuzzy sets to consider the degree of experts' consensus. Availability of data and knowing the 100% reference may be a challenge linked to this.

The proposed morphological analysis, although specialized on the PPU model in its current form, can be extended to cover other PSS models as well, such as leasing, renting, or subscription models. While the BMC and CBM characteristic features will remain unchanged, the PPU model design options will need to be revisited and adapted to the specifics of the investigated alternative model. However, because in the PPU model, the term "unit" can be interpreted flexibly, some alternative models can be seen as special types of PPU models, therefore not requiring any modifications. For example, in a subscription model, the PPU value unit can be set to the subscription period (e.g., one month).

6. Conclusion

This article proposes a methodology for analysing the feasibility of the PPU model for transforming an existing product and service offer into a PSS. Companies are facing this challenge primarily in the quest for increasing circularity to prolong product lifetimes but also for increasing economic viability while reducing geopolitical dependencies. This methodology relies on a morphological analysis in early concept design phases. The design of the morphological matrix associates characteristic features of circular business models with the business model canvas, and relates PPU model design options to these features. This is key to facilitating the full involvement of knowledgeable, diverse practitioners and decision makers in all areas affecting the value system design of the target PPU. The key scientific originality lies in the systemic, systematic, and universally comprehensible aspect of the morphological analysis for the specific purpose of facilitating PSS concept design. Successful validation in a company desiring to transition to a PPU model for water pumps confirmed the method's added value in revealing essential challenges, risks, opportunities, and barriers related to this transition. The method can be generalized to cover alternative PSS models by revisiting and/or extending PPU model design options. Future work shall address current limitations, such as integrating the levels of confidence of expert judgements and their levels of consensus.

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8. Conference Articles

This chapter summarizes the conference articles developed to support the contributions of the thesis. In total, six conference papers, all published, are presented.

Conference Article 1 introduces a parametric LCA method that is integrated into the decision-support approach detailed in Article 1. It supports the first contribution of the thesis. The method assesses the environmental impact of a product within a circular value chain, considering both the performance of processes involved and the SoH of the product as it evolves over time. It was presented at the 31st CIRP Conference on Life Cycle Engineering (LCE) and published in *Procedia CIRP* (Elsevier, 2024).
https://doi.org/10.1016/j.procir.2024.01.029

Conference Article 2 presents a generic framework for assessing product SoH. It supports the first and second contributions of the thesis. Designed to be applicable across a wide range of products, the framework is structured around three main steps: Condition-Based Maintenance (CBM), Prognostics and Health Management (PHM), and a decision tree based on SoH thresholds used in Article 1. It was presented at the 29th CIRP Conference on LCE and published in *Procedia CIRP* (Elsevier, 2022).
https://doi.org/10.1016/j.procir.2022.02.009

Conference Article 3 adapts this SoH assessment framework specifically for electronic products. It also supports the first and second contributions of the thesis. The paper was presented at the 29th European Systems, Software and Services Process Improvement and Innovation Conference (EuroSPI²) and published in the conference proceedings by Springer (2022).
https://doi.org/10.1007/978-3-031-15559-8_11

Conference Article 4 establishes a list of criteria for repairability assessment. This represents the first step in developing the user-centric Repairability Index method formalized in Article 2. It supports the third contribution of the thesis. The work was presented at the 56th CIRP Conference on Manufacturing Systems (CMS) and published in *Procedia CIRP* (Elsevier, 2023).
https://doi.org/10.1016/j.procir.2023.08.049

Conference Article 5 introduces a first morphological box designed to assess the transferability of a PSS model from one department to another within the same company. This represents an initial step toward the morphological box for PaaS model replication presented in Article 4. The study helped to define relevant features for characterizing PaaS models as well as organizational capabilities. It supports the fourth contribution of the thesis. The paper was presented at the 31st EuroSPI² and published in the conference proceedings by Springer (2024).
https://doi.org/10.1007/978-3-031-71142-8_1

Conference Article 6 presents a design flowchart to guide companies in defining product value chains within a component-as-a-service business model. This work represents a further step toward developing a quantitative method for assessing the environmental and socio-economic performance of CBM/PaaS models, beginning with component-as-a-service. The proposed value chain also establishes the link between step 3 and step 4 of the bottom-up transition approach toward a circular economy (*See Fig. 15*). It supports the fourth contribution of the thesis and represents a direct continuation of the thesis research work. The paper was presented at the 32nd EuroSPI² and published in the conference proceedings by Springer (2025).
https://doi.org/10.1007/978-3-032-04291-0_3

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8.1. Conference Article 1: Parametric LCA integrating a product's State of Health: A decision-making tool based on environmental impact in the context of circular strategy.

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31st CIRP Conference on Life Cycle Engineering (LCE 2024)

Parametric LCA integrating a product's State of Health: A decision-making tool based on environmental impact in the context of circular strategy.

Christian Wandji[a,]*, Helmi Ben Rejeb[a], Andreas Riel[a], Peggy Zwolinski[a]

[a]*Grenoble Alpes University, CNRS, Grenoble INP, G-SCOP, 46 Avenue Félix Viallet, 38000 Grenoble, France*

* Corresponding author. Tel.: +33 787254279; *E-mail address:* christian-berenger.wandji-wouapi@grenoble-inp.fr

Abstract

Circular processes such as remanufacturing, reuse, recycling, make it possible to extend the life of products and thus reduce their environmental impact. However, they introduce uncertainties of quantities and qualities that bring significant challenges for manufacturers and others stakeholders. To reduce such uncertainties and give decision-makers more information for selecting a circular strategy driven by the environment, a parametric life cycle analysis method is essential. The aim of this article is to propose a method based on the performance parameters of each process of product closed-loop to calculate the environmental impact of a product in different closed loops, considering the product's state of health. To achieve this objective, the product life cycle process with closed circular processes were first specified. Then, its parameterization was completed to simulate different scenarios. Based on parameters defined, formulas to facilitate the simulation of several circular scenarios for a given product has been defined. This allows identifying the circular strategies with the lowest environmental footprint. Illustrated by a case study on an electric circuit breaker, our approach demonstrates its effectiveness in supporting eco-responsible decisions.

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Keywords: Parametric LCA; Circular Strategies; Decision-making; Decision-Aid; State of Health

1. Introduction

Today, the environment is one of the greatest challenges. Industry has always been operating on the basis of a linear economy, i.e., it designs a product, extracts the raw materials, and transforms them to produce a final product. The final product is then integrated in another product, or directly used by the end-customer, who ultimately disposes it as waste. In this context, the main objective has always been to increase profits either by increasing productivity or product quality or responding to changing customer needs. With this linear economy strategy, industry is one of the biggest contributors to environmental degradation [1]. Today, in the context of sustainable development, they are transforming their economy together with scientists to make it more circular. The aim is still to increase profits, but with environmentally-friendly activities that reduce the environmental impact (EI) they generate. The circular economy (CE) aims to extend the life of products and thus reduce their impact on the environment, which introduces more uncertainties on quantity and quality of recovered products into the circular value chain [2]. These uncertainties pose even greater challenges to manufacturers than before. In addition, there are many circular processes such as remanufacturing, refurbishing, reusing, repurposing, repairing, recycling, etc. Furthermore, industry sometimes has a wider range of products. All these issues make it difficult to define a circular strategy (CS). It is therefore ambiguous for industrials to decide which CS to implement in this context. There is a real need to support them in defining a CS suited to their activities and which is environmentally viable. To meet this need, a methodology is required for simulating different CS products in different use cases, taking into account the issues mentioned above. This article proposes a method for assessing the EI of a product based on the Life Cycle Analysis (LCA) at each stage

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of the product life cycle [3]. This method integrates the State of Health (SoH) of the product into the simulation, as well as the performance parameters of each circular process.

The remainder of this article is organized as follows: Section 2 summarizes the state of the art and formulates the gaps in the form of a research question. The proposed methodology is presented in Section 3. The parametric LCA method is developed in Section 4. Section 5 presents an application of the proposed method to an electric circuit breaker. Section 6 is dedicated to analysis and discussion. Section 7 concludes.

Nomenclature

LCA	Life Cycle Analysis
SoH	State of Health
CE	Circular Economy
CS	Circular Strategy
Sc	Scenario
EI	Environmental Impact
EoL	End-of-Life
EoU	End-of-Use
EIME	Environmental Improvement Made Easy

2. State of the art

Making the decision to select a CS with the lowest EI is a real challenge. Many researchers have conducted comparison study to support the decision making. It is the case of Sutherland et al [4] who carried out a comparative analysis of the EI of remanufacturing and the EI of manufacturing of a diesel engine. Their aim was to highlight the benefits of remanufacturing to help manufacturers make decisions about the circularity of their products. One of the limits of CS is uncertainty, which poses significant challenges for industrials.

Some researchers have also addressed those limits. Harter et al. [5] presented a method to carry out the Life cycle Energy Assessment with the goal to reduce the uncertainties influence at the design stage. Moreover, decision on the environmental-based choice of the optimal CS should be done early at the design stage [6]. Numerous papers evaluated the EI of products both in linear [7] and circular [8–12] context according to the recommendations of standardized LCA methodology.

In that way, Gehin et al. [3] proposed an LCA method for assessing the EI of a product at each stage of its life cycle. This method is very useful for simulating the EI of an EoL scenario to support decision making in CE at the design stage. It is based on the calculation of the EI per stage of product life-cycle, such as the raw materials stage, the component manufacturing stage, etc. Those papers perform LCA on the closed-loop process without addressing the simulation of scenario with parameters.

This is one of the challenges taken up by Luis Amaya Rivas in his thesis [13]. He proposed a methodology to simulate remanufacturing and recycling closed-loop scenario using parameters at each stage of the product Life cycle. This parameterization poses an allocation problem at certain stages of the process, depending on the boundary chosen for the study [14]. Luis Amaya Rivas proposed a parametric method for simulating circular scenarios for a product use case. But he did not address simulation for different use cases and for multiple use of the product and its components in a sales business model. Furthermore, he does not consider the SoH of the used product that is one crucial to define a CS [15]. The main challenge that this paper tackles is how can manufacturers be helped to easily make a decision on the choice of environmentally optimal CS, considering different use cases of the product and its SoH? The following sections attempt to give an answer to this question.

3. Methodology

The aim of this article is to establish a methodology that allows simulating the EI of the circular life of a product based on its SoH and the performance parameters of each stage of the closed-loop processes. This aids decision making on selecting the optimal circular process for different use cases. This methodology is made up of four main parts. For the first part, the closed-loop processes are modelled from raw material extraction to the End-of-Life (EoL) phase. The closed-loop processes are Remanufacturing, Reuse and Recycling. Parameters, some of them considering SoH, are defined for each stage of the processes, with the aim of simulating different alternatives. In the second part, based on the closed-loop processes and parameters previously defined, formulas for assessing the EI of the product by unit of use and at each stage of the product life cycle are determined. In the third part, three scenarios and different use cases were defined in order to compare circular strategies, and identify the one with the lowest EI value. Finally, calculations are performed to determine the EI of each stage of the closed-loop process. These calculations have been refined and validated using LCA software SimaPro and EIME in the fourth step.

4. Parametric LCA method

The parametric LCA method is a method that uses parameters at each step of the product life cycle to simulate EI of CS scenario. This method is inspired by the thesis of Luis Amaya Rivas [13] and the work of Gehin et al. [3]. The objective is to help manufacturers to select the lowest EI circular strategy for their business by testing different alternatives. This method is made up of three main parts. The first part, which is the definition of the closed-loop process and the parametrization, is presented in the next sub-section.

4.1. Closed-loop process and parametrization

The parametric LCA is defined to simulate three CS, namely the remanufacturing, reuse and recycling of product components. The aim is to keep the product and its components in a life cycle as long as possible. The closed-loop process has been defined at both single component and product assembly level. Two types of recovery level have been integrated. One is the recovery of a product at End-of-Use (EoU), i.e., a product recovered before its EoL and still able to fulfil its main function. The other is the recovery of a product at EoL, i.e., a product recovered for disposal because it can no longer fulfill its main function. The EoU strategies on product-level considered here are reuse, remanufacturing and recycling of components. The EoL strategies considered are recycling,

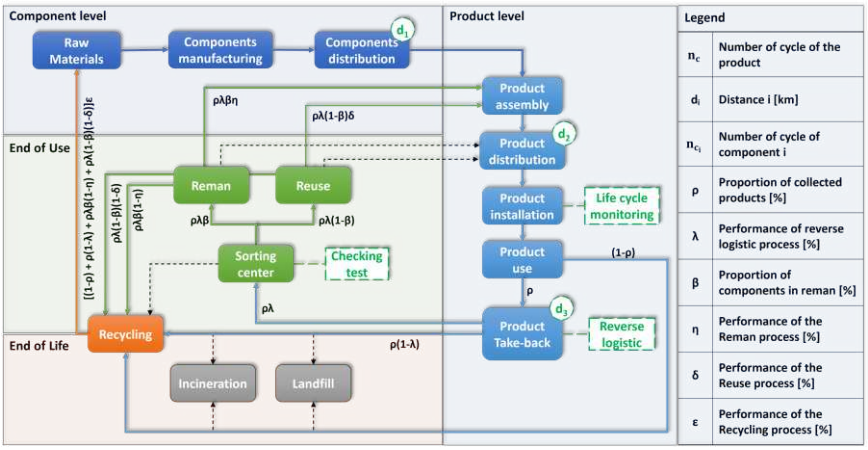

Fig. 1. Closed-loop circular product process with parameters

incineration and landfill. The closed-loop process begins with the extraction of raw materials to manufacture components, which are then transported to the assembly plant where the final product is assembled. This product is then transported to the distribution center and to the end-user, where it is installed. It is used for a certain period of time before being recovered through reverse logistics. The reverse logistics process involves the dismantling of the product at the premise of the end-user and the supply chain back to the assembly plant. After visual inspection, the product will be directed either to the recycling process, or to the sorting center where it is disassembled. Depending on the state of health of its components, these are either remanufactured or directly reused spare parts to refurbish a product. The Fig. 1 summarizes the closed-loop process with parameters.

In this type of circular process with many alternatives, allocation is sometimes inevitable. In line with the ISO 14040 standard on LCA recommendations, allocation should be avoided whenever possible. In this way, the definition of closed-loop process boundaries helps to avoid allocations.

To be able to simulate different alternatives, parameters was defined for each stage of the circular life of the product. These parameters are the performance in terms of efficiency of reverse logistics, reuse, remanufacturing and recycling. In addition, there are parameters for the proportion of used products collected and proportion of components in remanufacturing. The choice to use performance of processes as a parameter was made not only to simplify the model, but also to assess the impact of process efficiency in circularity. Each process has different factors that can influence its performance. For example, at the reverse logistics stage, dismantling time, transport mode, facility location, planning, etc. are all variables likely to influence process performance. [16,17]. In addition, the different distances of transportation have been considered: the distance (d_1) of the transportation of components from their manufacturing facility to the assembly plant; the distance (d_2) of the transportation of the product to the distribution center and to the end-user; and the distance (d_3) from the premise of the end-user to the assembly plant.

Among the parameters that are inputs for the simulation, the component proportion parameter in remanufacturing (ρ) is obtained based on the SoH value of the components. Wandji et al. have proposed a general framework for assessing the SoH of a complex system and SoH threshold intervals to be considered for optimal component remanufacturing [15,18]. Thus, the parameter (ρ) is the ratio of the number of components whose SoH value lies within the SoH threshold interval to the total number of components in the product.

4.2. Definition of formulas for calculating EI per unit of use

The formula to quantify the EI at each process step level per unit of use is the product of the EI of each process by its parameter factor. The EI of a process is obtained using a LCA software. Basically, it is the conversion of cumulative elementary flows of the process in an impacts categories using the PEF EF 3.0 method [19]. For the transport stage, the EI is obtained for a distance of 1 km, making it possible to simulate different distances for CS. The Table 1. summarizes the formulas for calculating the EI at each step of the closed-loop process, based on the process flow model in Fig. 1.

Table 1. Formulas for calculating EI.

N° of steps	Step of closed-loop process	Formula for calculating EI at each step.
1	Extraction of raw materials	$EI_{R-mat} = \sum_{i=1}^{n} EI_{mat_{Component_i}} \times \left(\frac{1+(n_{c_i}-1)\left[1-\left[(1-\rho)+\rho(1-\lambda)+\rho\lambda\beta(1-\eta)+\rho\lambda(1-\beta)(1-\delta)\right]\varepsilon\right]}{n_{c_i}}\right)$
2	Manufacturing of components	$EI_{man_{Components}} = \sum_{i=1}^{n} EI_{man_{Component_i}}$
3	Distribution of components	$EI_{dist_{components}} = \sum_{i=1}^{n} EI_{dist_{Component_i}} \times d_1$
4	Assembly of the product	$EI_{ass} = EI_{ass_{product}} \times \left(\frac{1+(n_c-1)[1-(\rho\lambda\beta\eta+\rho\lambda(1-\beta)\delta)]}{n_c}\right)$
5	Distribution of the product	$EI_{dist_{product}} = EI_{dist_{product}} \times d_2$
6	Installation of the product	$EI_{Inst} = EI_{inst_{product}}$
7	Use phase of the product	$EI_{use} = EI_{use_{product}}$
8	Take-back phase of the product	$EI_{take-back} = \left(\frac{(n_c-1)\times(\rho)}{n_c}\right) \times EI_{take-back_{product}} \times d_3$
9	Remanufacturing of components	$EI_{reman} = \sum_{i=1}^{n} EI_{reman_{Component_i}} \times \left(\frac{(n_{c_i}-1)\times(\rho\lambda\beta)}{n_{c_i}}\right)$
10	Reuse of components	$EI_{reuse} = \sum_{i=1}^{n} EI_{reuse} \times \left(\frac{(n_{c_i}-1)\times[\rho\lambda(1-\beta)]}{n_{c_i}}\right)$
11	Recycling of product and components	$EI_{recy} = \frac{\left[EI_{recy_{EoU}}\times(n_{c_i}-1)[\rho(1-\lambda)+\rho\lambda\beta(1-\eta)+\rho\lambda(1-\beta)(1-\delta)]\right]}{n_{c_i}} + \frac{\left[EI_{recy_{EoL}}\times[1+(n_c-1)[1-(1-\rho)]]\right]}{n_c}$
Total EI of the process		$\mathbf{EI_{Total} = \sum_{j=1}^{11} EI_j}$

The total EI is the sum of the EI calculated at each step of the process. These formulas are used to simulate scenarios that define the CS for different use case of the product.

4.3. Use case and scenarios

In a linear economy, whether B2B or B2C, products are used in different environments. The same product may be used in a building, a wind turbine or a solar installation, all of which have different conditions of use. Certain stages of the closed-loop process may therefore change, such as the use phase and the take-back phase. Product use cases can have an influence on the EI of the product. They are therefore taken into account in this paper.

In addition, two scenarios have been defined in order to compare the CSs. The scenario zero (Sc_0) is the baseline scenario in which, for two life cycles, two new products are used and then disposed at their EoL or EoU. The other is the circular scenario (Sc_1), in which a new product is used during the first life cycle. It is then recovered for refurbishment and used in the second life cycle. Refurbishment follows the closed-loop process shown in section 4.1. The Fig. 2 illustrates these two scenarios.

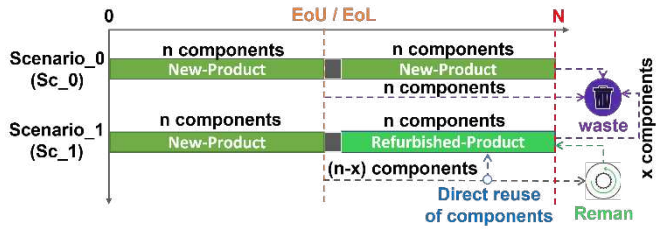

Fig. 2. Two Circular Scenarios for simulation

The following assumptions have been made for the simulation:

- In the scenario_0, the product is disposed and treated as waste at its EoL or EoU.
- In scenario_1, the refurbished product in the second life cycle comes from the new product in the first life cycle. The time of refurbishment is not taken into consideration.

These assumptions and the method described in this section are applied to a circuit-breaker use case.

5. Electric circuit-breaker use case

The electric circuit-breaker studied is an electrical protection device made up of 19 components, as shown in Table 2. It is used in a wide range of applications. In this application, its uses in wind turbines, solar energy and buildings are taken into account for the simulation. In these three applications areas, the product is subject to different conditions. Hence, it will not have the same lifetime. The lifetime is 2 years in wind turbines, 5 years in solar power and 15 years in buildings. For the CS simulation, the number of cycles for each component is defined for the two scenarios presented in section 4.2 and in the three application areas selected above (wind power, solar energy and buildings). They are illustrated in Table 2.

Table 2. Number of components cycles (n_{ci}) per scenario and use case.

		Wind turbine		Solar		Building	
N°	Components	Sc_0	Sc_1	Sc_0	Sc_1	Sc_0	Sc_1
1	Mobile Contact	1	2	1	2	1	2
2	Fixed Contact	1	2	1	2	1	2
3	Arc Chamber	1	2	1	2	1	2
4	Charging Motor	1	2	1	2	1	2
5	Clusters	1	1	1	1	1	1
6	Connection Terminal	1	1	1	1	1	1
7	Trigger Unit Base	1	1	1	1	1	1
8	Trigger Unit	1	1	1	1	1	1
9	Coils	1	2	1	2	1	2
10	Sensors	1	1	1	1	1	1
11	Filerie (Electrical Cable)	1	2	1	2	1	2
12	Housing And Accessories	1	1	1	1	1	1
13	Plastron	1	1	1	1	1	1
14	Mechanism	1	1	1	1	1	1
15	Pole Shaft	1	1	1	1	1	1
16	Mechanism Chassis	1	2	1	2	1	2
17	Chassis base	1	1	1	1	1	1
18	Auxiliary contacts	1	1	1	1	1	1
19	Others accessories	1	2	1	2	1	2
	Product	1	2	1	2	1	2

Closed-loop process parameters are also defined for the two scenarios defined in section 4.2 and for the three selected application areas. The wind turbine is assumed to be 900 km by truck from the assembly plant, the solar 500 km and the building 350 km. The refurbished product is also manufactured in the assembly plant. They are illustrated in Table 3.

Table 3. Parameters by scenario and use case.

		Wind turbine		Solar		Building	
Symbols	Parameters	Sc_0	Sc_1	Sc_0	Sc_1	Sc_0	Sc_1
N	Total Life cycle [Year]	4	4	10	10	30	30
n_c	Number of cycles of the product	1	2	1	2	1	2
d_1	Distance to the assembly plant	2000	2000	2000	2000	2000	2000
d_2	Distance to the distribution center and to the end-user	900	900	500	500	300	300
d_3	Distance of the reverse logistic	900	900	500	500	300	300
ρ	Proportion of collected products [%]	0	80	0	60	0	40
λ	Performance of the reverse logistic process [%]	0	70	0	50	0	20
β	Proportion of components in remanufacturing [%]	0	42	0	47	0	42
η	Performance of the Reman process [%]	0	80	0	80	0	80
δ	Performance of the Reuse process [%]	0	80	0	80	0	80
ε	Performance of the Recycling process [%]	70	70	70	70	70	70

6. Results analysis and discussion

This section is structured in different analysis points. In this analysis, it is assumed that components with a SoH value of between 50% and 70% should be remanufactured, and those with a SoH value of between 70% and 80% should be reused.

The first analysis point is the identification of the main contributors. In Fig. 3-a It has been found that the manufacturing and use phases in the wind turbine area are the main contributors in Sc_0. Therefore, in Sc_1, with parameters

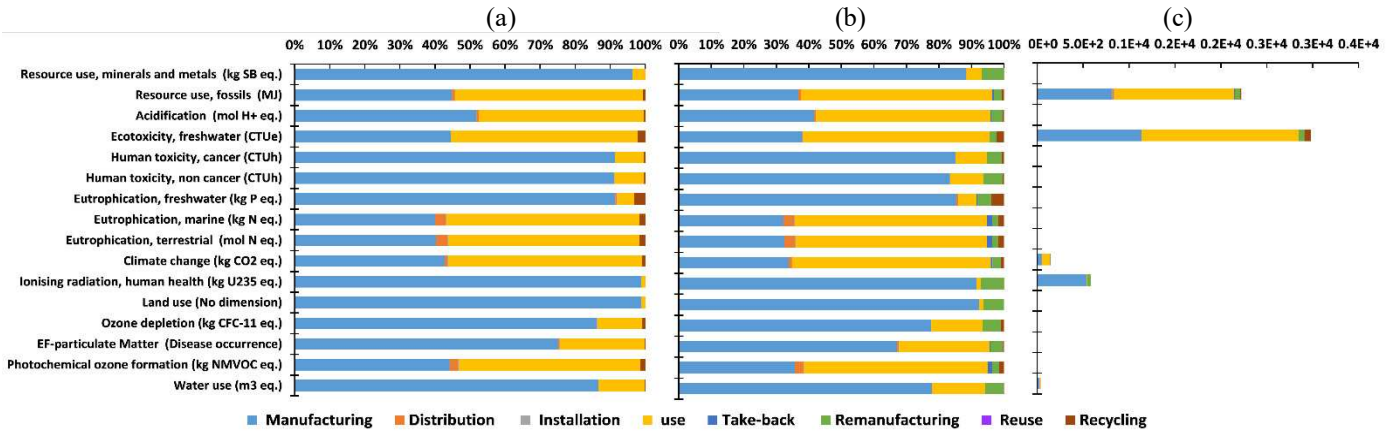

Fig. 3. (a) 100% stacked bar of the EI of a circuit-breaker in Sc_0; (b) 100% stacked bar of the EI of a circuit-breaker in Sc_1; (c) Stack bar of the circuit-breaker.

ρ, λ, β, η, δ and ε set at 50% and a remanufacturing of 9 components out of 19 (i.e., 47%), the main contributors are the same. However, with those parameters set to 100% and 47% of components in the remanufacturing process, it was found in Fig. 3-b. that the remanufacturing phase is the third contributor. These main contributors are the same for the other use cases.

The second point of analysis is the identification of the impact categories most concerned. It has been found in Fig. 3-c that ecotoxicity, freshwater; resource use, fossils; ionizing radiation, human health and climate change are of the greatest concern, whatever the use case.

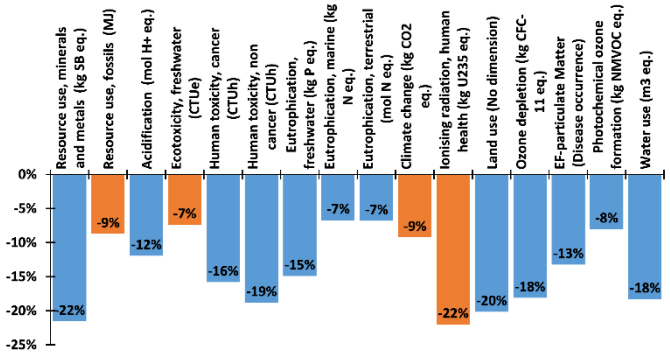

Fig. 4. Relative deviation of Sc_1 from Sc_0 for wind turbine application

According to Fig. 3-c, the circuit breaker has the greatest impact in the ecotoxicity category, freshwater, which poses a problem for aquatic species. The resource use category, fossil fuels, is also affected, which can disrupt hydrocarbon formation. Human health is also affected, as the manufacture and use of this product also generates impacts in the ionizing radiation, human health and climate change categories. Circularity is one of the keys to reducing these impacts, and the parametric LCA method fosters it. The third analysis point shows the influence of parameters in a LCA analysis.

To demonstrate this, the relative deviation of Sc_1 compared to Sc_0 under the same conditions has been calculated with parameters ρ, λ, β, η, δ and ε set at 100% and 47% of components remanufactured. The result shows a minimum EI reduction of 7% and a maximum of 22% in all impact categories. Focusing on the impact categories of greatest concern identified earlier, EI in the ionizing radiation (human health) category was reduced by 22%, the EIs in the climate change and fossil resource use category were reduced by 9%, and EI in the ecotoxicity (freshwater) category was reduced by 7%. Moreover, the EIs for the categories Resource use, minerals and metals; Human toxicity, non-cancer; Land use; Ozone depletion and Water use have been reduced by at least 18%. Fig. 4 sums it all up for wind turbine application. In addition, Fig. 5 shows the difference between the relative deviation of Sc_1 from Sc_0 with parameters set at 50% and that with parameters set at 100% for the all use cases.

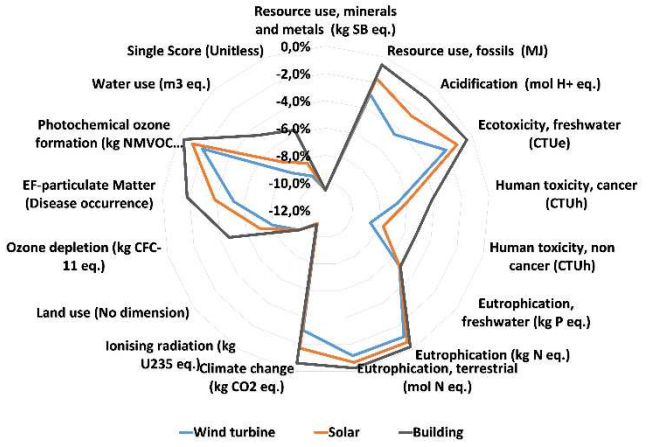

Fig. 5. Relative deviation with 50% to 100% parameters variation

In Fig. 5, it is observed that the relative deviations are all negative, meaning that varying the parameters from 50% to 100% reduces the EI in all impact categories. However, this relative deviation does not change from one use case to another for certain categories such as: Resource use, minerals and metals; Eutrophication, fresh water; and others. For other categories, on the other hand, it has been reduced from application for wind turbines to application for buildings. In the climate change category, for example, the relative difference is -3.1% for wind turbines, -1.7% for solar energy and -0.6% for buildings. This reduction is due to the operating conditions and lifetime of the circuit-breaker in these different applications. This implies that there is a limit at which the effort to extend product life no longer produces any significant environmental change. This analysis proves the influence of process performance parameters in generating process impacts.

Finally, this last point of analysis shows a simulation of three Sc_1 CS based on 47% remanufacturing of components under the conditions defined in Table 3 for the wind turbine application. In the first CS of Sc_1, the 47% are remanufactured, in the second they are all reused and in the last CS of Sc_1, there are 26% remanufactured and 21% reused out of the 47% upgraded. Fig. 6 shows that Sc_1 with 47% reuse components, has the lowest impact likely 10% less than the others for the climate change indicator. With the exception of ecotoxicity, one of the categories of greatest concern, where this Sc_1 is the second least polluting. This strategy is also the most advantageous because the EI of the reuse process is lower than the EI of the remanufacturing process. This analysis shows more or less the same result in the other use cases.

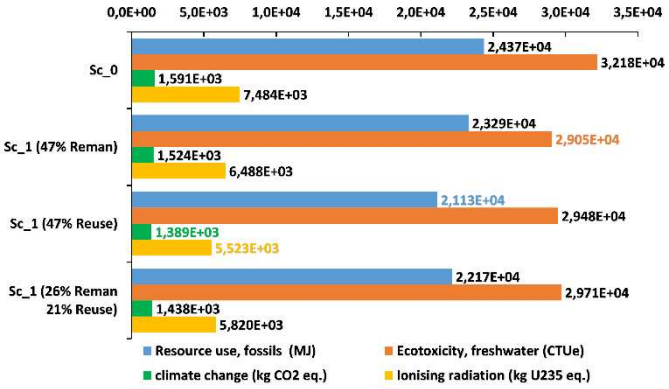

Fig. 6. Comparison of CS by scenario.

Finally, the proposed method has allowed the industrial partner to choose among three scenarios the one (Sc_1 with 47% reuse) which is optimal in terms of EI. The industrial partner has confirmed that this decision would be ambiguous to make without the simulation tool of the proposed method.

7. Conclusion

The parametric LCA method is effective for finding the CS with the lowest EI. It is useful for optimizing decision-making on the CS of a product in different use cases. It is based on performance parameters of circular value chain processes and product SoH. However, for optimal use, prior work must be carried out to assess the SoH of the product and its components, and to define with the manufacturer the values of the input parameters for the simulation.

The application of parametric LCA to the use case of an electrical circuit breaker first enabled us to simulate different SoH scenarios by varying the parameters and the number of components recovered for circular processes. Secondly, it showed that the CS of Sc_1, which consists in reusing 47% of recovered components, is the optimal strategy in environmental terms for the wind turbine application. This Sc_1 showed 10% less EI on average than the other scenarios for the climate change indicator. This decision would be ambiguous to make without the simulation tool based on the proposed method.

Future work will involve adding a life-cycle cost analysis (LCC), studying the CS of product transversality from one application area to another, and comparing it with others.

Acknowledgements

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8.2. Conference Article 2: Characterization of the state of health of a complex system at the end of use

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Characterization of the state of health of a complex system at the end of use

Christian Wandji[a]*, Helmi Ben Rejeb[a] , Peggy Zwolinski[a]

[a]*Univ. Grenoble Alpes, CNRS, Grenoble INP,G-SCOP, 46 Avenue Félix Viallet, 38000 Grenoble, France*

* Corresponding author. Tel.: +33 4 76 57 48 44, E-mail address: christian.wandji-wouapi@grenoble-inp.fr

Abstract

The state of health (SoH) of an end-of-life product is one of the levers for optimizing the circular economy (CE) process in order to allow the product life-extension. Many approaches have been developed in the literature to estimate the SoH of a complex system (CS). In this study, we asked ourselves the following two questions: First, how to optimize the circular lifecycle scenarios of the components of a product at its end of life? And second, how to estimate the SoH of a product at the end of its life? To answer these questions, we proceeded as follows. First of all, the state of health of a product needs to be considered as an important parameter as well as performance or reliability. To estimate the SoH, it is necessary to identify the product parameters to be observed. The problem here is to choose the most relevant parameters among all those available for a CS. To do this, we have proposed a conditional-based maintenance approach (CBM) which consists in establishing the fault tree of a product. It consists of functionally breaking down a product into its various components and identifying the main failures for each of them. Then, these failures are used to identify the parameters to be monitored. Second, based on the most relevant parameters, the health indicators needed to estimate the SoH of the product are obtained. Then, the Prognostic and Health Management approach (PHM) is proposed in order to estimate the SoH. In the objective of providing a general solution that could be used for estimating the health status of any product, we have proposed a generic framework for the PHM approach. It serves as a guide in choosing the right approach according to the situation. Then, we proposed a decision-making strategy to optimize the process of orienting components in circular loops. This strategy is based only on the technical-functional indicator, which is the SoH of the components. Finally, we showed an example of the implementation of the proposed method for the case of the electrical scooter motor.

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Keywords: Health indicator; Sate of health ; circular economy; lifecycle engineering, condition-based maintenance; Prognostic and Health Management.

1. Introduction

Having become aware of the real danger that threatens our environment, manufacturers and scientists use several concepts, such as sustainable development, circular economy, to minimize energy waste and pollution and optimize the use of resources. Within this framework, the project Smart 2020 entitled: “Collaborative construction of the state of health of a product to be regenerated throughout the lifecycle” has been launched and supported by the French network S.mart. This latter federates an academic community to drive scientific, technological and societal change at local and national levels for the industry of the future. The study presented in this article tackles the issue of optimization of the circular scenarios of end-of-life (EoL) products. The CE is one of the most important concepts that really impacts the resources management. It is made up of many processes that allow to recapture the added value of the product at different levels of the value chain, the user, the service provider, the product manufacturer, and the component manufacturer. Those processes are reuse, repair, repurposing, refurbishment, remanufacturing, and recycling and then constitute a close loop system [1]. They are widely discussed in the literature but the question on the optimization of their use is not yet clear. In other words, how to direct the components of a complex system (CS) towards the appropriate CE processes in order to reduce

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waste and recapture the value-added of the components as much as possible? To do this, the knowledge of the state of health (SoH) of these components is paramount. Therefore, the question of the ways to assess the health state of the components of a CS deserves a particular attention. In this paper, CS is defined as a system made up of several subsystems or components from different fields (mechanical, electronic, electrical, among others) [2]. The SoH is more related to the state of degradation that has widely been assessed in the literature using the prognostic and health management approach (PHM) [3], [4]. Therefore, PHM is most effective when applied to critical components. Therefore, it is necessary to identify them first. Thus, we have proposed a condition-based maintenance (CBM) method that is compatible with PHM in the case of a combination of both approaches [5].

The remainder of the paper is organized as follows: section 2 summarizes the methodology proposed to presents the research questions. The literature review is presented in section 3. The development of our general framework, in which CBM approach, PHM approach, and the decision-making strategy were presented, is discussed in Section 4. The section 5 presents an illustration of the implementation of the proposed method on an electrical scooter motor. Finally, the conclusion is given in section 6.

Nomenclature

CBM	Condition-Based Maintenance
CE	Circular Economy
CS	Complex System
EMD	Empirical Mode Decomposition
EoL	End of Life
EV	Electric Vehicle
FA	Functional Analysis
FMEA	Failure Modes and Effects Analysis
FMMEA	Failure Modes, Mechanisms and Effects Analysis
GRNN	Generalized Regression Neural Network
HHT	Hilbert-Huang Transform
HI	Health Indicator
LIB	Lithium-Ion Battery
LRT	Linear Rectification Technique
ML	Machine Learning
PDF	Probability Density Function
PHM	Prognostic and Health Management
PLM	Product Lifecycle Management
PoF	Physic of Failure
RCM	Reliability-Centred Maintenance
RFID	Radio Frequency Identification
RMS	Root Mean Square
RUL	Remaining Useful Life
S.mart	Systems Manufacturing Academics Resources Technologies
SoH	State of Health

2. Research methodology

The objective of this paper is to estimate the SoH of a CS in order to optimize the process of directing components towards CE scenarios. To achieve this goal, we proposed a method that could be considered as a general framework for SoH estimation and decision-making method towards implementation of CE scenario. The method needs to be versatile and robust enough to cope with different situations, whether operating history data are available or not. It combines several methods from the areas of reliability engineering, data science and artificial intelligence. The general research methodology that we have used in order to construct this framework consists of the following two steps. First, a comprehensive and systematic literature review has been carried out. It is through bibliographic research that we have traced the path of methods used for failure detection, diagnosis, and prognosis. Second, a 3-step framework is proposed, which aims at the identification of critical component, SoH estimation, and decision support for circular scenarios. We have proposed the CBM approach to identify critical components of the system and their main failures. Then, the PHM approach which on the basis of these failures will select the important parameters from which the Health Indicators (HI) will be extracted for the SoH estimation. Finally, the SoH ranging from 0 to 1 is estimated for each component, and it is used with a decision-making strategy to direct the components to one of the following circular processes: reuse, repair, repurpose, remanufacture, refurbish, and recycle. This decision-making strategy only considers the technical functioning indicators expressed in terms of SoH, but it could also consider other indicators such as economy, ecology, business, market.

3. Literature review

The SoH concept comes originally from medicine and was used to characterize human health. Since then, it has been used to characterize the health of systems. The question of the SoH of an item of a piece of equipment arose in reliability engineering, because one of the missions of maintenance on a technical level is to increase the lifespan of the equipment. Thus, the concept of maintenance was concerned first with promoting repair of a piece of equipment at each failure, then it promoted the systematic or conditional change of the components before the failure occurs [6]. Indeed, from the systematic maintenance, the follow-up of the state of degradation was introduced. Zhang et al. [7] proposed a solution to estimate the remaining useful life of a system with high fluctuating degradation. They proposed to use degradation process and standard deviation as performance variable to calculate the Probability Density Function (PDF) and then the conditional reliability function which is the estimation of the RUL. The purpose of the reliability calculation is to increase productivity, so it concerns much more the equipment available in a factory where the environment and the conditions of use are known. So, what about the reliability calculation of a product that operates in an unknown environment, or a product used by a third party, for which a regular follow-up is not possible.

To address those questions, Morello et al. [8] proposed to use Product Lifecycle Management (PLM) to track the status of a smart product during its whole life cycle. This consists in recording the operating information of an intelligent product in the memory of an RFID card installed on it. This method is extremely useful on a simple system like the example of the hydraulic cylinder that Morello shown in his article. But it could become much less efficient or terribly expensive in the case of a CS. However, following a demand from industry for greater reliability with lower cost, the PHM approach has emerged in recent years as an essential solution for estimating the RUL as presented by Kalgren et al. [6]. PHM is the most suitable approach for predicting the RUL of a CS because it incorporates the principles of CBM as well as those of Reliability-Centered Maintenance (RCM) [9], [10]. It can be classified into three types: model-based, data-driven and hybrid approach [2], [11].

A model-based approach consists of mathematically model the physical degradation of a product. It gives most accuracy than the others approach. But because of costly and the difficulty of implementation on a system with several subsystems and components, it has low applications in real life [12]. On the other hand, model-based approach is suitable for new products because it reduces the design margin [8]. However, because of the complexity of this approach, it is not enough employed by researchers compared to data-driven approach.

The data driven approach is useful when the product has already been manufactured. It traditionally consists of analyzing online and offline data to provide degradation behavior, then constructing a HI using different methods to finally predict RUL using a trained data model. There are many models of data to predict RUL and the most used are those of Machine Learning (ML). Compared to the model-based approach, data driven approach has many applications. For Lithium-ion battery [14], [15], turbofan [4], [16], bearing [3], [17], [18] and others. To avoid the shortcomings associated with the use of one of the above approaches, some researchers have used hybrid approach (i.e., a combination of two or more approaches).

One most used hybrid approach is the combination with model-based approach and data-driven approach. This approach is recently used to estimate the SoH of lithium-ion batteries in real time without RUL prediction. It takes advantage of the data-driven least squares support vector machine and the model-based unscented particulate filter shown by Song et al. [19]. On the other hand, still for Li-Ion batteries, Su et al. [20] proposed a hybrid PHM approach to estimate the remaining capacity using a generalized regression neural network (GRNN).

Our literature review determine that the main purpose of estimating the RUL through the PHM is to optimize the maintenance actions. However, in the application of the PHM there is always a final decision-making step. Very few studies used PHM to estimate the SoH of a product for decision making in the context of the CE. In this perspective, some publications on decision-making strategies have been identified. This is the case of Alamerew et al. [21], [22] who proposed many decision-making strategies regarding different criteria in the context of circularity. Those criteria are mainly environmental (EoL impact indicator, CO2 emissions, SO2 emissions, energy consumption, among others), economic (such as logistic cost, product cost, disassembly cost) and societal (such as number of created employees, exposure to hazardous materials). But it is also possible to consider other criteria such as legislation, business, market and technical. It is also the case of Anityasari et al. [23] who proposed a decision-making tool to direct components at the end of their life toward reuse, remanufacturing, and recycling process on the basic of profit margin, market price, product life cycle cost, cost of remanufacturing, and cost of warranty.

4. General framework

Our work aims to fill a gap in the literature by proposing an approach for estimating the SoH of a product in order to optimize the choice of circular scenarios for the products EoL. To achieve this goal, we propose to combine CBM approach, PHM approach and a decision-making method as it is illustrated in Fig. 1.

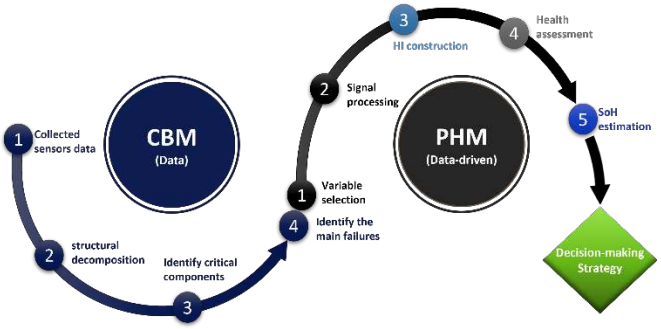

Fig. 1. General framework

On the one hand, PHM approach has been selected because it incorporates the principles of CBM as well as those of RCM, and it is recommended for RUL prediction using health assessment. It is made of several steps that start with the selection of relevant variables related to components. Then, the data is processed, and the HI is extracted to monitor the degradation of the component. Finally, the SoH is evaluated and can be estimated. However, it is recommended to use the PHM for the most critical components, as they best describe the degradation of the system. Hence, it is combined with the CBM approach. On the other hand, the CBM approach is used for data or information collection, detection and diagnosis of the main critical component and the main failures of each critical component. It uses detection and diagnostics to monitor a CS with the aim of identifying degradation status, faults, their severity, and their causes [5]. CBM and PHM are followed by the decision-making step of the framework, which used the SoH value to direct the CS components to the appropriate CE scenarios.

4.1. Condition-based maintenance approach

CBM methodology consists of monitoring the state of degradation of an item of a piece of equipment and then triggering maintenance actions each time the predefined thresholds are exceeded on the basis of several significant

criteria [13]. In our proposition, we used the CBM approach to identify the critical components of a CS and their main failure. Thus, we proposed a process made up of a set of maintenance analysis tools such as Failure Mode and Effects Analysis (FMEA), Functional Analysis (FA), Pareto chart and Fault Tree method.

The process presents two possibilities to establish the fault tree of a CS. One possibility is to make a FA of the CS in order to obtain its hierarchical structural decomposition into its components. Then, Pareto chart on the number of downtime (N) of each CS component allows the identification of its critical components. Indeed, this possibility of using the FA and Pareto chart tools is only possible if the operating data of the system are available and the information on the system such as its structure is known. Otherwise, the second possibility consisting of making a FMEA analysis on the CS. FMEA allows to highlight the potential critical part of the system, their main degradation modes and failures and their criticism. Thus, the criticism is calculated on the basis of the manufacturer's technical documentation (TD), as well as the experience and expertise of the engineers in charge. FMEA is most useful tool when the system is unknown, and the data are not available.

Finally, whatever the path taken, the final result is to build a fault tree that will show the critical components and their main failure identified using the above-mentioned tools. So, knowing the main failure of critical components, we can monitor the variables that best characterize the degradation of the system. They will be the inputs of the next approach, which is PHM.

4.2. Prognostic and Health Management (PHM)

This section aims at estimating the SoH of each identified critical components from the CBM approach, as explained above. PHM approach is therefore classified into three types, model-based, data-driven and hybrid approach. Depending on the type of system (i.e., complex, or simple), the ability to model degradation, type of degradation (i.e., progressive, or sudden), acceptable uncertainties and available data, the selection of the appropriate PHM approach has been proposed. Indeed, depending on the failure of the critical component from the CBM approach, the choice of the appropriate PHM approach is required.

The model-based approach is chosen when the degradation of a component can be physically modeled. Better known as Physics of Failure (PoF), it is an approach based on modelling the physical degradation of the system [13]. It is mainly based on the experience and knowledge of experts. It uses product lifecycle load conditions, failure modes, failure mechanisms and some product information (such as composition, material properties, relationships between components) to assess the reliability of the product [11]. Its implementation can be based on Failure Modes, Mechanisms and Effects Analysis (FMMEA), as it is used to identify potential failure modes and high priority failure mechanisms, in addition to determining the causes and effects of failures as FMEA does. Within this perspective, the PoF implementation approach developed here is based on FMMEA. Then, based on certain information on the CS like its compositions, properties, lifecycle load conditions and experts advices, a FMMEA table is constructed as the example shown on Table 1 [24], [25].

It also provides the relevant parameters (loads) that need to be monitored. For example, in the FMMEA example in Table 1, the relevant load for the pump controller is temperature. For each load of each component, a physical model is selected to calculate the damage and then estimate the SoH. Still in FMMEA example, the physical model that could be applied for the pump controller case is the nonlinear or power law model (Coffin - Manson).

Table 1. Example of FMMEA table for a fuel delivery system [24]

Components	Function	Fault	Causes	Mechanism
Pump controller	Regulate signal	Short circuit	High temperature	Thermal degradation
Fuel Tank	Provide Liquid	Partial crack	Contamination	Corrosion

Unlike the model-based approach, the data-driven approach is recommended when the degradation of a component cannot be physically modeled. It can only be used if historical sensor operating data are available. Data-driven approach mainly consists in training a model on data with ML methods in order to predict the degradation behavior of the system in the near future before the failure occurs.

The application of the data-driven approach is based on the use of history HI data. These data are divided into two main types: on the one hand, the variables, which represent the records of the sensor signal, and on the other hand, the target, which is what we want to estimate. In this paper, the target is the SoH levels for different CE scenarios.

There are several steps to implementing the data-driven approach. Then, the first step consists to identify the most relevant variables. This variable selection step could rely on the result of the fault tree carried out in the CBM approach and which provides the failures and their causes for each component. Thus, the parameters that can measure the cause of the failure could be the relevant variables. Nevertheless, it is recommended to use other methods such as particle filter algorithm, wrapper selection to find the correlation between these variables and the target. The second step is about performed the signal processing in order to get residual reliable signal using data analysis methods such as using Empirical Mode Decomposition (EMD) [3], Fourier method or Linear Rectification Technique (LRT) [18]. Then, features or HIs are extracted in the third step from the relevant variables (those that best describe the system degradation). Many methods have already been used, such as the Root Mean Square (RMS) used by Ahmad et al. [18], or Hilbert Huang Transform (HHT) used by Soualhi et al. [3]. In the case of this paper, four HIs were considered, namely the slope, the intercept of the curve fit, the mean, and the variance. They have already been used by Mosallam et al. [4] to estimate the RUL of a lithium-ion battery (LIB) and a turbofan engine. In addition, these HIs can be extracted from any existing signal. That is why they are proposed here. Then, the next step is to train many ML models in order to keep the one with the best score or the minimum error. A ML model is an algorithm that learns the degradation

behavior of a system from history HI data and predicts the future behavior of the same system with the current real-time HI data. Finally, the processing of online and real-time data is similar the one of offline data, it consists of three steps (variables selection, then signal processing and then HI extraction) and uses pretty much the same methods. A selected model is trained with the historical HI data and then it is used on the online data to estimate the component SoH.

However, data-driven approach is data-depending and because of that, it could be limited with the lack of data or the lack of reliable data. And it is less accurate than the model-based approach. That is why model-based approach is most recommended for the RUL estimation. But its implementation remains complex and costly. Even more so in the case of a CS, it might be extremely complicated, if not impossible, to model the physical degradation of system. To overcome the gaps related to the application of one of the two previous approaches alone, we have proposed to use the two approaches in a complementary. It means, record data of the components we have to apply data-driven approach and model the physical degradation of those for which we cannot obtain data using model-based approach. Thus, we recommend using a data-driven approach for critical components for which we have sensor data and using a model-based approach for others.

4.3. Decision-making strategy

The main objective is to optimize the CE scenario of the components based on the knowledge of their SoH, keeping as much value as possible in the manufactured product. In fact, if the SoH estimation gives a result between 0.8 and 1, it means that the component is still healthy, and that it is in the mature phase of its life. It can therefore be repaired or reused in case of failure. But, if the SoH is between 0.6 and 0.8, three scenarios are possible. The first is that the component is reassigned if it can be used for another application. This is the case for example of LIB battery for electric vehicles (EV). When its capacity reaches 80%, it can be repurposed in less demanding application (energy storage or less power-intensive mobility applications). Of course, if the capacity alone reflects the SoH of the LIB. The second scenario is remanufacturing or refurbishing if the component in question is re-manufacturable. But if the component is not reusable, it is recyclable. Or in the worst case, the component is thrown away.

This decision strategy is based on only one indicator, the SoH of the component. But it could take into account other indicators such as environmental (environmental impact assessment), economic (cost price), social (job creation potential), marketing (market needs). But also, the legislation, the companies, the market.

5. Illustrative case

In this section, the implementation of the general framework is showed for the case of an electric scooter motor. This application is part of Smart 2020 project and relies on the Progress 4.0 platform of the University of Lorraine, which studies the challenges raised by Industry 4.0 concept. The objective of this platform is to disassemble the product to the optimal level of decomposition. This optimization of the decomposition level is defined according to the SoH of the product to be regenerated. The principle is then to estimate the SoH of the product and to make a decision on its future. It is either stored because it has a good SoH, or disassembled into different components. Then, the SoH of each of its components is estimated before a decision is finally made.

Thus, to evaluate the SoH, the method proposed in this paper was used. Because of the unavailability of engine operation data, the FMEA tool was used to identify the main failures and their causes. Then, the PHM approach was applied to the whole engine and depending on the result, the engine must be either decomposed to evaluate the SoH of its components, or simply stored. Since the data is missing, the PoF-based PHM approach can be applied, which requires the integration of experts. Its application consists of identifying potential failure modes and high priority failure mechanisms, namely power degradation in the case of the engine. Then, the relevant parameters, called health indicators, related to this power degradation are determined. Finally, the appropriate analytical model for estimating the SoH is selected. However, this model needs the vibration sensor data as the relevant parameters. Finally, the vibration sensor data must be recorded in order to evaluate the SoH result with the chosen Basquin model according to the experts. During these tasks, experts in the engine field are integrated in order to provide their experience and knowledge about the identification of relevant health indicator and model for estimation of SoH.

6. Conclusion

The method proposed in this paper is a solution to optimize the process of orienting the components of a complex system to the appropriate CE scenario while keeping the maximum value put into the manufactured product. Thus, this proposal is a set of three approaches, the CBM that allows to identify the critical components of a complex system, the PHM that allows to estimate the SoH of these components and a decision support strategy for the orientation of these components to the CE scenarios. The added value of this work will be the time saving in the orientation towards the circular economy processes, the conservation of the maximum value put into the manufactured products and an optimization of the design stage, because in this case, for instance it will be possible to design with the aim of being able to remanufacture a component of a product after a certain threshold of use. Moreover, it can be combined with several tools of the industry 4.0 concept like IoT, Big data for better monitoring and prognostic performance. Finally, this work presents points that could be deepened such as the question on the reliability of the data recorded by the sensors, the methodology of choosing the appropriate machine learning model for the data collected in the framework of the data-based approach. Another perspective to this work is conduct a study on a product with the use of operating data of its different parts enabling to determine the SoH of its components. This could be an opportunity to fully test the decision method approach proposed and bring constructive methodological and practical insights about its use within the implementation of circular economy scenarios.

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8.3. Conference Article 3: Characterization of the State of Health of Electronic Devices for Fostering Safety and Circular Economy

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Characterization of the State of Health of Electronic Devices for Fostering Safety and Circular Economy

Christian Wandji, Andreas Riel(✉), Helmi Ben Rejeb, and Peggy Zwolinski

Grenoble Alpes University, CNRS, Grenoble INP, G-SCOP, 46 Avenue Félix Viallet, 38000 Grenoble, France
{christian-wandji.wouapi,andreas.riel}@grenoble-inp.fr

Abstract. Inspired by the concept of the health of the human body, the state of health (SoH) determination of products has been gaining importance for preventive maintenance and product lifetime extension. In electronics, Remaining Useful Life (RUL) estimates often focus on temperature as the key ageing parameter. They neglect other influential factors such as humidity and vibration. This article proposes a method for determining product SoH which combines the analysis methods FMMEA and Fault Tree Analysis (FTA) for a more relevant identification of the causes and reasons of failures. The proposed method allows the estimation of SoH based on several health indicators and hence takes into consideration several factors of product degradation. The product's SoH is obtained by aggregating the SoH derived from each single ageing factor through the use of multi-criteria techniques, such as Analytic Hierarchy Process (AHP) and weighted sum methods. The article discusses this method's potential and limitations based on insights gained from its initial application to a consumer product.

Keywords: State of health (SoH) · Electronic device · Failure Mode, Mechanism and Effect Analysis (FMMEA) · Fault Tree Analysis (FTA) · Physic of Failures (PoF) · Prognostic and Health Management (PHM)

1 Introduction

Nowadays, due to the automation of systems and industry for the transition to Industry 4.0, electronics has become an essential part of everyday life [1]. They have been used in many devices and in many applications. As a logical consequence, large numbers of devices mean large numbers of waste that negatively impact the environment. According to the Global E-waste Monitor 2020 report, the world generated 53.6 million metric tons of Waste electronic and Electrical Equipment (WEEE) in 2019. So, an increase in e-waste of about 20% in just 5 years since 2014, and it will probably reach 74.7 million metric tons by 2030 [1]. Many researchers are challenging this serious problem today. Moreover, apart from the environmental impact that e-waste could produce; electronic plays a vital role in the functioning of devices. Designers and developers of electronic technologies have continuously improved their performance to enhance their reliability and their longevity.

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From the perspective of functional safety standards such as the IEC 61,508 [2] and the ISO 26262 [3], the likelihood of failure of electronic components is characterized by FIT (Failure in Time) rates. These are statistically calculated static figures, which not consider the actual ageing of electronic components in their real use [4]. This hinders circular economy models to be deployed in safety critical products, since the FIT rates only apply to newly fabricated components.

This paper proposes a new method for determining the State of Health (SoH) of electronic devices based on the tools of Fault Tree Analysis (FTA), Failure Mode, Mechanism and Effect Analysis (FMMEA) and Analytic Hierarchy Process (AHP). Moreover, we will also consider the aspect of operational safety because of the important functional value that an electronic device has in the proper functioning of any device. This new method is based on general framework for determining the state of health of complex devices published in the literature, and is focused on the model-based part of the framework. It has been adapted to be effective in the context of electronic devices.

This paper is divided into 6 sections. We will present the state of the art in Sect. 2. Then in Sect. 3, we will present the research question and methodology that led us to the electronic device SoH determination solution proposed in this paper. Then, in Sect. 4, we will develop the proposed SoH determination method. This work will be discussed in Sect. 5. Finally, we will conclude in Sect. 6.

2 State of the Art

For years, product life extension has been at the heart of many scientific investigations. This started in maintenance with the creation of numerous methods of product diagnosis to understand the reasons for product failures [5]. The objective is to increase the availability of the machines for an optimal production. Therefore, this need for availability for production will favor the passage from diagnosis to prediction [6] with methods of stochastic reliability calculation. And today we talk about prognosis to anticipate a failure with more precision not only for maintenance, but also for the new concepts of sustainable development, eco-design and circular economy. The Prognostic and Health Management (PHM) approach is one of the most widely used approaches to estimate and predict the Remaining Useful Life (RUL) of a product today. According to Mathew et al. [7], this approach can be classified in three different categories, which will be explained in the following.

The first category is a data-driven approach that applies supervised and unsupervised learning methods on product-related data to estimate RUL and SoH. Many researchers such as Si et al. [8], Bhargava et al. [9] have proposed a synthesis of learning methods related to it. This approach is used in many applications on products such as gearboxes [10], bearings [11, 12], turbo fans [13] and pumping units for aircraft [14].

The second category includes model-based approaches, which gather a large family of techniques, among them the Physics of Failure (PoF). It consists of mathematically modeling product degradation model based on the failure mechanisms that lead to that degradation [15]. Pecht et al. [16] propose a reliability determination method based on the PoF of products, which requires the identification of the failure mechanisms and the calculation of the failure times for each mechanism. They also highlight that four

types of stress, namely mechanical, electrical, thermal or chemical, generally cause a failure of an electronic device. Several applications of this PoF approach in electronics have been realized on DC-DC converters [17] and power modules [18]. This approach is also applied on electrical products [19, 20] and on mechanical products [21–23]. In the same way, Gu et al. proposed an approach to implement PoF based on FMMEA for a more efficient diagnosis of the failure mechanisms that form the basis of this approach [24, 25]. Fan et al. [26] applied this FMMEA-based PoF approach on High Power White Light Emitting Diode Lighting to evaluate its reliability. The PoF approach consists of several steps, one of the most important of which is the identification of the main causes and reasons of failure. This step is crucial in the SoH determination of the products and the FMMEA method is very often used to do this. However, this method relies on the experience, organization and involvement of the members of the working group responsible for applying it. Moreover, it is limited in determining the path that led to a failure. This is also important in identifying the reason for a failure. The literature mentions the possibility of using other analysis tools such as FTA or Event Tree Analysis (ETA) for the same purpose. However, very few articles propose a combination between some of these analysis tools in view of the importance of the step of identification of the main causes and reasons of failure. A combination could be a way to improve the identification step. Moreover, in electronics, most of the researches consider mainly the temperature in the estimation of RUL or the reliability calculation. This is the case of Khan et al. [27] who proposed a new indirect technique to evaluate the reliability of an electronic system during its use phase. This proposal is based on the effects of aging on the range of input voltages and operating temperatures of the system, just like other research mentioning the diagnosis of the causes and mechanisms of failures [28–31]. Chauhan et al. [32] demonstrated that temperature is a very important parameter in the evaluation of SoH of electronic components. From their point of view, solder interconnections are obvious parts of the degradation of electronic components. Therefore, monitoring the temperature at these interconnections would be useful for determining their condition and then determining the SoH of the component. However, we believe that taking into account other factors such as humidity, vibration, voltage and others in addition to temperature could lead to a better reflection of the health of the electronic device. So that is where our work comes in. First, it will improve the identification of the causes and reasons of critical failures by combining several methods of risk analysis of failures. Also, it will allow taking into account several factors, which will be identified as the most descriptive of the pre-identified critical failures.

The third approach for the RUL estimation called the hybrid approach and consists of a combination of data-driven and model-based approaches to avoid the shortcomings related to the use of one of the approaches alone.

3 Research Question and Methodology

The literature review showed some limitations in the existing methods of determining the SoH of electronic devices for fostering safety and circular economy. Many of them consider temperature as the only critical parameter and use an inductive FMMEA approach to identify the main causes of failures. The research question that emerges from

this review can be formulated as follows: *How can the SoH of an electronic device be determined in a way that leverages circular economy*?

To answer to this question, we propose method specific to electronic devices because the aging or degradation of electronic devices is very different from mechanical, electrical and other devices. In electronics, there is no visually observable crack or degradation. So, our evaluation proposal should take into consideration electronic devices specifications. It is based on the general framework method for determining the SoH of complex systems developed by Wandji et al. [33], and supplements it with application to the electronic sector and uses a multi-criteria approach. This general framework method is divided into three main parts: a Condition-Based Maintenance approach (CBM) consisting in identifying the critical components of a system and their main failures. A PHM consisting in determining the SoH based on the critical components of the system and a decision-making strategy for the optimal orientation of the systems towards the appropriate circular processes. The Fig. 1 shows these three main parts. The CBM and PHM approaches are applicable to systems either based on usage data of the system concerned or based on its model. Thus, the data-driven approach has been well-explained [33], but the model-based approach has not yet been well addressed in the literature. Therefore, we have applied the model-based part to the electronic device in this paper. Moreover, according to many researchers, the issue of reliability of electronic devices should be applied to the design stage of the device. Following this recommendation from the literature, we propose a method that will allow combining the experience of experts to define important parameters of the degradation or aging of electronic devices at the design stage and the data recorded due to the monitoring of these parameters. This method is the combination of FTA and FMMEA analysis tools within a model-based PHM approach. This method is about to be applied to an electric/electronic consumers product.

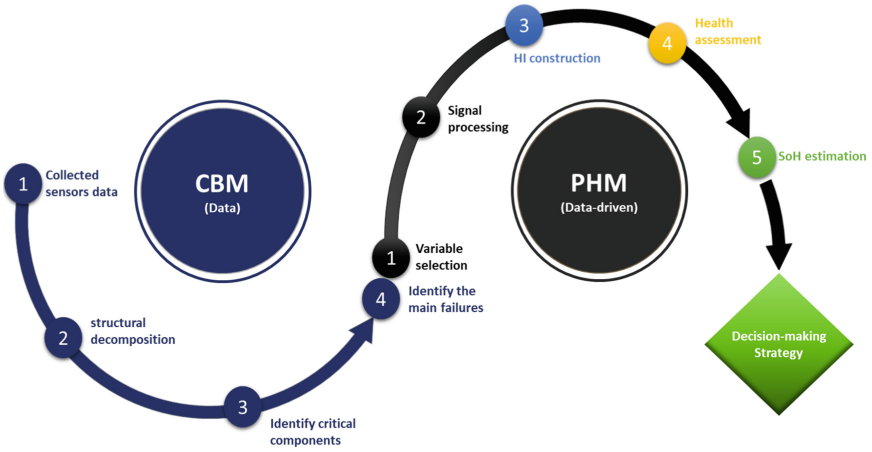

Fig. 1. General framework from [33]

4 Development of the Concept

This work aims to extend the life of electronic devices while ensuring their functional safety. Thus, from our point of view, the determination of the SoH is one of the key elements to globally describe the aging of these devices. Because the SoH takes into account several factors, those that most influence the degradation of the device. Especially, according to most researchers, the aging or degradation of electronic devices is very often due to several factors (physical parameters) such as temperature, vibration, humidity, pressure and dust [9].

The question is to be able to consider all the most important factors of electronic device aging in the evaluation for a reliable SoH score. To do so, it is necessary to be able to identify them, especially since they may not be the same from one electronic device to another. This is the reason why we propose to apply the FMMEA method to identify the main failures, their main causes and failure mechanism, as well as their criticality. Then to apply the FTA method only on the critical failures previously identified to first confirm and/or complete the causes of failures identified with the FMMEA, but also to determine the critical path leading to these failures. The comparative results of these two tools will allow defining the parameters strongly linked to each cause of failure. These will be monitored and the recorded data will be used to calculate the SoH of the electronic device. Figure 2 illustrates the overall method of determining the SoH of electronic devices based on the FTA, FMMEA tools, failure model and AHP method. In the next paragraphs, we will detail the three main steps of the implementation of this method. The first step consists of the identification of the main causes of critical failures. The second consists of the determination of important parameters and their corresponding computational models. Finally, the third step consists of the use of method AHP and weighted addition.

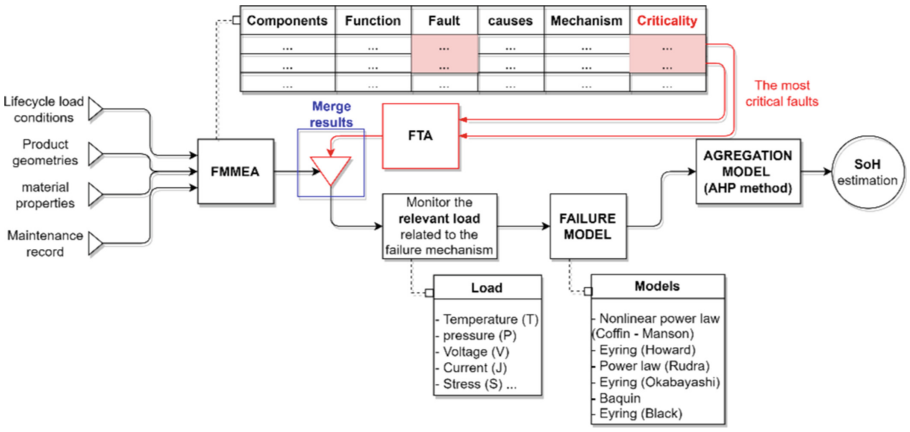

Fig. 2. Method of determining the SoH of an electronic device based on the FTA and FMMEA analysis tools

4.1 Identification of the Main Causes of Failures

Failure diagnosis is a process initiated in maintenance to understand the reason for a failure in order to reduce or even avoid the risks of failure. Many tools are used to do this, FMMEA and FTA are among the most used and they are vital to reduce the risk of system failure. Although leading to the same results, these tools are different and from our point of view, they can be used in a complementary way. To assess the SoH of an electronic device, we base our approach on the causes and mechanisms of its main failures. This is why it is important not to make mistakes when identifying the causes of failures. Thus, we propose to use the FTA and the FMMEA in a complementary way as illustrated in Fig. 2.

FMMEA is a variant of FMEA, which is used to identify failure modes, their causes and mechanisms. Based on the product composition, material properties, product life cycle conditions and additional product information (such as maintenance history and description), an FMMEA table is constructed as shown in the Table 1 [24, 34].

Table 1. Example of FMMEA table for a fuel delivery system [34]

Components	function	Fault	Rank severity	Causes	Rank occurrence	Mechanism	Rank detection	Criticality
…	…	…	…	…	…	…	…	…
Pump controller	Regulate signal	Short circuit	4	High temperature	2	Thermal degradation	2	16
Fuel tank	Provide liquid	Partial crack	2	Contamination	1	Corrosion	2	4
…	…	…	…	…	…	…	…	…

The FMMEA analysis also allows highlighting the most critical failures through its criticality calculation, which is the multiplication of the gravity by the frequency and the detection. These three criteria are quantified according to a ranking from 1 to 5 for each one: In the case of severity, 1 represents the least serious failure and 5 the most serious. Within the framework of the frequency, 1 represents the rarest failure and 5 the most regular. In the framework of the detection, 1 represents the easiest failure to detect and 5 the undetectable one.

Finally, on this basis, a failure will be considered as critical when its criticality value is higher than the limit of the criticality threshold defined by the working group or the FMMEA experts.

Next, FTA is applied to each critical failure to identify the main cause and the critical path leading to it. FTA is a top-down approach that identifies the potential source of a failure in order to avoid it. It is graphically presented as a tree that consists of gates, events and remark elements. Moreover, each tree can contain sub-trees, which are referenced in the main tree by means of “transfer” gates. Figure 3 shows an example of an FTA diagram extract from [35]. Rectangles in this figure represent events, which correspond to possible failures. Gates represent logical combinations of such failures. Circles represent the failures rates of the components. Finally, the numbers next to the gates represent the

failures rates calculated from those of individuals components depending on the gate types (OR, AND).

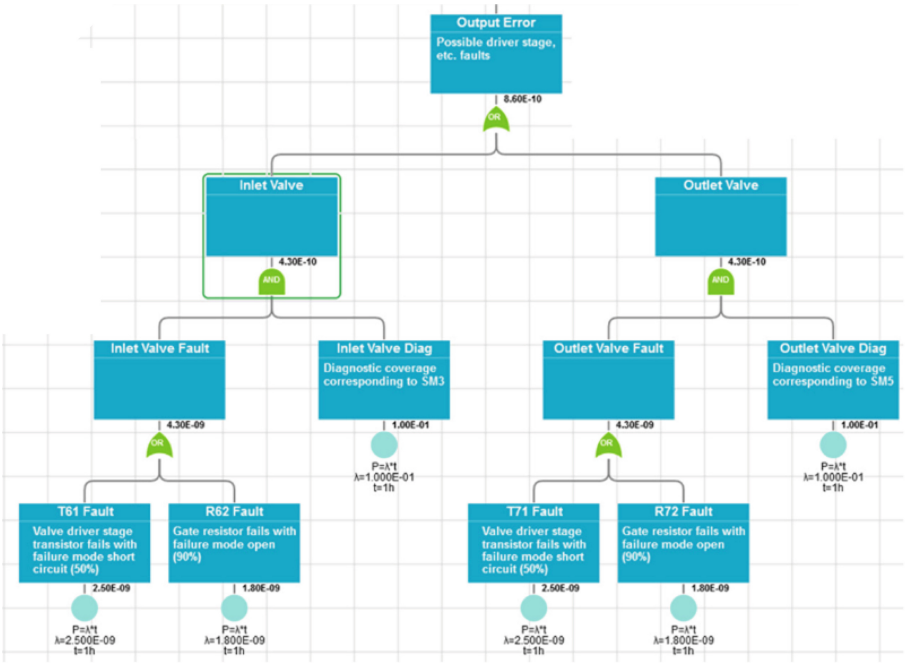

Fig. 3. Example of FTA diagram extract from [35]

FTA allows identifying the main causes of a critical failure, to quantify the probability of occurrence of this failure as well as the critical path leading to its occurrence. This makes it possible to compare these results with those of the FMMEA in order to draw up a list of the main causes of failure to be monitored.

4.2 Determination of Parameters and Their Computational Models

The choice of physical parameters to measure to monitor the degradation or aging of an electronic device depends strongly on the causes of failure, their mechanisms and the critical path to access them. For that, it will be necessary once again to rely on the experience and the synthesis spirit of the experts to choose the physical parameter corresponding to a failure cause and its mechanism. For each cause previously identified, an important parameter must be assigned for the calculation of the corresponding damage. In the same scope, the damage calculation is done based on mathematical model specific to the chosen physical parameters. Table 2 shows the correspondence between some physical parameters and their damage calculation models, which consequently reflects the SoH of the electronic device according to the physical parameter concerned. The physical model of damage calculation corresponding to the temperature parameter is the non-linear power law, but it could also be the Eyring model.

These physical models make it possible to calculate the damage linked to a physical parameter, which thus translates the SoH by inversely because when the damage increases, the SoH decreases.

Table 2. Physical model corresponding to the relevant load [36] related to critical failure

Fault	Causes	Mechanism	Criticality	Relevant load	Models
…	…	…	…	…	…
Short circuit	High temperature	Thermal degradation	16	Temperature (T)	Nonlinear power law (Coffin – Manson)
Partial Crack	Contamination	Corrosion	4	Moisture (M), Voltage (ΔV), Temperature (T)	Eyring (Howard)
…	…	…	…	…	…

4.3 Weighting of the State of Health

In this part, it is about assigning a weight to each SoH value found which corresponds to the different physical parameters chosen previously. In this document, the aim is to evaluate the SoH of an electronic device by taking into account several important factors of its aging or degradation. Thus, after calculating the states of health (SoHi) related to each parameter i, the weighted addition method is applied to calculate the SoH of the states of health (SoHi) related to each physical parameter i previously defined. The formula (1) illustrates this weighted addition.

$$SOH = \alpha * SoH_{Temperature} + \beta * SoH_{Humidity} + \gamma * SoH_{Vibration} + \ldots \quad (1)$$

The weights (α, β, γ …) of each SoH are chosen using the AHP method based on the experience of electronics experts and the literature. The AHP is a multi-criteria decision-aid method based on a hierarchical system of ranking different criteria against each other based on importance. It consists of four steps:

1. Identify criteria that are critical physics parameter (temperature, humidity, vibration …) in our case.
2. Conduct pairwise comparison using the Saaty scale [37]. This comparison is based on the judgments of importance of each critical parameter, which are determined by the electronics experts.
3. Calculate the weight of each physics parameter.
4. Identify the best option by calculating something called utility, i.e., a numerical representation of how useful or beneficial something is to you.

For more details on the above steps, Li et al. [38] provide a complete and detailed explanation of the application of the AHP method with a short case study.

5 Discussion

The objective of this paper is to estimate the SoH of an electronic device in order to make it live through the circular economy. To achieve this goal, we have used existing tools such as FMMEA, FTA, and AHP whose effectiveness and implementation have already been proven. The combination of well-established tools based on the physics of failures in a comprehensive approach is our main contributions. The main challenges in implementing this approach lie in the combination between the FMMEA and FTA tools. Because, FMMEA is an inductive analysis while FTA is Deductive. Moreover, the application of these two tools in a complementary way can be time consuming. The method proposed in this paper also consists in aggregating the SoH of the different critical parameters using the AHP method to obtain the final SoH score. The application of this method is highly depended on the experience of electronics experts, which can be a considerable limitation. Finally, another big challenge is the availability and accessibility of data of the electronic device. We are currently in the process of applying our method to an electronic consumer product, and we will derive and publish quantifiable insights from this.

6 Conclusion

Electronics is a sensitive field and more and more indispensable nowadays with the advent of industry 4.0. It is therefore important to ensure the functional safety and circularity of electronic devices to reduce the number of electronic waste in exponential growth. This reduction of electronic waste passes by the follow-up of their SoH, which is not always easy because the degradation or the ageing of these devices is very often due to several factors related to its environment, which are external to it. Previous studies have used the PoF approach based on FMMEA for SoH evaluation and only with temperature as an important aging parameter. To improve the evaluation of SoH and to overcome the limitations of previous methods related to the application of FMMEA and the consideration of a single aging factor, we have proposed in this paper a novel approach. It consists of using AHP and Sum weighted methods in the SoH determination by combining FMMEA and FTA analyses and considering several factors of degradation or aging at the same time. This work has a novel value for the circular economy, sustainable development and the environment as it is a real decision support for the life extension of electronic devices. The next work will be to apply this proposal to some electronic products and to compare the results with existing methods. Moreover, it will be used to support the decision-making strategy for circular economy optimization. However, it could still be improved by combining this approach with artificial intelligence, supervised and unsupervised learning prediction methods in a hybrid PHM approach. Also in terms of data collection which could be done online using RFID (Radio Frequency Identification) or IoT (Internet of Things) technology for example. And much more, it

could be improved by taking into account the impacts of its industrial implementation on the environment.

Relationship with the SPI Manifesto
Digital, electronics- and software-controlled systems are at the very core of the long, successful EuroAsiaSPI^2 history. This works contributes to putting the community in the new Circular Economy context.

The SPI manifesto defines the values and principles required to deploy SPI efficiently and effectively [39]. The principle "**Use dynamic and adaptable models as needed**" means that models we use for designing and evaluating our product, services, processes, and underlying organizations need to be continuously adapted to the dynamically changing economic, ecologic, and social context.

Glossary

AHP	Analytic Hierarchy Process
CBM	Condition-Based Maintenance
ETA	Event Tree Analysis
FIT	Failure-in-Time
FMEA	Failure Mode and Effect Analysis
FMMEA	Failure Mode, Mechanism and Effect Analysis
FTA	Fault Tree Analysis
IoT	Internet of Things
PHM	Prognostic and Health Management
PoF	Physic of Failures
RFID	Radio Frequency Identification

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8.4. Conference Article 4: Leveraging circularity through repair standards: A comparison of methods for assessing product reparability for extended use on mechanical products.

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Leveraging circularity through repair standards: A comparison of methods for assessing product reparability for extended use on mechanical products.

Christian Wandji[a,]*, Helmi Ben Rejeb[a], Andreas Riel[a], Peggy Zwolinski[a], Cyrille Dalla Zuanna[b]

[a]*Grenoble Alpes University, CNRS, Grenoble INP, G-SCOP, 46 Avenue Felix Viallet, 38000 Grenoble, France*
[b]*Technical Center for Mechanical Industries (CETIM), 7 rue de la presse, 42952 Saint Etienne, France*

* Corresponding author. *E-mail address:* christian-wandji.wouapi@grenoble-inp.fr

Abstract

The EN 45554 standard deals with the assessment of Reparability, Reusability and Upgradability of Energy-related Products, and aims to extend the life of those kind of products. According to the 2021 report of the French Agency for Ecological Transition (ADEME), 83% of French people are concerned about the environment. This means a growing interest for repair. In addition, consumers want products that are increasingly reparable. Therefore, knowing the reparability score of any type of products has become crucial, but this standard only applies to products that consume energy during use. Hence, there is a need to extend reparability to a wider range of products, including mechanical and mechatronic products. To achieve this main objective, one important step of comparison of existing methods is necessary. This paper aims to compare the EN 45554 standard to the existing methods in the literature for assessing reparability. First, a literature review is conducted to identify existing methods for reparability. Then, a comparison study is performed. Finally, based on this comparison, a set of criteria is obtained as an outcome.

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Keywords: Reparability; Circular Economy; EN 45554 standard; Energy-related Product; Mechanical product

1. Introduction

The ecological transition is a shift in our thinking towards sustainable thinking. The circular economy, which is one way to make products sustainable, contributes to this transition. To support this circular economy concept, the standard EN 45554 has been established under recommendations from the European Commission and the European Free Trade Association. This standard aims to assess the ability of an Energy-related Product (ErP) to be reused, repaired or upgraded [1]. Nowadays, reparability has become a sort of mindset whose relevance is increasingly confirmed. In fact, according to the French agency for ecological transition ADEME 2021 report, 83% of French people are concerned about the environment [2]. Therefore, they have a good feeling about the concept of repair, since they prefer to buy a product with a high reparability index. This shows a growing interest in repair. Knowing a score reparability of the product is a key element to ensure service availability and quality. But the EN 45554 and several other methods for assessing reparability only apply to ErP or EEE (Electrical and Electronic Equipment). This is why the reparability of non-ErP should also be addressed. Furthermore, in the context of Industrial Product-Service Systems, controlling product availability has become a key challenge for

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design and operation [3]. So, the extension of the EN 45554 standard to mechanical and mechatronic products is necessary to improve the reparability of a wider range of products that getting increasingly circular. However, many methods have been developed in order to study the reparability. It is crucial to compare these methods to determine their strengths, weaknesses, and overall effectiveness in promoting sustainable product design and circular economy principles. This comparative study is the main goal of this paper.

This article is structured as follows: in section 2, the research methodology is described. The results of the overall comparison study between methods for reparability assessment are presented in section 3. The discussion of these results is presented in section 4. Finally, section 5 concludes this paper through a summary and future research work.

Nomenclature

ADEME	French Agency for Ecological Transition
AGEC	French law against waste and for Circular Economy
AsMer	Assessment Matrix for ease of repair
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
EEE	Electrical and Electronic Equipment
ErP	Energy-related Product
JRC	Joint Research Centre
JTC	Joint Technical Committee
RSS	Repair Scoring System

2. Methodology

A methodology was defined to compare existing methods for assessing product reparability with that of the EN 45554. This methodology consists of the following three steps:

- Study of the EN 45554 standard by extracting its requirements and formalizing its fundamental principles.
- Identification of existing methods in the literature from papers that either propose methods similar to the one of the standard or directly use the method described in the standard to assess the reparability of mechanical products.
- Analysis of selected methods by identifying similarities and differences between them and the standard.

3. Results of the comparative study

3.1. Study of the EN 45554 standard principles

The French standard EN 45554 entitled “General methods for the assessment of the ability to repair, reuse and upgrade Energy-related Products” has been prepared by CEN/ CENELEC/JTC 10 in 2020, and it refers to some international standards [1]. EN 45554 elaborates a method and criteria for assessing the ability of parts or products to be reused, repaired or upgraded. It also presents two additional methods as example. The principle of this reparability assessment method is resumed in Fig.1 below.

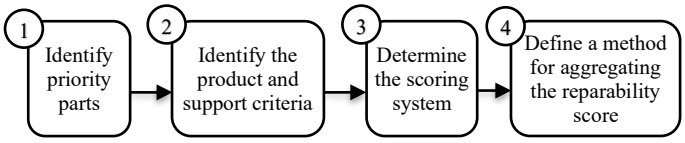

Fig. 1. Principle of the assessment method elaborated in the EN 45554 standard for ErP.

The first step of the standard principle is the identification of the priority part, because on a product, there are parts that do not need to be included in the evaluation to avoid long calculation time. It is therefore important to prioritize the parts of the product. A priority part is determined by these two points:

- The probability of its failure: parts with a high average level of failure are considered with high priority;
- Its function in the product: the parts that have or contribute to primary and secondary functions are concerned with priority.

The second step consists in identifying the product-related and support-related criteria and their applicable categories for the evaluation of each priority part. The product-related criteria are: Disassembly depth, Fasteners and connectors, Skill level, Tools, Working environment and Diagnostic support and interfaces. The support-related criteria are: Availability of spare parts, Types and availability of information, return models for repair, Data transfer and deletion and Password reset and recovery of factory settings. It is up to the user of the EN 45554 standard to define the relevant criteria to be selected for their product category.

The third step of this standard principle is the determination of the scoring system. Here, an alphanumeric value is given to each identified criterion and then replaced by a numeric value to calculate the reparability index score.

Finally, in the fourth step, an aggregation formula is used to calculate the score of reparability using a weighted system. Each criterion can be combined with a weight to form a factor that is used in this formula.

3.2. Identification of existing methods for assessing reparability.

The objective in this section was to find papers, reports or scientific research that propose a method for assessing reparability, and that have some similarities with the method described by the standard. The literature has been investigated using the Web of Science, IEEE Xplore (Institute of Electrical and Electronics) and Google Scholar databases. Over 534 articles were found with the word "repairability", and 470 articles with the word "reparability". The number of articles was then reduced by successively using keywords such as "evaluation", "determination", "assessment", "case study", "products", "score", "index". The number of articles obtained by successively adding each keyword was also sorted according to “relevance” and “number of citations”. After this systematic research, 12 papers and 2 scientific reports were found. Once these documents had been fully read, 7 articles and

2 reports were selected. They have been selected because they offer comprehensive methods for assessing reparability of EEE with example of applications. In this literature review, we did not find any papers that addressed the assessment of reparability for non-ErP. In the following, we will give short overview of the 9 selected methods. Wiens and Soules created in 2003 a repair assistance website called i-Fixit [4]. This website shows the steps to repair several EEE. For a few years now, it has been displaying the EEE reparability score obtained by the i-Fixit reparability scorecard. It therefore calculates the repair score based on a checklist of 15 criteria. The i-Fixit reparability scorecard has been applied on several EEE, such as smartphones, smartwatches, tablets, laptops and others EEE. In 2014, an Austrian standard that describes a method for assessing reparability of white and brown goods has been created. It is the ONR 192102 standard [5] which is also based on a set of criteria. It has 40 criteria for white goods (refrigerators, washing machines). It has also 53 criteria for brown goods (televisions and media players. Flipsen et al. [6] proposed a 20-criteria reparability method for electronic products based on the i-Fixit Reparability Scorecard method. They have mentioned three categories of tools which define the reparability. There is a first category of tools for measuring data, a second category for ease of disassembly and the third category is checklists that are used in the i-Fixit Reparability Scorecard method. Vanegas et al. have developed a method to assess the easy of disassembly (eDIM) in a technical JRC report in 2016 [7]. Pamminger et al. [8] developed a re-design process of a digital voice recorder in order to foster the reparability. To do so, they define a reparability analysis named Reparability Assessment Method (RAM) in collaboration with i-Fixit. This RAM is based on 6 evaluation criteria, their evaluation scales, as well as their associated weightings. Cordella et al. [9] presented a comprehensive framework for assessing the reparability and the upgradability of an ErP taking into account its environmental impact. This approach includes three levels of evaluation: qualitative based on a checklist, semi-qualitative based on parameters and quantitative based on technical and environmental criteria. In a KU Leuven Report, Bracquené et al. [10] presented a methodology for assessing reparability based on three types of criteria on information, design and service throughout the repair process. This methodology, named Assessment Matrix for ease of repair (AsMer), has 24 criteria. It has been applied on washing machines and vacuum cleaners. Another JRC technical report on the Repair Scoring System (RSS) was proposed by Cordella et al. in 2019 [11]. It is also based on 15 criteria and a weighting system. In 2020, in anticipation of the European program on ecological transition, the AGEC law [12] was voted in France and applied by virtue of article 16-I of the law n° 2020-105 against waste and for the circular economy. It aims to encourage the reuse, repair and recycling of products and industrial waste. It therefore proposes a method for assessing the reparability of several categories of EEE. An implementation of this method is available online for free in the form of an Excel grid [13]. EEE designers are required to post their reparability scores for the following products: smartphones, laptops, televisions, lawn mowers, washing machines, dishwashers, vacuum cleaners and pressure washers.

With regard to all these methods found, there are common points and divergences which are presented in the following section.

3.3. Cross-analysis of the selected methods.

In this section, a comparison between selected methods found is carried out, based on EN 45554. Among the 9 methods identified in the literature, some have similarities such the 20-criteria reparability method [6] and Reparability Assessment Method [8] that are based on the i-Fixit Reparability Scorecard [4]. After a process of inclusion and merging, such as including the easy of disassembly method [7] in the Assessment Matrix for ease of repair methodology [10], 4 quantitative reparability analysis documents have been finally selected: the i-Fixit reparability method [4], the Repair Scoring System (RSS) from European Commission [11], the Assessment Matrix for ease of repair (AsMer) [10] and the AGEC law in France [12].

The first comparison concerns the principle of the methods in terms of structure. It is a question of verifying whether the research methods follow the same principle as that of the standard presented in subsection 3.1. This comparison is summarized in Table 1.

Table 1. Comparison of the structure based on the EN 45554 principles

EN 45554 principle	i-Fixit	AsMer	RSS	AGEC law
Priority part definition		x	x	x
Method based on criteria	x	x	x	x
Use of a scoring system	x	x	x	x
Use of a weighting system			x	
Final score obtained by aggregation	x	x	x	x

The second point of comparison goes deeper into the principles, in terms of content. These details are illustrated in Table 2. In this point, some details are highlighted about the differences between these methods. In this table, the number of criteria, their scoring system, the weighting of the criteria as well as the weighting of the priority part and the method of calculating the aggregation of each selected method are identified and summarized.

Table 2. Comprehensive comparison

	EN 45554	i-Fixit	AsMer	RSS	AGEC law
Number of criteria	11	20	24	15	12
Range of criteria scoring system	0 to 1	1; 2 or 3	0; 2; 5 or 10	0 to 1	0 to 13
Criteria weighting	Defined	1	1	1 or 2	1
Priority part weighting	-	-	-	1 or 3	-
Aggregation calculation method	Weighted sum	Sum divided by 4	-	Sum divided by total weight	Sum divided by 10

The third point of comparison concerns the criteria used in each assessment methods. First, each of the selected methods has different criteria, they are listed in Appendix A. The cross-

analysis of the lists of criteria has made it possible to highlight common criteria, which can be merged, and others that are singular and specific to a certain method This cross-analysis has resulted in a set of 39 criteria that is not yet exhaustive. This set of criteria is presented in Table 3 below.

Table 3. Summary list of the condensed criteria of the selected methods.

N°	Criteria	EN 45554	i-Fixit	AsMer	RSS	AGEC law
1	Disassembly depth/sequence	x	x	x	x	x
2	Disassembly time			x	x	
3	Tools	x	x	x	x	x
4	Fasteners	x	x	x	x	x
5	Availability of diagnostic support and interfaces	x	x	x	x	
6	Accessibility of diagnostic support and interfaces			x		
7	Availability of identification support		x	x		
8	Accessibility of identification support		x	x		
9	Availability of technical support for disassembly and reassembly			x		
10	Accessibility of technical support for disassembly and reassembly			x		
11	Technical support for reconditioning - accessibility			x		
12	Working environment	x	x		x	
13	Skill level	x	x		x	
14	Availability of spare parts by target groups	x	x		x	
15	Duration time of spare parts availability	x		x	x	x
16	Delivery time of spart parts					x
17	Interfaces of spare parts	x			x	
18	Price of spare parts		x	x		x
19	Modular design of the product		x	x		
20	Standardized design			x		
21	Supply of spare parts - content			x		
22	Type of information/documentation	x				
23	Availability of information or documentation by target groups	x		x	x	x
24	Duration time of information or documentation availability					x
25	Return options	x			x	
26	Software and firmware				x	
27	Ease of restoring product to working condition after repair				x	
28	Availability of OEM qualified service engineers				x	
29	Password reset and recovery of factory settings				x	
30	Data transfer and deletion				x	
31	Warranty management	x		x		
32	Remote assistance					x
33	Ease of identification		x			
34	Accessibility of identification	x	x			
35	Robustness of identification		x			
36	Product designed for easy failure detection	x	x			
37	Product designed for ease of recovery to working condition after repair		x			
38	Environmental issues at end of life	x				
39	Risk of injury	x				

The last point of comparison concerns their fields of application. All these methods apply to EEE or ErP. The i-Fixit reparability score is applied to smartphones, smartwatches, tablets, laptops, solar powered LED light, and others EEE. The AsMer and RSS are applied to washing machines, vacuum cleaners and laptops. The AGEC law method is applied on smartphones, laptops, televisions, lawnmowers, washing machines, dishwashers, vacuum cleaners and high-pressure cleaners.

4. Discussion

This section consists in discussing the results obtained from the comparison between the existing methods. The literature review conducted in Subsection 3.2 highlighted a major gap in the methods for assessing reparability. It showed that there are no methods to directly assess the reparability of non-ErP, such as mechanical products. Indeed, all the methods found dealt with the reparability of the ErP or EEE. There is a need to extend the reparability to a wider range of products. Addressing this need begins with a comparative study, which is the aim of this paper. Therefore, four levels of comparison have been performed in Subsection 3.3. In the first level summarized in Table 1, the comparison between these methods based on their structure has revealed that only the RSS method uses a weighting system as recommended in EN 45554. However, the definition of priority parts is almost common to all methods, except for the i-Fixit method. All methods found are based on different criteria, use different scoring systems and aggregation calculation to obtain the final reparability score. These remarks can be confirmed in the second level of comparison which is focused on the content of the principle of each method. First, regarding the criteria, it was observed that each method has a different number of criteria. The EN 45554 standard method has 11 criteria, and scores each of them between 0 and 1. It is up to users of this standard to define their own weighting of the criteria. The i-Fixit reparability method has 20 criteria that are scored as 1, 2, or 3 while the AsMer method has 24 criteria scored as 0, 2, 5 or 10. The RSS method has 15 criteria, and the scores for each criterion range from 0 to 1. Therefore, the weights for each of its criteria are set to 1 by default, but can be doubled if the criterion is deemed more important for the product. The AGEC law method has 12 criteria that are each scored between 0 and 13. The criteria weights for the i-Fixit,

AsMer and AGEC law methods are all set to 1. Second, only RSS proposes a weighting system for priority parts. If priority parts are associated with at least 3% of failure rate, the assigned weight equals to 1. But if priority parts are associated with at least 10% of failure rate, then the assigned weight equals to 3. Finally, for all these methods, the final score is obtained by adding all the scores of the criteria and dividing it either by the sum of the weights of the criteria (in the case of the RSS method), or by a fixed value such as 4 in the case of the i-Fixit method, or by 10 in the case of the AGEC law. All these methods have differences in term of principle. But there are some similarities between EN 45554 standard and RSS on the scoring system. But also, between all of them on the criteria weighting. There are also some unclear points in the choice of the number of criteria, but also in their scoring system. According to the standard, the list of criteria can be adapted to different type of ErP. These criteria are also too generic even for ErP. Furthermore, the transition from a qualitative or semi-qualitative rating to a quantitative rating is specific to each method. This transition has not been included in this comparison study. The third level of comparison resulted in a list of 39 criteria from this study. After a cross-sectional comparison of each criterion between the methods, we found that there are some common criteria. These criteria are merged to be counted only once in the criteria list. That is the case for instance of disassembly depth, tools and fasteners criteria. There are criteria specific to a method which are also counted once, such as the criterion “Accessibility of diagnostic support and interfaces”, which is specific to the AsMer method for instance. There are also criteria with quite similar meanings that are merged and counted only once. This is the case for the “warranty problems” criterion of the i-Fixit method and the “commercial guarantee” criterion of the RSS method. They are merged into a criterion named “warranty management” which mainly concerns the number of years of commercial warranty offered. But it also takes into account some related problems linked to the respect of the warranty or not. Finally, there are criteria with sub-criteria that have been developed. For example, “Availability of spare parts” criterion has been divided into “Availability of spare parts by target groups” and “Duration of availability of spare parts” criteria for the case of EN 45554 standard. This list is made by criteria that have an impact on the whole reparability process of products. It will be used in future work as a basis of criteria for the development of a method to assess the reparability of a mechanical product. But the usefulness of these criteria should be checked in that. In the last level of comparison, we can mainly notice that there are no reparability assessment methods for products such as bicycles or bearings. The compared methods mainly have application on products that consume energy during their use phase.

5. Conclusion

The aim of this study was to compare existing methods for assessing reparability between them and with the EN 45554 standard. This research study has highlighted an important gap in the literature regarding methods for assessing reparability. Through the literature review, we found that there are no methods that directly address the reparability of mechanical product. Existing methods are only for ErP or EEE. Following this comparative study between existing methods, we have obtained a set of 39 criteria. This set of criteria could be useful for the development of a method to assess the reparability of a mechanical product. As perspectives for this study, validation study using experts survey could be achieved in order to select the relevant criteria for the case of mechanical products. This study on reparability holds promise for facilitating the development of more sustainable PSS models that prioritize longevity and resource efficiency models by promoting standardization, improving product design, increasing compatibility.

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Appendix A. List of criteria by methods

The following lists the criteria for each of the following methods: EN 45554 standard, the i-Fixit reparability rubric, the Assessment Matrix for Ease of Repair, the Repair Scoring System, and the AGEC law method.

N°	EN 45554	i-Fixit reparability rubric	Assessment Matrix for Ease of Repair	Repair Scoring System	AGEC law method
1	Disassembly depth	Identification of the problem	Ease of identification	Disassembly depth/sequence	Documents/information
2	Fasteners and connectors	Availability of a repair guide	Accessibility of identification	Fasteners	The wording cumulatively refers to
3	Tools	Warranty issues	Robustness of identification	Tools	Technical bulletins
4	Working environment	Technical knowledge	Availability of identification support	Disassembly time	Information regarding access to professional repairers
5	Skill level	Availability of spare parts	Accessibility of identification support	Provision of diagnosis support and interfaces	Instructions for self-repair
6	Diagnostic support and interfaces	Spare parts costs	Instructions for problem identification - content	Availability and type of information	Definition of a fastener

7	Availability of spare parts	Number of tools needed	Product designed for easy failure detection	Spare parts	Operating mode
8	Types and availability of information	Types of tools needed	Availability of failure diagnostic support	Software and firmware	Definition of spare parts distributors
9	Return models for repair	Critical components are readily accessible.	Accessibility of failure diagnostic support	Safety, skills and working environment	Commitments on the availability of spare parts and delivery times
10	Password reset and restoration of factory settings	Repair actions needed	Disassembly instructions - content	Password reset and restoration of factory settings	Delivery time
11	Data transfer and deletion	Number of screws	Product designed for ease of disassembly	Data transfer and deletion	Operating mode -calculation of the ratio for the price criterion
12		Removability of fasteners	Required tools for disassembly	Commercial guarantee	Remote assistance
13		Visibility of screws and other fasteners	Availability of technical support for disassembly and reassembly	Return of models	
14		Identification of the components/parts	Accessibility of technical support for disassembly and reassembly	Availability of OEM qualified service engineers	
15		Risk of injury	Information for spare parts	Ease of restoring product to working condition after repair	
16		Environmental issues at end of life	Information for 3D printing of spare parts		
17		Fragility or robustness of components	Modular design of the product		
18		Internal organization of components	Standardized design		
19		Clarity of reparability	Supply of spare parts - content		
20		State after repair action	Supply of spare parts - availability		
21			Supply of spare parts - cost		
22			Instructions for reconditioning of product		
23			Product designed for ease of restoring to working condition after repair		
24			Technical support for reconditioning - accessibility		

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8.5. Conference Article 5: Qualitative Assessment for the Transferability of an Industrial Product-Service Systems from One Application Field to Another Within the Same Organization.

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Qualitative Assessment for the Transferability of an Industrial Product-Service Systems from One Application Field to Another Within the Same Organization

Marly Valderrama(✉), Christian Wandji, Andreas Riel, Helmi Ben Rejeb, and Peggy Zwolinski

Grenoble Alpes University, CNRS, Grenoble INP, G-SCOP, 46 Avenue Félix Viallet, 38000 Grenoble, France
marly-fernanda.valderrama-gutierrez@grenoble-inp.org

Abstract. Currently, the manufacturing industry has a growing tendency to increase the added value of its offer through the implementation of the product-service system. The development of this system includes servitization as a strategic objective, since it allows providing more complete solutions aimed at customer satisfaction. However, the transfer of a product-service business model (PSS) in industrial scenarios generates uncertainty due to the weak definition of key criteria that contribute to its success. This research investigates the replicability of a PSS within organizations having a similar organizational culture. This article introduces a qualitative assessment of this transfer using a graphical tool called morphological box that meets the criteria defined in the systematic literature review. The established criteria and sub-criteria are based on the Business Model Canvas. The sub-criteria represent the possible configurations of the criteria within the business model. The "morphological box" is adapted to guide the graphical analysis of the capabilities, resources and competencies of the traditional business model vs. the PSS to be replicated. This research has been applied to evaluate the potential transferability of the "Pay per unit of service" business model in the field of industrial air compressors to the field of water distribution in a French company. This company includes in its offer the option of monitoring, surveillance and maintenance to ensure its continuous availability. The research demonstrates the feasibility of the proposed approach and tool in industrial settings by suggesting an easy-to-use guide about the criteria to be considered during the transfer.

Keywords: Product-Service System (PSS) · service · qualitative assessment · innovation transfer · business model design

1 Introduction

The Product-Service System (PSS) model proposes a hybrid solution, through the combination of tangible products and intangible services that meet the needs determined by the customer [1]. The servitization strategy is one of the concepts used in the development of PSS. This strategy consists of integrating the service approach into the traditional

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product-oriented Business Model (BM) [2]. The PSS model gained strength thanks to the success of Xerox, which gradually switched to the service "document management" model. Its main offer was not to sell the photocopying machine but to offer the "Pay-per-unit" of each printed document. In addition, it guaranteed the availability of the service to the customer. [3].

In light of the growing emphasis on sustainability within emerging organizations, PSS models have become increasingly pertinent. Assessing sustainability through the three dimensions of the 3Ps (People, Planet, and Profit) is likely to promote a more efficient, economically sustainable, and socially just system within the organization. There is a growing consensus in the scientific community on the potential for three-dimensional sustainability present in PSS model due to the reduction in production and efficient use of products during their life cycle [4, 5].

In particular, the automotive sector is currently undergoing a historical transition from product-orientation to service-orientation, given the need of the traditional OEM's to increase control over the use and end-of-life phases of their complex, safety-critical products, which are constantly moving towards higher levels of autonomation, decreasing end-users' interest to own and be responsible for such vehicles [6].

However, the way to implement the servitization strategy in the industrial environment has not yet been widely explored [7, 8]. Risk management, reorganization of the business model, new strategic objectives, and the management of external and internal customers are some of the obstacles that the industry faces [9]. Inadequate organizational management can lead to the dreaded "service paradox" where after a large investment to include services within the portfolio of offerings, it does not generate the expected profitability [10]. Currently, there are still limitations in terms of the tools or techniques to mitigate the potential risks inherent to service among manufacturing companies. It is hypothesized that by adopting the service BM transferability method, it can better lead to the successful transition from a traditional product-oriented BM to a PSS. A great deal of research has been carried out on the transition of the BM from a product-oriented service to a use-oriented or result-oriented service. However, the literature shows little evidence of a clear framework to guide and examine the transfer of a PSS model from one field to another. The aim of this paper is to propose a method for assessing the possibility of transferring a PSS model from one field to another.

This article is organized as follows. Section 2 details the literature analysis used to identify the gap in the transferability of a PSS model. Section 3 describes the research methodology. In Sect. 4, the qualitative assessment of this PSS model transferability is presented with details. Section 5 presents the application of the proposed method within a French company, and the results obtained. Section 6 outlines the limitations of this method and its perspectives for extension. Finally, Sect. 7 concludes with the achievement of the objectives set by the research questions.

2 State of the Art

To be able to interesting papers on the topic of the transferability of BM, the research was guided by keywords. The keywords rely to this topic such as "assessment", "criteria" and "transfer" with their synonyms such as product-service system, PSS, servitization,

PaaS, IPSS, Industrial-product-service was used for this literature review. Some have been added as the literature review progressed such as hybrid-offering, hybrid-offer. A systematic literature review was performed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method [11].

First of all, the used of those keywords in Web of Science and Scopus database generated 8655 and 16782 articles. Then after removing the duplicated articles using Excel, we obtained 22868 articles. To screen this result, two conditions have been added. The first was to limit the year of publication of articles to a maximum of 10 years, thus guaranteeing the non-obsolescence of information [12]. The second condition was to restrict the research areas to engineering, multidisciplinary sciences, and business and management. This was due to the commercial and technological approach of the PSS model. Including these conditions led to screening the selection at 7361 articles.

The titles and abstracts of the remaining articles were examined and 95 articles were selected for a full read. Through a full read of those articles, 14 relevant ones have been selected. In addition, 6 articles were added that despite their publication date (older than 10 years), their relevance in the field has endured, along with 2 handbooks. Finally, based on this PRISMA method, a total of 22 articles were selected. This analysis is summarized in Fig. 1. Moreover, an overview of the existing approaches on the transfer of BM have been clearly draw to highlight the gap in this research.

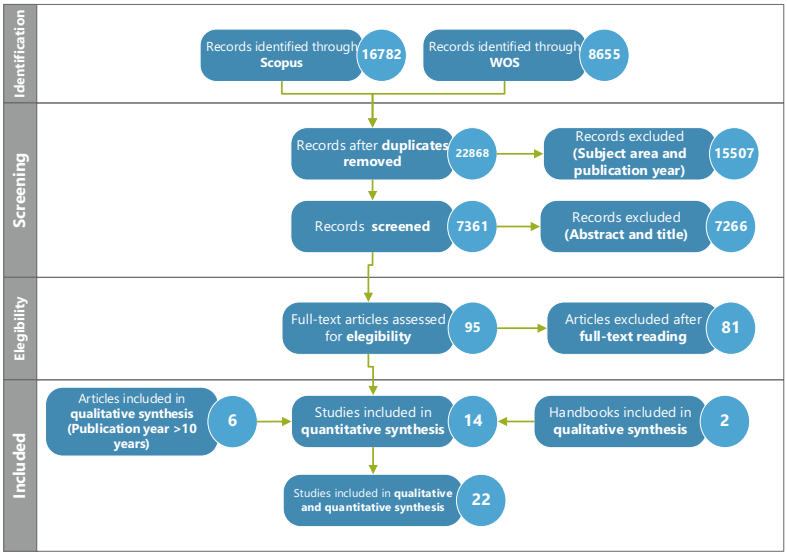

Fig. 1. Systematic literature review based on PRISMA Method

According to the literature review, the word "transition" is most commonly used to refer to a move by a company from a product-oriented service to a use or result-oriented service [7, 13, 14]. This transition is guided by a set of criteria identified by researchers and scientists [1, 8]. Lim et al. [15] emphasizes how the BM allows reflecting the adopted servitization strategy according to its capabilities, resources and competences to achieve

it. Its multidisciplinary approach by bringing together strategic management, finance, marketing and operational components guides the transition to services in manufacturing companies.

Adrodegari et al. [16] define the CANVAS Business Model (BMC) as a graphical tool that allows to quickly visualize how the business model is configured and to make possible adjustments to it. The BMC coordinates the resources for the simultaneous operation of the product and service to deliver the value proposition. Leitao et al. [17] state that understanding the PSS concept allows changing the product-oriented models to design a system that delivers a hybrid offer. In this way, Meier et al. [18] supports the advantage of versatility offered by the BMC to understand how the different stakeholders interact for the delivery of the system to the customer.

The path towards the transition to a PSS model requires an analysis of the organization's capabilities, resources and competencies. Reinartz [1] points out the unique capabilities and resources that companies must possess to generate competitive advantage. Story et al. [19] expose the challenge in establishing the appropriate configuration of the organizational components required for the creation and delivery of the value proposition through the service BM.

The identification of constraints that hinder transition and methods for mitigating these negative effects are addressed by some papers. The SWOT analysis proposed by Sholihah et al. [9] identifies the key competencies and constraints in an organization wishing to implement service. The Multi-Criteria Decision Making (MCDM) method proposed by Bertoni [20] quantitatively evaluates the criteria defined by the stakeholders for the design of the specific PSS. This demonstrates the relevance of criteria in such assessment. Lay et al. [21] propose a morphological box with eight parameters for differentiation of PSS models. Each parameter has a list of options that allows characterizing the PSS from a BM approach. Even, methodologies for the design of PSS models, such as the one explained by Garcia Lechuga et al. [22] establishes a methodology for the design of the PSS by combining the BMC and Blueprinting (BP) to visualize how the various components interact in the BM. Fang et al. [7] is another example of the application of BMC in the distribution of resources for the simultaneous operation of the product and service, by coordinating the heterogeneous features of a BM.

These articles addressed the issue of transitioning to the PSS model by assessing an organization's resources and capabilities, the use of criteria to evaluate the transition through the BMC, design methods and constraints on the part of the company. However, these investigations do not address the feasibility of replicating the characteristics of a PSS model in another product-oriented BM. The notion of transferring a successful PSS model into a new application is still not addressed, or not well formalized. In the industrial environment, there is still ambiguity about the application of PSS business models. In the case of manufacturing companies, the lack of information impedes the efficient transfer of PSS.

The initial hypothesis of the present research suggests that the challenges inherent in the transition to a PSS are decreased by transferring in the same company the resources, capabilities and competencies from one service BM to another where it operates with a traditional product-oriented BM. The current gap in the literature does not mention a methodology for managing the transfer of a PSS model for companies. In order to support

the critical task of decision making on the viability of the adopted organizational strategy, it is necessary to investigate how to evaluate the performance of the transition process in the firm. Therefore, the main question of the present research is: How to qualitatively assess the transferability of the PSS business model from one field to another?

From this question arises the need-to-know criteria that should be considered in the transferability of an existing PSS model in one field to another. Furthermore, the objective is carried out a qualitative analysis applied to both fields, in order to assess their performance. Only the qualitative analysis is considered within the proposed framework, because to date it is the only step validated with the case study.

3 Methodology

This section consists to define the research methodology that allowed to come up with the method for the research purpose. The proposed framework is the result of the adaptation of existing methodologies, which combined, bring an answer to the research question. A morphological box, which is tool to visualize and evaluate the criteria defined for the transfer of a PSS model is proposed. The present research is developed through 3 phases, as shown in Fig. 2.

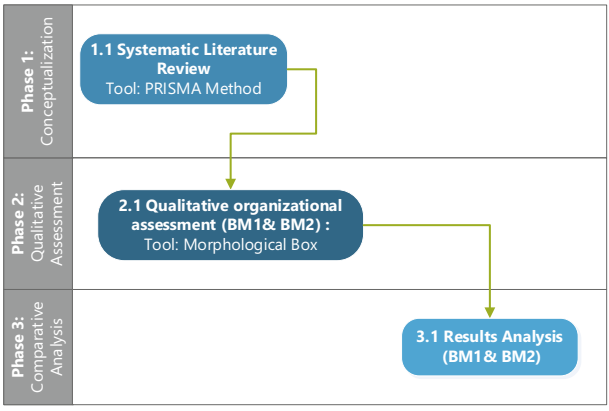

Fig. 2. Research methodology

Phase 1 consists of the conceptualization of the study through a systematic review using the PRISMA method. In this stage, the theoretical foundations for the research and development of the transfer of a PSS business model are compiled. The knowledge gained from the literature review was used for the construction of the framework for the evaluation of the criteria and sub-criteria for the transfer of a PSS. The results of the review are detailed and presented in sub-Sect. 3.1.1. In phase 2, based on the criteria and sub-criteria identified, they are grouped by features of the BMC in an instrument that is based on the morphological box innovation tool [23]. Finally, in phase 3, a comparative analysis of the qualitative assessment performed is carried out.

4 Qualitative Assessment Method

4.1 Definition of Criteria and Sub-criteria

The literature review identified key characteristics in the conceptualization of PSS models. The criteria initially recognized for the transition are extended for use in studying the replicability or transferability of the service BM from one application field to another. The establishment of these criteria in the present research focuses on the potential for use in the analysis of transfer. It was assumed that the criteria that were relevant in the transition to PSS models would also be important in the transfer. Because the transition from product-oriented BM to PSS is considered as a transfer of model. The common use criteria were considered as the most relevant one for the transferability assessment method.

The criteria are used to assess the potential of the BM transfer in terms of the requirements for the development of the PSS. The sub-criteria are established to homogenize the various parameters present in each criterion, allowing to characterize and differentiate each PSS as a BM in industrial scenarios. The BMC has been used for the development and analysis of new PSS business models in previous research [22]. The adoption of this approach decreases the complexity in understanding how to manage the organization's resources and capabilities to implement the PSS [14]. Linking the criteria to the BMC gives a more holistic understanding of how the company adjusts its strategy, operations and processes for the performance of the PSS. That is the reason of its used on this study, but only 8 of the 9 BMC features are used to build the assessment method. The features used in the methodology are: Customer segment, value proposition, profit stream, channels, customer relationship, key activities, key resources and key partners. The cost structure feature was not included due to the limited literature available on its management within a PSS model. The Table 1 provides a comprehensive overview of the criteria identified in the cross-reference analysis for managing PSS transfers.

These define how the company monetizes the value delivered to the customer. The details of the 22 criteria are explained below.

The *Customer Relationship feature* is evaluated using the criteria *type of relationship, contractual relationship* and *property right*s. These criteria evaluate the type of interaction established with the customer. The *relationship type* criterion refers to the type of links that the organization maintains with its customers. When implementing the service, it is necessary to involve the customer more in the process [25]. The relationship with the customer can be direct or indirect. The direct relationship is where the company directly delivers the service to the end customer. Co-creation between the organization and the customer enables efficient and cost-effective performance [18]. This criterion is complemented by the *contractual relationship* maintained with the customer, which should evolve from transactional to relational. Frequently, the contact that a product-oriented company maintains with the customer is reduced to the initial contact made during the sale [24]. Defining who is responsible for ensuring the availability and reliability of the tangible resource when required by the customer is key during the development of the offer [25].

Table 1. Assessment criteria identified in the systematic literature review linked to BMC

(Year,Author)	COSTUMER RELATIONSHIP			COSTUMER SEGMENTS		REVENUE STREAMS			CHANNELS	KEY ACTIVITIES							KEY PARTNERS			KEY RESOURCES		
	1. Relationship type	2. Property Rights	3. Contractual relationship	4. Costumization	5. Market type	6. Share service revenue	7. Service Profitability	8. Revenue model	9. Sales channel	10. value delivery	11. Business Model	12. Risk management (Agency mechanism)	13. Circular Strategy	14. Digitalization	15. Human Competence	16. Innovation	17. Org. support	18. Risk management	19. Service delivery	20. Automation resources	21. Data Collection	22. Tangible resources
Ritcher et al., 2010 [29]		x	x	x						x	x							x				
Gebauer et al., 2005 [38]	x		x			x									x		x		x			
Reinartz, 2011 [1]				x										x	x				x		x	
Tukker, 2015 [30]		x						x		x	x			x	x				x			
Tenucci et al., 2020 [10]						x																
Lerch et al., 2015 [36]													x	x	x	x			x	x	x	
Song et al., 2017 [39]				x																		
Sholihah et al., 2019 [13]																	x					
Reim et al., 2018[32]			x																			
Sousa et al., 2017 [28]			x			x		x		x				x							x	
Huikkola et al., 2018 [24]	x		x	x	x	x		x		x				x								x
Meier et al., 2010 [18]	x	x	x		x	x				x						x		x	x	x	x	
Reim et al., 2015 [26]	X	X	X	X	X			X		X		x			x				X		x	
Paschou et al., 2020 [35]												X	X		X	X				X		
Zhang et al., 2022 [33]												x										
Eggert et al., 2014 [41]						x	x															
Fang et al., 2008 [7]							x												x			
Kamalaldin et al., 2020 [37]			x											x	x	x			x	x	x	
Tukker, 2004 [31]											x											
Kohtamaki et al. [2]				x	x			x					x	x		x				x		
Adrodegari et al., 2017 [27]																						
Annarelli et al. [25]	x	x	x	x						x					x				x		x	

The *property right*s criteria define who has control over the product. Customer ownership is present in traditional product-oriented business, where ownership is transferred at the time of the transaction [26].

The *customer segment feature* includes the criteria *customization* and *type of market*, to detail the type of customer to whom the offer is addressed. *Customization* is related to the level of flexibility included in the hybrid offer. Fluctuating customer needs require the organization to respond quickly to change to ensure sustainability over time. Define the ideal level of flexibility where the investment costs do not outweigh the benefits obtained. In PSS business models, it is common to visualize three *types of markets* in the provision of its offer: Business to Business (B2B), Business to Costumer (B2C) and Business to Government (B2G). In product and use-oriented models the customer segment may vary between B2B or B2C. In result-oriented models the offering is mainly targeted at industrial customers due to the complexity of the required system performance [24].

The *revenue stream featur*e includes the *share of service revenue's impact*, *service profitability* and *revenue model*. The move towards a service system requires a large initial investment for the acquisition of products and human resources. The *share of service revenue's impact* allows to understand the performance of the service in the company. Service transition has a positive effect when the ratio of earnings from service is higher than 30%. This criterion is linked to *service profitability,* where the risk that the investment does not generate the expected return is analyzed, which is called the "Service Paradox". *Revenue model* defines the cost structure of how the company will earn profits based on the generated customer sales [27]. In this way, the payment mechanisms common in PSS models are proposed: The profits obtained in the traditional product sales model. The service fee for additional services offered around the purchased products; such as: repair, maintenance or supply of spare parts. Subscription or contract where the customer pays periodically for the use of the offer. Pay-per-use where the charges are linked to the frequency of use of the offer.

The *sales channel* criterion is part of the *channels feature*, which evaluates how the organization communicates and delivers its offer.

The *value proposition feature* is evaluated by the criterion *value delivery* to examine how the system of products and services delivers the value proposition to the customer. The *value delivery* refers to the value-in-exchange for which the customer is willing to purchase the offering. In product-oriented PSS models, the added value lies in the improvement of product characteristics. Focusing on extending the product life cycle by manufacturing with high quality materials [28]. Subsequently, complementary services aimed at guaranteeing product availability, reliability and functionality can be added; such as: repair, maintenance and spare parts [24, 29]. However, the above value offerings are not sustainable in the long term due to the high risk of plagiarism in the competition that threatens the competitive advantage gained [30]. However, the management of the company's activities is limited by the clarity and accessibility of the information shared between the parties. Finally, offering "an end-to-end solution" represents the value delivered in results-oriented PSS models. The supplier must adjust the system offered to the customer's organizational structure [25], and this model increases the company's economic competitiveness due to the complexity of replication in the competition [18].

Within the *key activities feature* were placed the criteria *main activity, risk management (mechanism), circular strategy, digitalization, human competences* and *innovation*. The above criteria describe the key processes for the successful development of its hybrid offer. The *main activity* criterion refers to the main activities performed by the company to create value through its offering. The business model varies according to the type of PSS. In the product-oriented PSS, the activity is mainly focused on the good offered, with services related to the product (maintenance, supply of consumables or final disposal), and consulting, which provides advice on the efficient use of the product. The use-oriented PSS, the good is owned by the supplier, offering the service of its availability to the customer. Finally, the result-oriented PSS agrees on a final result without involving a predetermined product. In the latter, there is the "Pay per unit" where the user pays for the units consumed, activity management lies in the outsourcing of a part of the production, and the final result where a result is delivered according to the customer's specifications [31]. In the current trend, where manufacturing companies are interested in implementing PSS in their business models, new risks appear. In order to create more personalized relationships, negligent behavior and disagreements on the part of the customer may appear. Therefore, predicting and calculating potential risks and how to mitigate them are part of the firm's key activities. The *risk management (mechanism)* can be designed with a focus on monitoring the behavior or performance of the final outcome. The monitoring mechanism is driven by behavior-oriented contracts where the responsibilities and obligations of the participants are defined. It generally requires the installation of digital components for system surveillance. The sharing mechanism has a result-oriented approach where profits and risks are shared. This agent incentivizes the optimal operation of the equipment by the customer. Finally, the trust mechanism where, due to long-term relationships, the user's good behavior is trusted. However, the supplier must include a premium cost in the offer as a backup in case of cost overruns due to inopportune behavior. [32] The *circular strategy* explains how the supply chain operations management is part of the transition to a circular economy. PSS systems could be adjusted to this new idea of sustainability by driving a net reduction of resources [5]. The circular strategy during the Pre-use phase (Reuse, rethink and reduce) refers to designing for smarter product use. The use phase (Reuse, repair, refurbish, remanufacture and repurpose) is aimed at prolonging the product life cycle. Finally, the post-use phase (Recycle and recover) responds to the use of salvaged materials after their use phase [33, 34]. Technology-based services increase the possible configurations in the business model design [35]. Automation optimizes resource allocation and responsiveness to customer requirements. The level of *digitalization* criterion is proportional to the amount of automation tools included. The basic level, where it does not generate a differentiating factor in branding (i.e., Digital text-files, e-mail, and video conferencing). IT-based services where information and communication technologies (ICT) are included; such as: Teleservices, monitoring and remote control of the system. Pure digital services which refer to simulation software, augmented or virtual reality, and tools for Big Data analysis. Finally, Full digitalized, where the complexity of the solution increases due to the high presence of digital tools [36]. The *human competences* criterion specifies the performance of the human resources in terms of knowledge and experience in the product and service to ensure the success of the strategy [30]. Not having enough trained

resources becomes a bottleneck in the industries [1]. Product know-how is characterized by capabilities for product design and engineering [28]. Field know-how refers to the skills needed to address technical needs in terms of equipment failure or maintenance. In addition, sales personnel must ensure an optimal purchasing experience by responding to customer needs with the offer [28]. ICT know-how is necessary when including digital systems within the offer, to take advantage of the added value generated by them [37]. Finally, people with a general knowledge of the overall operation of goods and services together to offer more complex hybrid solutions [1]. A new *Innovation* scheme where services are included in the innovation process is required [38]. Extending R&D beyond the traditional focus on improving features in individual products or services to hybrid offerings influences the success of PSS [1]. In addition, it is necessary to include the customer in the process of co-creation of new solutions [25].

In the *key partners feature* are *organizational support, risk management sharing* and *service delivery* criteria. It records the composition and structure of the network necessary for the execution of the PSS BM. *Organizational support* is a key partner during the transition to services. Skepticism related to the profitability of intangible assets restricts the success of service. An organizational strategy improves the distribution of resources, the cooperation of the various elements, and the achievement of goals [38]. The business model must be consistent with the service strategy. Misalignment of objectives between the organization and management causes resistance in the transfer [13]. *Risk management sharing* related to guaranteeing the availability and optimal functioning of the system is one of the possible barriers during the process. By integrating services into the system, this risk is transferred from the customer to the supplying organization. Adding services includes new processes that must be developed within the organization. Therefore, the *service delivery* criterion establishes who will deliver the service to the client is required. Organizations that prefer to deliver it themselves must make the service area independent to avoid possible internal conflicts of interest [7]. Another option is to resort to outsourcing or alliances with third parties to execute some tasks of the process to compensate for the lack of competencies of the organization [26]. These alliances with third parties should be evaluated periodically to measure the efficiency of the resources and competencies acquired [37].

Finally, the *key resources feature* groups the criteria *automation resources, data collection* and *tangible resources*. This feature reviews the distinctive resources required for the delivery of the final system to the customer. *Data collection* is a key resource in the design and improvement of new offers. It is necessary to identify the relevant variables for processing the information collected, and convert it into real knowledge [18]. Historical information contributes to better risk estimation, design of more customizable offers, more efficient maintenance plans and develop a better pricing policy [19]. Finally, the digital era has made it possible to collect and share real-time system data. The *automation resources* employed in the development of the PSS are directly proportional to the level of *digitization* of the organization. The *tangible resources* for the development of the offer are a differentiating factor in the market. This includes workshops, spare parts stores, testing machines and information systems [25].

Morphological Box

The present tool is the adaptation of the morphological box proposed by Lay [21]. Lay

originally proposes an 8-parameter architecture for PSS design. The present research framework adapts this graphical method to qualitatively assess the performance of an organization in terms of resources and capabilities. Moreover, assuming that, if one department of a company can provide a service mainly based on its resources and capabilities, another department can do the same if it has the necessary resources and capabilities. This tool allows a better understanding of an organization by graphically representing the link between the characteristics of the business model, resources and capabilities. It is used to evaluate the organization of two departments of the same company, in order to assess the replicability or transferability of a PSS model from one department or application field to another. The criteria are placed in relation to the BMC features to which they belong, taking advantage of the interdisciplinary approach given by the BMC for the analysis of an organization. The method uses 8 of the 9 BMC characteristics for the construction of the morphological box. The sub-criteria represent the possible configurations of each criterion with respect to the resources and capabilities. A percentage bar is introduced in the sub-criteria of 20 criteria in case a criterion has more than one sub-criterion during the study, but also to highlight the different in a sub-criterion of the two comparative department of application field.

The percentage bar of 10 intervals of 10% from 0 to 100% represents the proportion of availability and presence of a sub-criterion in the organization of the department or field of the company. The criteria "Share of service revenue's Impact" and "Service profitability" do not have this percentage bar because the definition of the sub-criteria is directly determined by the percentage (%) of perceived revenue.

The morphological box is filled in by indicating each of the sub-criteria that conceptualize how each criterion operates in the organization. If more than one sub-criterion is selected per criterion, the proportion of each sub-criterion present must be indicated in the percentage bar. The above filling out process is carried out in the same morphological box to evaluate the two comparative department of application field. In this way, the comparison is simplified by visualizing in the same graph the configuration of each BM. The path drawn between the criteria represents the organizational performance within each of the BMC features in a company. At the end, two trajectories are drawn in the morphological box to highlight the differences and similarities between the BMs. Finally, a comparative analysis of the two business models evaluated is carried out to define the possible barriers or drivers in the transfer. The result can show potential BM opportunities for both fields. It gives an idea about the replicability of a PSS model into another field. The morphological box tool is presented in Fig. 3.

5 Case Study

The use case is a French company that provide service in two sectors where customer needs, resources, capacities and technologies can vary. This company provides pay-per-unit and pay-per-performance services using air compressors to guarantee cubic meter of compressed air with a quality level and energy efficiency per unit or use. The company is organized by departments; the air department is structured with resources and capacities to provide the service on compressed air per unit of use; the water department and the mobile energy department. The study aims to qualitatively assess the organizational

performance of the air department as well as the water department within the company using the morphological box tool.

The current business model in the water field is product-oriented by offering mainly the sale of pumps, together with services related to ensuring their availability and reliability (i.e., maintenance, repair and spare parts sales).

Data collection was conducted through two workshops with a multidisciplinary team from the water and air fields. The team was composed of personnel from R&D, marketing, technical/maintenance, after-sales and management disciplines. The participants worked separately in 2 teams according to the field they belonged to. The participation of different roles is necessary to understand the different points of view that contribute to transferability within the organization. The workshops had an estimated duration of two hours where each one was conducted to evaluate the existing business model in the air sector and later in the water sector.

The work sequence and tools were similar in the two workshops. Initially, the framework of the present research was briefly explained to the participants together with the methodology with which the workshop was going to be developed. Memo fiches and a board with the morphological box template printed on it were used as interactive visual tools. These types of tools encourage active participation and dynamic cooperation of all participants. Each of the rows with the criteria and sub-criteria of the morphological box was assigned a distinctive color related to the BMC feature they evaluated. The sub-criteria were individually represented by memo fiches that plotted each of them with a pictogram. In addition, a brief explanation and an example of the sub-criterion was provided on the reverse side for greater understanding. Due to the diverse backgrounds of the participants in the multidisciplinary teams, it was relevant to use a vocabulary in the tools that would facilitate the interpretation of each of the participants.

The participants had to evaluate each of the criteria identified on the morphological box board using the memofiches. In the case that the qualitative evaluation of a criterion required more than one sub-criterion, they had to assign an approximate proportion (%) of the availability of this sub-criterion within the business model. The information gathered from the workshops was processed and the path representing the organizational performance in the industrial water and air field was drawn. Finally, the qualitative evaluation is carried out by comparing the two paths drawn. The results of the workshops are summarized in the morphological box presented in Fig. 3.

By analyzing the paths traced in the morphological box, it can be seen that the two fields have different configurations in their business model. The criteria considered as drivers in the transfer are value proposition, main activity, human competencies, automation resources, data collection, and material resources. The configuration of these criteria is similar, although with a different proportion in the availability of each one within the BMs. The water field shares with the air field a close configuration of the criteria, facilitates the replicability of the PSS model in terms of competencies and resources. The water field has the base concept for the management of these criteria for the delivery of an offer similar to that of the air field. However, the criterion “organizational support” can become a potential barrier if not properly managed. The service replicability can lead to inconsistencies between strategic direction and resource allocation. The alignment of organizational strategy is a key factor in the transfer of a PSS model.

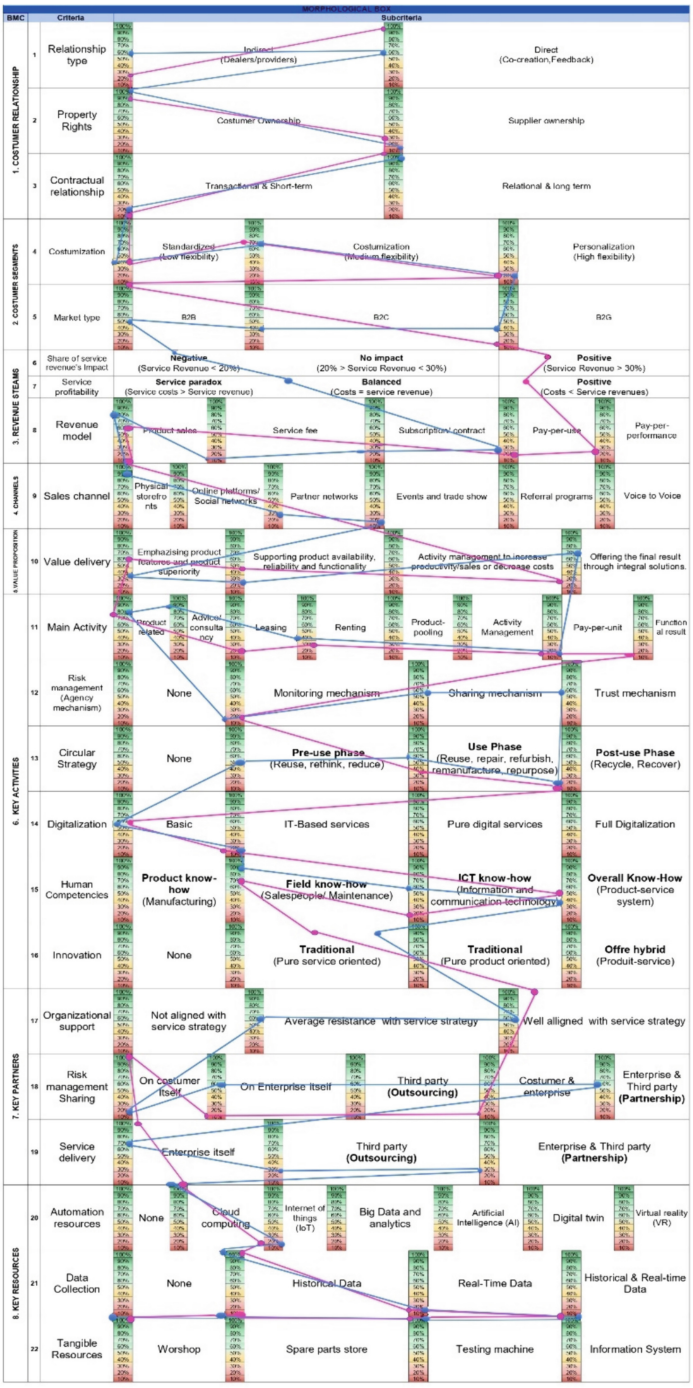

Fig. 3. Qualitative evaluation of the business model of the air sector (ffuchsia path) and water sector (blue path). (Color figure online)

The two fields share the same value propositions but in different proportions. In the water field, the value proposition lies mostly in offering a "final solution" to the client, then ensuring the quality in the operation of the products sold, and finally, through maintenance plans, ensuring the availability of the equipment. This BM offers free advice on the optimal functioning and operation of the equipment as part of its competitive advantage. The key activities related to the water field are to provide consulting services on the efficient operation of the equipment at the client's facilities. This activity is not monetized to increase customer loyalty to the company. However, designing a strategy to take advantage of the economic potential could contribute to improve the share of service revenue. Ensuring product superiority (70%) and leasing contracts (30%) are the main revenue-earning activities. On the contrary, the air field is committed to product superiority (63%), considering that its main revenue model comes from its sale.

In the water field, there are more personnel with field know-how competence (85%) than in the air field (60%). The water field has in greater proportion the skills to offer better advice to the client on the solution to be acquired, and to attend the technical services (installation, repair or maintenance). In terms of ICT skills, the water sector has 50% of its personnel trained in this discipline; in contrast, only 8% of the air sector has this skill. The ICT skills present in the organization are mainly related to the use of office automation tools required during the development of their responsibilities. The organization in general does not have enough personnel specialized in the operation and monitoring of advanced digital tools (i.e. digital twin, 24/7 remote monitoring, virtual reality, big data). This reflects the fact that the main activity offered in the two fields does not require high levels of digitalization. Finally, in the competencies related to global know-how, the air sector has more presence of these; which allows to have an overview on the efficient convergence of the product-service within the offer.

Due to the level of basic digitization present in the two BMs, the automation resources required by the organization are minimal. The tools commonly used are cloud storage for document management. The Internet of Things (IoT) is used to a much lesser extent due to the restricted access to the information provided through the installed sensors. The customer by cyber security measures limits the processing of data related to the operation of the system. This minimizes the benefits of digitized servitization caused by the inadequate exploitation of data for the implementation of more complex offers. Finally, the two fields share the same proportion of tangible resources. The organization has a compressor and pump testing machine that generates a competitive advantage in the market.

6 Discussion

The major gap present in the literature review is the lack of a framework for assessing the feasibility of transferring a PSS business model. Through the combination of several existing tools, a methodology is proposed for the qualitative analysis of the evaluation criteria needed to explore the replicability of a service business model.

The proposed framework provides a set of criteria related to the performance of each of the features established in the Business Model Canvas (BMC). The list of 22 criteria established in the research provides an overview of the possible configurations

in the capabilities and resources of a PSS model. In the frameworks proposed by [18, 21] the identified criteria are not sufficient to evaluate the structure of an organization. Although [20, 39] provide methodologies for the evaluation of the BM in the initial stage of the PSS, they do not allow to analyze the replicability of a service BM. The tactics of marketing, contracts, networks, product and service design proposed by [26], describe an architecture on the functioning of a BM for the creation and delivery of value in a PSS, but not its application in industrial cases.

The integration of the BMC and the morphological box in the analysis of the replicability of resources and capabilities enhances innovation-oriented PSS scenarios because it adapts to the different architectures present in service BMs. The case study demonstrates that the challenges inherent to the transfer can be better interpreted by visualizing in a single dashboard the criteria that assess its feasibility. However, even if the transfer is performed in the same organization, it does not guarantee its success. The BMs evaluated may even operate in the same regional organization but not share the same distribution of resources and competencies, as evidenced in the case study. It is necessary to analyze the influence of organizational culture, strategy and structure on the replicability of a PSS between two departments in the same organization.

The business vocabulary used in the definition of the criteria and sub-criteria is not widely known by the workshop participants. The understanding of this terminology is relative to the background of each participant during the qualitative assessment. The use of graphic tools (i.e., memofiches and morphology box board) facilitates the understanding of the vocabulary and interaction between the multidisciplinary teams.

The assumption used in defining the list of required criteria and sub-criteria could impact the results of the evaluation. The researcher can modify the proposed list by adding or reducing the criteria required for the analysis. The sub-criteria linked to the configuration of each criterion in the organization could simultaneously vary by adding more options. The experience and knowledge of the evaluator may affect the criteria selected to analyze the transfer.

The definition of this list may be limited due to the restriction applied in the systematic review of the literature related to the subject area. The literature review conducted by [30], demonstrates the considerable participation of the subject areas' computer science and environmental sciences, contributing to the possible definition of new criteria related to the environmental approach of PSS.

The morphological box is an easy-to-use tool that provides a comprehensive overview of the BM configuration for its evaluation and performance analysis. The tool proposed by [21] is adjusted for the graphical representation of business models. However, the "Cost Structure" feature of the BMC was not included in the evaluation of the transfer. The financial model is key in the research because the profitability of the PSS model varies at each stage according to the chosen BM configuration. The non-inclusion of this approach limits the understanding of the relationship of service and the performance of the organization because new variable costs arise with this new key activity.

7 Conclusions

In this research, a new approach is provided to evaluate the feasibility of transferring a PSS model. The concept of the morphological box has been used to evaluate the configuration of the business model when integrating the service. The tool was built by systematically reviewing the literature to define the criteria to be assess during the transition from selling business model to PSS model. Multiple criteria connected to the 8 features proposed by the BMC were established to know the potential of transferability. The objective of this framework is to help companies in the industrial sector to develop a qualitative analysis by comparing the structuring of the multiple resources and capabilities present in a traditional product-oriented BMC with respect to the service BMC they wish to transfer.

The results obtained in the case study with the evaluation of BM transfer demonstrate that the framework is applicable in industrial contexts. The transfer of the service offered by the air sector to the water sector is possible if the organization takes advantage of the potential of the driving criteria and reduces the possible barrier identified in the morphological box. The case study of the transfer of the BM service from the air field into the traditional product-oriented BM in the water field is an example of the comparative analysis; which allows to establish the feasibility of the replicability of the PSS configuration. The evaluation of the replicability of the PSS can be extended to scenarios where BMs operate in different organizations. However, the results may vary when transferring between two different organizations. It is necessary to extend the practical part of the tools in other industry sectors, analyzing the resources and competencies required in the operation of each BM. Finally, the transfer of a PSS within the same organization does not guarantee the absolute success of the transition. The management of resources, capabilities and competencies of a BM reflects the adopted strategy. Analyzing how organizational culture can affect the replicability of the PSS in business models is part of future research.

Certainly, the present research has limitations. The morphological box tool does not contemplate the "Cost structure" feature proposed by the BMC. Future research should implement this approach in the evaluation, due to the relevance of knowing the amortization of the initial investment required for the integration of services. In addition, a quantitative analysis should be integrated to get accurate results about the feasibility of the transfer, as should be the use of multi-criteria decision-making tools (MCDM) to quantify the relevance of each criterion in the transfer of the business model. Also, incorporating the client's needs is relevant, since the service potential is ultimately defined by the value perceived by the client thanks to the final offer delivered by the company.

Relationship with the SPI Manifesto

Like many other industries, the automotive industry is currently in the transition from a product-oriented towards a service-oriented industry. This works contributes to putting the community in the new Circular Economy context.

The SPI manifesto defines the values and principles required to deploy SPI efficiently and effectively [40]. The principle "**Use dynamic and adaptable models as needed**"

means that we need to continuously adapt the models we use for designing and evaluating our product, services, processes, and underlying organizations to the dynamically changing economic, ecologic, and social context. Furthermore, the principle **"Create a learning organization"** is emphasized in this research as it proposes a methodology to foster learning from a business model transformation undertaken within an organization.

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8.6. Conference Article 6: Transitioning Towards a Component-as-a-Service: A Business Model Design Overview.

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Transitioning Towards a Component-as-a-Service: A Business Model Design Overview

Isabella Burzelli[1,2(✉)], Christian Wandji[1], José Hidalgo Crespo[2], and Andreas Riel[1]

[1] Grenoble Alpes University, CNRS, Grenoble INP, G-SCOP, 46 Avenue Félix Viallet, 38000 Grenoble, France
isabella.rodrigues-burzelli@grenoble-inp.org

[2] LCPI, Arts Et Métiers Institute of Technology, HESAM Université, 155 Boulevard de L'Hôpital, 75013 Paris, France

Abstract. In searching for resource efficiency, life cycle extension, and achieving sustainable objectives, companies in different sectors are exploring alternatives to servitization. In this context, the Component as a Service (CaaS) emerges as a potential transition from a sales-centric to a use-centric business model. To support the challenges of this transition, this paper explores the current state of knowledge of this circular business model (CBM) in the Literature and market, integrating the main findings to propose a structure that facilitates its business model design. The methodology includes a systematic literature review and a market review that identified 10 CaaS cases in the industry. The results provide a systemic and comprehensive landscape and aim to guide OEMs in developing a more resilient, efficient, circular model focused on the value delivery of their products.

Keywords: Component-as-a-Service · CaaS · Circular Business Model · Design Guidelines

1 Introduction

One of the main strategies fostering the Circular Economy (CE) is servitization. This concept refers to a shift from a product-centric business model to one focused on delivering services besides or instead of physical products, focusing on customer satisfaction through the delivery of the product's inherent service and value [1, 2].

When shifting from a traditional sales-centric to a service approach, manufacturers can innovate their business model [3], and maximize the product's life cycle by increasing the usability of products and enabling goods to be better repaired, refurbished, and upgraded [4].

In this context, Product as a Service (PaaS) is proposed as a circular business model (CBM) capable of offering multiple uses of the products by different customers, with an integrated role of maintenance and repair [5]. In addition, a relationship between the

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OEM and customers exists where there are information links during the usage phase [6]. The retention of ownership by the OEM opens opportunities that allow the implementation of circular strategies, such as refurbishment, remanufacturing, parts extraction, reverse logistics, and recycling, as well as an impact on product design aspects for circularity [7].

The Component-as-a-Service (CaaS) is an alternative to the PaaS. In this model, the company sells the product and offers one of the components as a service, such as Battery-as-a-Service (BaaS). This can be an attractive business model for consumers to avoid the prevailing uncertainty of Battery Electric Vehicles' lifetimes and residual values, predominantly determined by the battery's ageing characteristics for a particular usage profile. For OEM's this model presents opportunities in realising the Circular Economy for the environmentally most impactful component of a BEV, as well as for collecting valuable data on the battery's ageing characteristics.

The CaaS figures as an emerging CBM that allows components to have better maintenance and repair options, contributes to resource optimization, especially in terms of raw materials, and compared to the PaaS, CaaS is cost-effective, both for the OEM and for customers. In terms of customer perception, as the user will own the main product in the traditional way and access just the component on a service basis, this has the potential to increase the acceptance of the model [8].

However, this type of transition requires complex and systematic organizational changes that must be incorporated into the business model (BM) structure. As the logic behind an organisation, BM is defined as the way a company operates and creates value for all parties involved in its processes. It differs from strategy because the former encompasses the tactical interactions of the business and the set of decisions that are executed [9]. At this point, product-centric companies have difficulty understanding how to reconfigure their BM elements [10].

To contribute to the knowledge of this CBM and support this transition, this paper aims to understand and clarify its business model design process, addressing the following research question: "What are the key points for a CaaS BM design in industry?". To achieve this, a systematic literature review was conducted, followed by a market analysis that identified 10 use cases. Based on the insights gathered, five core phases of the CaaS BM structure are identified and discussed, highlighting the main critical points.

This article is organized as follows. The methodology used is explained in Sect. 2. Section 3 presents the key findings of the literature review, followed by the market review overview in Sect. 4. The results are presented in Sect. 5, followed by the discussion and limitations in Sect. 6, and the conclusion and key takeaways in Sect. 7.

2 Methodology

To ensure a comprehensive and systematic identification of relevant academic contributions, a literature review following the PRISMA methodology was applied. It consists of a four-phase flow to identify, select, and evaluate relevant research, and to analyse data included in the review [11].

The search was conducted on the databases Scopus and Web of Science. The strings included variations of keywords as "product service system", "product-as-a-service",

"component-as-a-service", "battery-as-a-service," and "battery swapping" (as it is the most advanced type of CaaS in terms of study and application), and "business models." All the strings are presented in the figure below. Only journal articles and conference papers published after 2005 were considered. After treatment using the package Bibliometrix [12] on R Studios to remove duplicates, the sample was composed of 665 documents. The software ASReview Lab [13] was used to carry out the abstract review. After this phase, 94 articles were selected for introduction and conclusion review. Finally, 31 articles were selected. Another 15 documents were included in the qualitative synthesis. The selection was composed of 46 studies (Fig. 1).

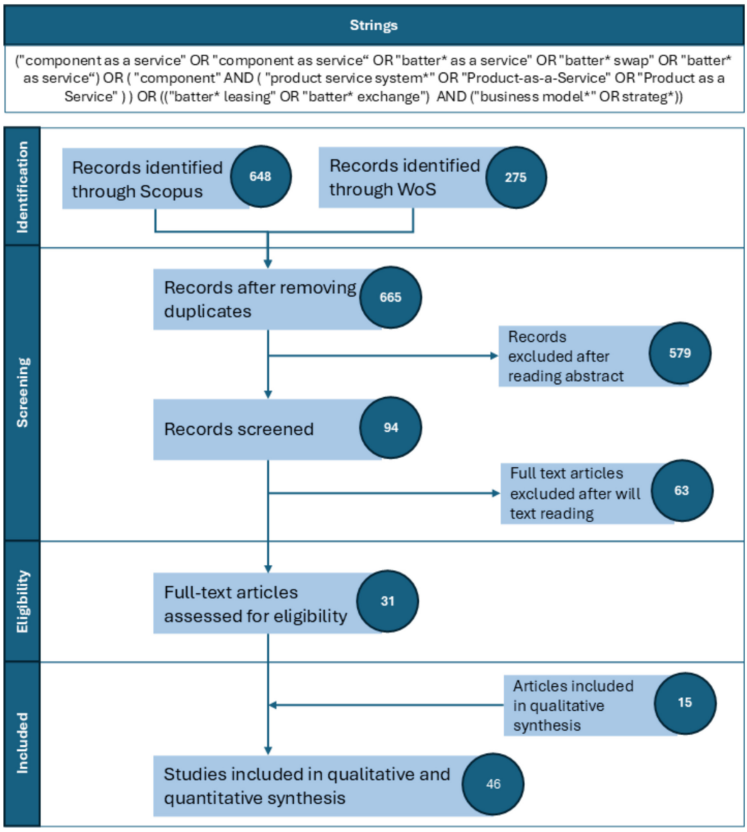

Fig. 1. PRISMA method for systematic literature review.

The selection criteria throughout the funnel were to select documents that touched on CaaS, and those that explored PaaS but focused on the design of the business model and the process of structuring it, as it serves as basis for CaaS.

The term "product service system" was important for the investigation, since "product-as-a-service" could exclude important records. However, many related studies refer to software topics, with keywords as "embedded systems", "cloud computing",

"information services", and "cyber-physical systems", which are not of interest to this study. Therefore, these studies account for most of the articles eliminated in the screening stage.

After the literature review, a market review with a qualitative and exploratory approach was conducted to identify companies that are already implementing strategies close to CaaS. It started by searching the cases identified in the literature review through a systematic review of the companies' websites, specialised news vehicles, and other open sources.

Subsequently, a secondary systematic search was conducted using a snowballing technique. The initially identified cases guided the discovery of additional ones through the exploration of related sectors and products.

Finally, iterative questioning and interaction with AI tools (specifically ChatGPT) were employed. A set of references was provided to the AI tool, and the AI was instructed to identify similar cases. Through an interactive process, results were progressively refined by highlighting relevant examples and requesting further details. For the previously selected cases, the same iterative approach was applied to obtain more in-depth information. The main aim of using the tool was to gain access to sources that would probably not have been reached using standard search engines. All sources were checked and only information from the companies' own websites and reliable news channels was considered.

The findings from the literature and market reviews were synthesized to identify and classify the decision-making pathway. This analysis enabled the definition of key phases essential in designing a CaaS BM. Each phase represents a structuring stage in the design process, and together, they provide a conceptual roadmap for BM development.

3 State of the Art

This section presents the key findings derived from the systematic literature review. As the literature for CaaS is still very limited, the review started at a macro level, understanding the conceptualization of PSS, then considering studies that address the BM process design of it and PaaS (this being a type of PSS and from where CaaS derived). Finally, it explored CaaS studies.

There are three types of PSS: product-oriented, use-oriented, and result-oriented. The first is when a client buys the usual product with additional services included. In the second, the client pays for the use or availability of the product. The latter, the client pays for the performance or capability of the product [14]. The first is still a sales model, while in the last two, the ownership of the product is retained by the firm.

Exploring the transition from a sales-centric to a use or performance-centric BM, some approaches are proposed in the literature. Rennpferdt et al. address the development of business model families for PSS in three steps: the development of BM concepts, a functional decomposition of these concepts to identify the functional elements, and a mapping of the functional elements into product and service components [15]. This approach supports the transition and aims to allow the development of PSS that can be offered simultaneously with the existing products, based on them.

This is in line with the findings of Velamuri et al. 2013 when investigating how manufacturers can drive business model innovation by PSS. Firms should prioritize service offerings that align with their existing expertise and core capabilities.

Focusing on manufacturing companies and their value network, Regina Moro et al. propose a PSS business model value architecture composed of value proposition, value configuration, value delivery, and value capture. In a second level, subcomponents as customer activities, key resources, partnerships, operating processes, cost, and revenue were considered. The study highlights that the main PSS business model design challenges are related to strategic issues and operations [16].

When it comes to the BM design, the studies mostly explore the Business Model Canvas (BMC) framework; there is a gap in structuring processes.

Sanfelice et al. 2024 investigate how the adoption of PSS business models works and propose a BMC for product-oriented and use-oriented PSSs [17]. In comparison, the use-oriented model presents more factors; the list of key resources, activities, and partners is more extensive, as well as the cost and revenue management. This illustrates the complexity and systematic coordination needed for its implementation.

Getting to CaaS literature, some of the BMCs we reviewed include a BMC for BaaS in Energy Communities [18], battery swapping [19] and CaaS for electrical and electronic equipment [8].

As mentioned before, the battery-as-a-service configures as the most advanced type of CaaS in terms of study and application. The term is related to "battery swapping", "battery management system," and others. The studies that explore the costs and investment implications within this BM are evident.

BaaS is more explored for electric vehicles (EVs), which can serve as a foundation for the development of other CaaS. Studies that analyse and support decision-making include the spheres of prices, consumer bases, and firm profits [20], raw material and product flows [21], supply chain [22, 23], cost-efficiency [24] and consumer behaviour [25].

One of the most notable cases of BaaS is that of the Chinese EV company NIO. It offers a swappable-battery leasing model. The model is generally more flexible than battery leasing, because it allows easy upgrades, fast charge stations and home charging solutions, extended warranty, and flexible withdrawal of the contract [26].

NIO's success in BaaS can be attributed to the set of different solutions and value delivery strategies implemented. By keeping the ownership of the battery, the company was able to develop a service ecosystem, which helps to maintain high customer satisfaction and value perception, and different sources of revenue [26, 27]. Furthermore, by closing the loop of the component, the company can offer the most up-to-date batteries to its customers and invest in battery technology without the issue of replacing older batteries [27].

More than these advantages, offering only the component in a subscription or other fee base is cost-effective for the costumer and the OEM; more flexible, upgradeable, scalable, and specialized components can be designed based on costumer's need; better maintenance and repair options can be offered, and the power of resource optimisation is increased [8].

Meeting the main findings of this literature review with the BMC for CaaS proposed by Hidalgo-Crespo et al., key factors for a CaaS BM are highlighted: the need for a dedicated take-back system, assessment of economic viability for component reconditioning processes, availability of storage points, tools for the assessment of the quality state of the component, reverse logistic chain, reconditioning partners (if it's not done by the OEM) [7].

4 Market Review

Table 1 below presents the ten cases identified and describes their business models, with a focus on services offered, pricing method, and infrastructure provided. We aim to study only CaaS cases in which the model is offered directly by the manufacturer of the main product, whether through partnerships or not. This means that the service operation is integrated into the business model. The investigation showed that the number of these cases in the market is still relatively low, with most cases observed in the automotive industry, primarily as BaaS..

Among the analysed models, Gogoro, Ample, and Sun Mobility offer the components exclusively as a service, through subscription or pay-per-use models. Gogoro provides

Table 1. CaaS identified in the market

Company Name	Sector	Component	Business Model Description
NIO Inc	Mobility -Electric Vehicles	Battery	Sells the vehicle and offers the battery through a subscription-based service. The customer pays a monthly fee for a specific number of battery swaps, performed at fully automated stations. Additional services include maintenance and the option to upgrade the battery (subject to eligibility). [28–31]
Better place	Mobility -Electric Vehicles	Battery	Provided electric mobility infrastructure and services in partnership with OEMs (e.g., Renault). The battery was offered through a monthly fee based on miles travelled, with swapping performed at automated stations. Faced difficulties in infrastructure costs, limited vehicle compatibility, low consumer adoption, and a lack of stable partnerships, leading to its failure. [31–33]

(*continued*)

Table 1. (*continued*)

Company Name	Sector	Component	Business Model Description
Renault	Mobility -Electric Vehicles	Battery	Sells the vehicle and offers battery leasing through its in-house company, Mobilize Lease&Co. The service is priced by annual mileage and includes battery assistance, maintenance, and replacement in case of failure. [34–37]
Amples	Mobility - Electric Vehicles	Battery modules	Provides modular batteries compatible with different EV models and the corresponding swapping infrastructure. Operates through partnerships with OEMs (e.g., Renault, Stellantis, Mitsubishi), mobility companies (e.g., Uber), and urban logistics providers. The payment model is based on miles traveled, with plans to offer a subscription option. [30, 31, 38–40]
Gogoro	Mobility - Electric scooters	Battery	Sells the electric scooter and offers the battery through a monthly subscription plan based on usage tiers. Additional consumption is charged per ampere-hour used. Operates by swapping stations
Sun Mobility	Mobility - Electric scooters	Battery	Provides modular batteries for rickshaws, scooters, buses, and electric vans. Works in partnership with OEMs and fleet operators. The service is offered by flat-rate monthly subscriptions or pay-per-use based on kWh or number of swaps. [41, 42]

(*continued*)

Table 1. (*continued*)

Company Name	Sector	Component	Business Model Description
Bounce Infinity	Mobility - Electric scooters	Battery	Sells the electric scooter and offers the battery by monthly subscription (flat rate) or pay-per-swap. The swapping service is provided by partners (e.g., Sun Mobility). [43]
Sandvik	Mining	Battery	Sells electric trucks and offers the battery as a service, and provides the charging infrastructure. Service packages include spare parts and maintenance. Customized types of contracts according to customer needs, payment method not specified. [44, 45]
HP	Printers	Printer Ink	Sells the printer and offers ink as a service by monthly subscription, based on the number of pages printed. Plans can be upgraded or downgraded. Includes monitoring services for automatic ink delivery and additional features like paper monitoring and delivery. [46–48]
Xerox	Printers	Printer Ink	Sells the printer and offers automatic ink order by cost-per-copy. Monitoring services to determine when supplies are necessary. Automated billing via a mechanism in the printer. [49, 50]

batteries for electric scooters through monthly subscriptions; Ample supplies modular batteries charged per mile driven or per swap, primarily targeting fleet operators; and Sun Mobility offers standardized batteries for commercial vehicles via pay-per-use or monthly plans. Meanwhile, NIO, Bounce Infinity, and Renault follow hybrid models: customers can purchase the vehicle with the battery or opt for a BaaS plan. For printers,

HP and Xerox provide both traditional purchase options and service-based models. HP still sells ink cartridges but also offers the Instant Ink subscription program. Similarly, Xerox continues to sell toner but also provides usage-based contracts.

Cases of tyre-as-a-service (TaaS) were also analysed. Although they resemble a CaaS, since the tire, a key component of the main product (the vehicle), is provided as a service, they are more accurately classified as PaaS. This is because the service is offered by tire manufacturers (e.g., Michelin), independently of the vehicle manufacturer, and separate from the sale of the main product. In this way, the tire is not embedded in the main product offering but rather delivered as an external option.

5 Results

The literature and market review provided the foundation for identifying five essential phases that structure the development of a CaaS business model, illustrated in Fig. 2. Each of them is discussed in the following subsections, highlighting the critical points.

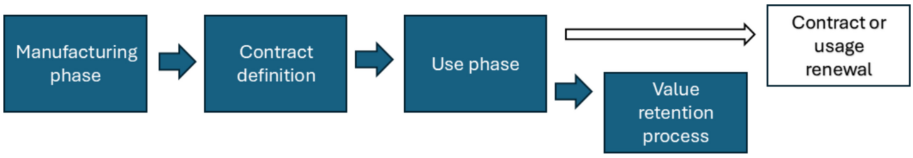

Fig. 2. CaaS business model phases

5.1 Manufacturing Phase

The process starts from the component manufacturing, which is either done by the OEM or a third party. In the automotive industry, for example, it is relatively rare for OEMs to manufacture their own batteries in-house. In cases like the partnerships with Ample, the startup manufactures the modular battery and provides the battery swapping infrastructure. In others, such as NIO, the batteries are supplied by external providers, but the swapping infrastructure is fully incorporated into the OEM's business model.

In other cases, such as for the ink, HP and Xerox handle in-house manufacturing of the component.

After manufacturing, the component needs to be stored, the OEM can consider internal or external storage, and joint or separate storage for first-life cycle components and reconditioned components.

In the long term, as the operation matures, the storage of reconditioned components coming from the value retention processes tends to be the same as the components coming from the manufacturing process, with no distinction made for new contracts or renewals.

5.2 Contract Definition

The contract definition is a significant decision phase. Two types of contracts for CaaS were identified: pay-per-use and subscription.

The first is seen as pay per mile or swap in BaaS cases, and pay per paper for ink. For it, the pricing method needs to be defined. For the subscription, different contract lengths can be offered and must be strategically analysed.

Studies have explored cost implications and pricing approaches that can provide strategic guidance for the development of a CaaS offering [20, 51–53]. This decision is instrumental in shaping both the firm's profitability and the customer's willingness to pay.

5.3 Use Phase

During the use phase, in addition to operational services such as maintenance, monitoring, and support, protection options can be offered, which may be perceived as advantages that encourage customer adoption. Some identified examples include early withdrawal, breakage assurance, and theft/loss coverage.

An efficient information and tracking systems are highly required for the management of this phase and can provide important data [54]. In PSS, information management can be configured as one of the services offered for the client (e.g., battery performance indicators, paper monitoring) as well as a source of data to help companies innovate and improve their value proposition and generate additional revenues [3].

When the component achieves its end of use, its replacement occurs. To that end, an exchange structure is necessary, whether it involves a physical location where customers bring the component or a logistics system for collection and delivery.

An important point, differentiated from a PaaS, is that the component exchange doesn't necessarily happen only at the end of the contract. In the case of subscriptions, the usage of the component may end during subscription coverage, which means that exchanges can happen during the same contract. This is the case of battery swapping by subscription, such as NIO and Gogoro, where consumers swap at the stations during the contract period. Also, it can be the case for ink. This depends on how the contract is defined and reflects the importance of alignment between this definition and the exchange structure that will be provided.

At this stage, two flows need to be well defined: an information system for renewing the contract or usage and a take-back system for directing the component to a value retention process.

5.4 Contract/usage Renewal

This phase represents the information flow required during the component exchange, for a new contract or a new cycle of use.

As a service-based BM, CaaS presents a close relationship with the consumer [17, 55]. As a result, each component exchange allows more than the renewal, but a constant offer of upgraded models of the component or bundle of services, which can be configured as a source of revenue [26, 27, 53]. This is implemented by NIO, Gogoro, HP, and Xerox.

5.5 Value Retention Process

In each exchange, the component is submitted to a state of health analysis, which determines the appropriate value retention process for the component.

A first state of health analysis can be performed to check whether it can be directly reused. This, in most cases, does not require component displacement. This is typically done in battery swap stations. In NIO's swap stations, an electrical performance inspection is done before recharging [27].

In a positive answer for direct reuse, the same component can be offered on favourable terms to the customer. This type of advantage can also influence consumer behaviour during usage [23].

In a negative result, the component is sent to a take-back system, and a full state of health analysis will determine the possible value retention. We can point out three main results: 1. The component can be repaired; 2. The component can be sent to a second life, going to a remanufacturing process or being sold to the market; 3. End-of-life determination and the component's parts are suitable for a value retention process.

In the first two options, after reconditioning, the component will go back to the storage system. In the third and final alternative, the parts must also pass through an inspection and may be subject to reconditioning or recycling. After it, these materials can be reintegrated into the component manufacturing process, configuring a contribution to raw material resource optimization [8].

All the value retention processes may be done by the OEM or third parties, depending on operational limitations and strategic options.

6 Discussion and Limitations

The literature review revealed that CaaS is an emerging topic, still in initial stages. However, figures as a potential enhancer to business model innovation, particularly in facilitating the shift from product ownership to service-based models. From the firm's perspective, it is aligned with the existing expertise and based on the existing product. From the customer's perspective, although it requires a change in the nature of the relationship with the product, it may have easier acceptance.

From the landscape provided, it is notable that BaaS is the most advanced type of CaaS in studies and applications. In this sense, the automotive industry provides the primary foundation of knowledge and experience for this business model. Nevertheless, its application has already expanded to other modes of mobility, such as electric scooters.

And to other battery applications, such as those found in the mining industry. Beyond BaaS, a consolidated example in the consumer durables industry, with printer ink, is explored.

The identification of key aspects for each phase of the BM enhances the understanding of the CaaS model structure and supports the decision-making process. The 5 phases identified are manufacturing, contract definition, use phase, contract/usage renewal, and value retention process. Some of the key points identified are manufacturing and reconditioning process responsibilities, storage systems, contract type and pricing, component exchange structure, and tracking and information management.

This study presents certain limitations that should be acknowledged. First, the market review was based exclusively on publicly available sources, without access to internal organizational insights. As a result, the analysis may not fully reflect internal processes faced by companies.

Second, the resulting propositions are primarily descriptive and have not been empirically validated. The conceptual elements identified were not validated through expert interviews, case study analysis or other empirical methods. Moreover, the components of the proposed model have not yet been applied or translated into practical and operational actions, which limits their immediate applicability.

7 Conclusion and Outlook

This study aims to support the transition towards a CaaS regarding the BM design process. The research has explored the current state of the art on CaaS and business model development through a comprehensive literature and market review. By integrating findings from both, a conceptual structure is proposed. The results give a systematic and comprehensive approach, highlighting key points that must be addressed throughout the design of a CaaS.

For further developments, the identified aspects can be explored in depth, as well as case studies application and industry expert's feedback. In addition, the findings may guide the design of practical tools with aim of access key performance indicators, measure maturity and success factors to support the operationalization of the proposed model and its transition. Employing a mixed-methods approach that combines quantitative analyses with qualitative insights from industry practitioners would further strengthen both the theoretical foundation and practical applicability of the findings.

8 Relationship with the SPI Manifesto

The SPI manifesto requests businesses to "use dynamic and adaptable models as needed" [56]. As major industries, including the automotive industry, are moving into PaaS and CaaS models to satisfy the market need of pay-per-use models, this work attempts to contribute in the area, clearly considering consumer needs and expectations.

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9. Discussion and limitations of the proposed methodology

The contributions of this thesis were applied and discussed through different case studies with three industrial partners, as presented in Chapter 6. Building on both literature and industrial experience, we defined five steps to guide companies in their transition toward the circular economy (*See Fig. 15*). Together, these steps form a comprehensive methodology. The four contributions of the thesis primarily address steps two, four, and five. Since each step is essential, their interoperability and compatibility are equally critical. This chapter discusses the interactions between these steps, their limitations, and future perspectives. It is structured in two phases, fulfillin the goals of the bottom-up approach (from circular scenario at the product level toward circular business strategy at the company level): (i) closing and improving loops at the product level, and (ii) monetizing these improved loops at the company level.

9.1. Methodology for leveraging the transition: Phase 1 of closing and improving the loop.

9.1.1. Discussion and limitations

The first phase of the bottom-up approach of the transition toward CE focuses on closing and improving the loop of the product (*See Fig. 15*). The primary targets are existing products already on the market. A preliminary step is to select products with high circularity potentials, i.e., products whose components can be recovered and reused to extend product life. Data on SoH, costs, and environmental impacts for these products are then used in step two to define the most viable circular strategy, specifying when to take back the product and which R-process to apply to each component.

Although the first step is essential for enabling the second, providing guidance on product selection is outside the scope of this thesis. For the application of the decision-aid method (*Contribution 1 in section 6.1)*, the products with the highest circularity potential were identified by industrial experts. This selection was done based on prior knowledge about degradation modes (SoH) and market conditions. In the second step, the ecologically viable circular strategy was defined using assumptions on the costs and environmental impacts of each R-strategy applied to product components, as well as their SoH (*Contribution 2 in section 6.2)*. This contribution thus aimed to close and improve the product loop, although the improvements were based on hypotheses. For this reason, the industrialization of R-strategies is critical, first at a macro level to validate and refine these hypotheses, and later at a micro level once the circular strategy is sufficiently well defined and supported by reliable data. At the macro level, processes are defined in general terms (e.g., product sorting in remanufacturing), while at the micro level, technologies are specified (e.g., manual versus automated conveyor sorting). This third step, partially addressed in the thesis, contributes to further improving closed loops. Step three has been considered through the design of a macro-level circular value chain integrated into a CBM model, developed at step four to align business models with the circular strategies defined in step two.

Missing guidance on step one (selection of a product with high circularity potential) and partial contribution in step three (definition of industrial processes for each R-strategy) represents a limitation in implementing the proposed comprehensive methodology for this first phase of closing and improving loops within the bottom-up approach. Interoperability between these steps is critical because targeting the wrong product can, for instance, demotivate companies, as transition efforts require substantial human, technical, and financial resources across the hierarchy and ecosystem. Similarly, circular strategies that are environmentally viable but economically unattractive are unlikely to be adopted at large scale.

Beyond establishing circularity for existing products, we also addressed the design of new products. To better align design choices with circular strategies and business models, we proposed assessing

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repairability using a user-centric index (*Contribution 3 in section 6.3*). Widely recognized by both consumers and policymakers (e.g., EU regulations), this index provides a criterion-based guideline to improve repairability and, by extension, circularity.

9.1.2. Perspectives

Future work should address market considerations in decision-making. For example, the case study on circuit breakers showed profitable outcomes for the company but higher costs for customers (*See **Article 1** in Section 7.1)*. Since customer acceptance is a key barrier to transition, methods such as game theory could help define circular strategies that balance environmental and social benefits with economic value for both companies and customers' perspectives [87]. This is therefore a continuation of the thesis work.

A second perspective is the development of standardized methods for product selection. Indicators such as the Product Circularity Indicator (PCI) [232], the disassemblability index [233] or the repairability index could help companies identify which products to prioritize for circularity.

A third perspective is the use of the repairability index as a proxy for SoH. Since the SoH assessment is often costly and requires historical or experimental data that are either not available or not accessible, the repairability index could provide a more accessible indicator of product degradation.

Finally, a fourth perspective is the development of methods for mapping processes and technologies at a macro level for each R-strategy (remanufacturing, reuse, refurbishing, repair, repurposing). This would validate assumptions and improve simulations during the definition of ecologically viable circular strategies.

9.2. Methodology for leveraging the transition: Phase 2 of monetizing the closed loop.

The first phase involves adding circular processes to existing linear systems, which requires investments, hiring, and risk-taking. Circular products may be more expensive than new ones, raising adoption challenges. Changing the business model is even riskier, but it offers companies better control over production scheduling, product use, and customer relationships. Importantly, it also enables customers to perceive the intangible value of circular business models (CBM) delivered through tangible products. This underscores the strategic importance of transitioning company business models toward circularity.

Interoperability between steps two, three, and four bridges product-level close and improve loop (phase one) with company-level monetization of the closed loop (phase two). This interoperability ensures that product-level decisions on circular strategies (*step two, Fig. 15*) and the corresponding definition of industrial processes (*step three, Fig. 15*) provide the necessary technical, environmental, and economic data to inform business model design (*step four, Fig. 15*). Without this interoperability, product-level circularity risks remaining technically feasible but economically unscalable, as business models would lack robust data on costs, impacts, and product condition to support credible adoption.

9.2.1. Discussion and limitations

Defining an appropriate CBM is challenging because it requires shifts in company culture and new responsibilities in customer relationships. Building a supportive ecosystem is necessary, but stakeholders often face conflicting constraints, objectives, and opportunities. A systemic perspective is therefore essential (*Contribution 4 in section 6.4*). proved useful for linking CBM features with company capabilities, including the R-strategies selected in step two. Outcomes from step two

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provided more reliable data to fill features such as cost structure, key activities, resources, and partnerships. They also helped prepare assumptions for the quantitative assessment of CBMs.

The quantitative phase, which involves designing the value chain of selected CBMs and assessing their socio-economic and environmental performance, was only partially covered in the thesis. For instance, a macro-level value chain was designed for a component-as-a-service model (***Conference Article 6****, section 8.6*). This limitation points to the need for further quantitative analysis.

9.2.2. Perspectives

Future work should focus on designing value chains for use-oriented and result-oriented PSS archetypes, such as subscription and pay-per-use models. While the qualitative assessment method (*Contribution 4 in section 6.4*) developed in this thesis identifies which PaaS models best fit a company's capabilities, it does not yet define in detail how the associated value chains should be structured. Designing such value chains requires specifying roles, flows of products, components, and information, as well as responsibilities across the ecosystem of stakeholders (OEMs, suppliers, service providers, customers). It also requires evaluating how R-strategies such as remanufacturing, repair, or refurbishing can be operationalized within these models, as we did for the design of the value chain of the componenet-as a service model.

A second perspective is the development of a comprehensive decision-support method that integrates quantitative simulations of the socio-economic and environmental performance of PaaS models. This would extend the current decision tools—namely, the product-level decision-aid method and the qualitative morphological box—by incorporating CBM value chain design and explicit trade-offs between performance dimensions. Economic indicators (e.g., costs, revenues, return on investment, gross margin) could be assessed using Life LCC, while environmental indicators (e.g., climate change, ozone depletion) would rely on LCA. Technical indicators could be derived from SoH evaluations or repairability indices, and social indicators could reflect customer perspectives, particularly regarding acceptance and perceived value. Together, these dimensions would provide a robust, multi-criteria framework for evaluating and comparing PaaS models under realistic implementation scenarios.

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10. Conclusion

10.1. Context of the thesis.

Human activities have exceeded six of the nine planetary boundaries, pushing humanity outside the stable conditions of the Holocene. Climate change, biodiversity loss, and resource depletion are now urgent global threats, with industry alone responsible for nearly a quarter of greenhouse gas emissions. International frameworks such as the Paris Agreement, the European Green Deal, and the Ecodesign for Sustainable Products Regulation (ESPR) aims to reduce these impacts by promoting carbon neutrality and circularity. National initiatives, such as France's AGEC law, reinforce this shift by mandating indices and penalizing planned obsolescence. Together, these actions create a strong policy ecosystem encouraging companies to move from linear "take–make–dispose" models toward circular business models.

Despite this progress, the implementation of the circular economy remains uneven. Many companies still struggle to integrate sustainability into their core activities due to several barriers. External barriers include fragmented regulations, rigid supply chains, and market uncertainty. Internally, firms often lack coherent circular strategies, reliable product data, or the skills and infrastructure needed for lifecycle thinking. Moreover, circular processes themselves consume resources and can trigger rebound effects, raising doubts about their net environmental benefits. These barriers highlight the need for robust methods to leverage the transition of companies that integrate technical, social, economic, and environmental dimensions. Furthermore, addressing these challenges requires a systemic approach, in which manufacturers commit to sustainable production while consumers engage in responsible consumption.

In this context, the thesis focuses on how companies can transform internal barriers, such as operational strategy, knowledge and competencies, and the business case, into enablers for transitioning existing products towards circularity through coherent circular business models.

10.2. Research questions and methodologies

This thesis is positioned at the intersection of engineering, sustainability, and business innovation domains, addressing the internal barriers companies face when shifting toward circularity.

The literature shows progress in areas such as optimization of R-strategies, LCA/LCC methods, SoH assessment methods, and CBM innovation design methods, yet existing approaches remain fragmented, product-specific, and difficult to replicate across sectors. This leaves firms struggling to decide when to take back products, what to do with the collected used products and how to value them to customers so that they perceive its intangible added value.

It is within this context that the main gap addressed by this thesis emerges: the absence of integrative knowledge and methods to help companies define appropriate circular strategies for existing products, while simultaneously considering technical, environmental, and economic criteria (*See Chapter 4*). To fill this gap, the thesis addresses five research questions.

1- RQ_1.1 determines **when to take back** a product by jointly optimizing technical, economic and environmental criteria using an algorithm.
2- RQ_1.2 determines **what circular R-strategy to apply at take-back,** using a decision tree based on SoH thresholds to route components to reuse, repair, refurbish, remanufacture, or recycle.
3- RQ_2.1 develops a generic **framework to assess product SoH** during use in a circular context, leveraging hybrid (model-based and data-driven) approaches.

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4- RQ_2.2 evaluates the extent to which product design enables SoH improvement, operationalized through a user-centric Repairability Index.
5- RQ_3 examines the **match between PaaS/CBM options and a firm's capabilities**, structured via a morphological box to reveal alignment and gaps.

Across these questions, the research methodology in Chapter 5, combines systematic literature reviews, experts' elicitations, semi-structured interviews and participatory workshops to ensure conceptual rigor and practical relevance in the definition of the comprehensive method (including the decision-aid, the SoH assessment, the user-centric repairability index, the morphological box and the value chain creation) and the applications in industrial cases.

10.3. Contributions and perspectives

This thesis positions itself at the intersection of product-level engineering and firm-level business model innovation by proposing a comprehensive methodology to leverage the transition. The methodology is made of five steps to guide the company from a linear to a circular economy. The methodology deliberately follows a bottom-up approach: from a circular scenario at the product level toward a circular business strategy at the company level). The first phase of the methodology consists of **closing and improving the loop** at the product level, to optimize performance across technical, environmental, and economic dimensions. The social dimension of circularity is not within the scope of this thesis. This phase contains three steps: first, identifying a product with a higher potential of circularity; second, defining the ecologically viable circular strategy (*Contributions 1 and 2*), and third, defining the processes for each R-strategy at both macro and micro levels. The second phase of the methodology consists of **monetizing the closed loop** through use-oriented and result-oriented PSS archetypes, also known as PaaS models. This second phase contains the fourth step, which consists of defining the CBM model aligned with the circular strategy (*Contribution 4*). As the two phases evolve iteratively, the redesign of a new product is highlighted at the fifth step to improve the circularity (*Contribution 3*).

Together, the four contributions fully answer RQ_1.1, RQ_1.2, and RQ_3, while partially addressing RQ_2.1 and RQ_2.2.

Contribution 1- Decision-aid method

It is a generic method implemented in an Excel Format tool, which combines SoH-based decision trees, P-LCA, and P-LCC methods to define the most **relevant R-strategy** per component and the **optimal take-back time**. It fully answers the question RQ_1.1. Applied to an electrical circuit breaker with an industrial partner 1, it identified remanufacturing as the best option, cutting CO_2 emissions by ~4–5% and increasing profit by ~22%. This first contribution demonstrates how to close and improve the loop. The main limitations are assumptions on degradation, approximated impact/cost data, and reliance on expert-based thresholds.

Contribution 2- SoH assessment framework

A conceptual framework integrating Condition-Based Maintenance and PHM to derive hybrid SoH indicators (data- and physics-based), aggregate them to the product level, and guide R-strategies via a threshold decision-tree. While not applied to a real case, SoH values were assumed in the circuit breaker case study in Contribution 1. Together with Contribution 1, they are used in an iterative way to define the circular strategy for closing and improving the loop at a product level. Its main limitation is the availability of reliable data.

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Contribution 3- Repairability Index user-centric method.

It is a method based on EN 45554 and AHP weighting, designed to integrate stakeholder perspectives (design, maintenance, independent repairers, consumers). Implemented in Excel, it estimates repairability over the product lifecycle and supports design-for-circularity. Applied to a heat-sealing packaging machine with a second industrial partner, it revealed profile-dependent RI values (8.4 for design, 8.1 for consumers, ~17% lower for maintenance), guiding redesign toward greater circularity. This contribution helps improve the loop by embedding repairability at the design stage. Limitations include reliance on expert judgment and early-stage modelling of RI evolution.

Contribution 4- Qualitative CBM/PaaS assessment (morphological box).

A workshop-based matrix and heat-map linking company capabilities to five PaaS archetypes features (leasing, renting/sharing, pooling, pay-per-service-unit, functional result). Applied to the water department of a third industrial partner, it identified pay-per-service-unit and functional result as the most aligned models, highlighting both strengths and risks. This contribution supports monetizing closed loops. Limitations include a non-exhaustive option set and the need for further workshops and quantitative assessments.

The methodology, although missing guidance on product selection (step 1) and on industrial process design (step 3), is applicable under the use of a product-specific approach at step 1 and macro-level assumptions at step 3. Moreover, consumer acceptance was not addressed. Although the electrical circuit breaker case showed that while circularity was profitable for the company, it increased costs for customers. Similarly, the CBM assessment method stops short of full quantitative evaluation of value chains, which remains essential for reliable adoption.

Future perspectives follow two phases of the bottom-up approach. In Phase 1 (closing and improving loops), further research should:

(i) integrate market acceptance, for instance, through game theory models to balance company and customer value;
(ii) standardize methods for product selection (e.g., Product Circularity Indicator, repairability index);
(iii) explore the repairability index as a proxy for SoH when data is lacking; and (iv) map R-strategy processes at both macro- and micro-levels to validate assumptions and simulations.

In Phase 2 (monetizing loops), perspectives include:

(i) designing detailed value chains for use- and result-oriented models such as subscription or pay-per-use;
(ii) developing integrated decision-support tools that simulate the socio-economic and environmental performance of PaaS models.

In summary, the thesis proposes a systemic and iterative methodology that links product-level decisions with company-level strategies, equipping sustainability managers with actionable tools to close, improve, and monetize circular loops.

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Résumé étendue

1. Introducttion

Cette thèse s'inscrit dans un contexte de pressions environnementales croissantes liées au modèle économique linéaire, fondé sur l'extraction, la production, la consommation et l'élimination des biens [2]. L'élévation des niveaux de vie et la demande pour des produits et services toujours plus sophistiqués ont entraîné une surexploitation des ressources naturelles, une hausse des consommations énergétiques et une dégradation des écosystèmes. Le cadre des limites planétaires montre que plusieurs processus critiques, notamment le changement climatique, l'intégrité de la biosphère et les cycles biogéochimiques, ont déjà dépassé les seuils de sécurité, principalement en raison des émissions de gaz à effet de serre issues de secteurs clés [3]. Face à ces constats, des politiques publiques structurantes ont été mises en place à différentes échelles, depuis l'Accord de Paris jusqu'au Pacte vert européen, au plan d'action pour l'économie circulaire, au règlement sur l'écoconception des produits durables et à la loi française AGEC, afin de réduire les impacts environnementaux et de promouvoir des modèles économiques circulaires [7–9,16].

Ces dispositifs ont commencé à transformer les comportements des consommateurs et les stratégies industrielles. L'affichage des indices de réparabilité a renforcé la sensibilisation du public [17,18], tandis qu'un nombre croissant d'entreprises publient des rapports de durabilité, mesurent leurs émissions par l'analyse du cycle de vie et investissent dans des projets de décarbonation et de circularité. L'économie circulaire apparaît ainsi comme un levier central de transformation, reposant sur la réduction des flux de matière, l'allongement de la durée de vie des produits, la réutilisation, le recyclage et l'appui sur les technologies numériques [25,26].

Cependant, un écart persiste entre les ambitions réglementaires et leur mise en œuvre effective. De nombreuses entreprises, en particulier les PME, font face à des freins réglementaires, économiques, organisationnels et technologiques. Le manque de compétences en conception circulaire, l'insuffisance de données de traçabilité, l'incertitude sur la rentabilité des modèles circulaires et les risques d'impacts environnementaux non maîtrisés constituent des obstacles majeurs [23,24,28].

Dans ce contexte, cette thèse se concentre sur trois barrières internes jugées prioritaires : la structuration des stratégies opérationnelles de circularité, le développement des compétences organisationnelles et la démonstration de la viabilité économique des modèles d'affaires circulaires. Elle vise à proposer des méthodes d'aide à la décision permettant d'évaluer simultanément la faisabilité technique, environnementale et économique des stratégies de circularité, en s'appuyant notamment sur l'analyse du cycle de vie (ACV) et sur l'extension optimisée de la durée d'usage des produits.

2. Etat de l'art, verroux et questions de recherche

La littérature scientifique établit solidement l'économie circulaire comme un levier central de réduction des impacts environnementaux des systèmes industriels. Les travaux d'Ellen MacArthur Foundation [25] ont formalisé les principes fondamentaux de la circularité, tandis que Konietzko et al. [26] et Bocken et al. [62] ont structuré les stratégies de bouclage, ralentissement, réduction et régénération des flux de ressources au niveau des modèles économiques. De nombreuses études s'appuient également sur l'analyse du cycle de vie pour quantifier les performances environnementales de stratégies telles que la réparation, la remanufacturation ou le recyclage [37,38], ainsi que pour explorer les effets rebond associés [39]. Les travaux institutionnels et académiques ont aussi identifié les freins majeurs à l'adoption de la circularité dans les entreprises, notamment à travers

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des enquêtes empiriques conduites par OPEO et INEC [30], des analyses de politiques publiques par CEPS [32], et des synthèses systématiques comme celle d'Assmann et al. [31], qui regroupe 54 déterminants structurés en huit catégories (culture, régulation, marché, stratégie, collaboration, opérations et connaissances). Enfin, plusieurs rapports soulignent le rôle croissant des technologies numériques dans la traçabilité des flux et le pilotage des chaînes de valeur circulaires, tout en mettant en évidence le besoin d'outils accessibles aux PME [34–36].

Malgré ces contributions importantes, la revue de littérature fait apparaître trois verrous majeurs qui structurent la problématique de cette thèse.

Verrou_1 : Absence de cadres méthodologiques intégrés et opérationnels

Les travaux existants traitent souvent séparément l'évaluation environnementale par ACV, la conception produit, la stratégie d'entreprise et la logistique inverse [26,27,31]. Peu de méthodes permettent d'orchestrer ces dimensions dans un processus décisionnel cohérent, applicable aux systèmes de production réels.

Pour répondre à ce gap, nous avons formulé la question de recherche (QR) suivante :

QR_1 : Comment déterminer une strategie circulaire qui soit écologiquement bénéfique et économique rentable pour un produiot d'une entreprise ?

Cette question a été subdivisée en deux sous questions à savoir :

RQ_1.1 : Quand récupérer un produit en service pour lui offrir une seconde vie de façon optimale sur les plan économique et environnemental ?
RQ_1.2 : Quelle est la stratégie circulaire appropriée au moment de la reprise du produit ?

Les questions précédentes se basent sur la notion d'état de santé d'un produit. Ce terme représente l'état de dégradation d'un produit. Cependant, l'évaluation de cet état de santé dans un contexte d'économie circulaire demeure complexe. Dans la literature, ces méthodes d'évaluation de l'état de santé sont principalement appliquées aux batteries lithium-ion. Cette limitation à ainsi donné suite au deuxième verrou adressé dans la thèse.

Verrou_2 : Manque de connaissances sur l'état technique du produit en matière de circularité.

La revue de la littérature dans ce domaine a révélé que les méthodes d'évaluation de l'état de santé du produit pendant sa phase d'utilisation contribuent à améliorer la boucle. Il existe très peu de méthodes pour évaluer l'état de santé d'autres types de produits, tels que les éoliennes [101], les roulements [102] et les boîtes de vitesses [103]. Ainsi, deux questions ont été formulées :

RQ_2.1 : Comment évaluer l'état de santé d'un produit pendant sa phase d'utilisation dans un contexte circulaire ?
RQ_2.2 : Comment mesurer dans quelle mesure la conception d'un produit permet d'améliorer son état de santé ?

Les deux précédents verrous était plus orienté sur la value résiduelle du produit d'une entreprise. La literature souligne que la conception et l'implémentation de la circularité dans une entreprise est autant concernané par la science de l'ingénieurie que par la gestion de l'entrprise, sa culture, son identité et son organisation. Les deux verrous précédents concernen le fait de concevoir et

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implémenter une chaine circulaire sur un produit existant. Une fois cela fait, un verrou important demeure, celui que la valorisation commerciale de la chaine circulaire des produits avec un modèle économique circulaire. Ceci, nous conduit au troisième verrou qui est celui de l'avluataion des modèles conomique adaptés aux activités des entreprises et qui favorise la chaine circulaire.

Verrou_3 : Difficultés à évaluer les modèles économiques alternatifs qui favorisent la circularité.

Si de nombreux travaux soulignent le potentiel économique de la circularité, peu proposent des outils permettant de relier performances environnementales, contraintes industrielles et création de valeur [34–36]. L'accessibilité de ces outils pour les organisations disposant de ressources limitées reste faible. Ainsi, pour adresser ce verrou, nous avons formulé la troisième question de recherche suivante.

RQ_3 : Comment évaluer le potentiel d'adéquation d'un modèle économique circulaire (économie de la fonctionnalité) avec les activités d'une entreprise ?

Pour répondre à chaque question de recherche, nous avons établi des hypothèses qui nous ont guidés dans le choix des méthodes de recherche appropriées pour l'étude.

3. Hypothèses et méthodologies de recherche appliquées

Afin de répondre aux questions de recherche, la thèse s'appuie sur cinq hypothèses principales reliant stratégies circulaires, évaluation technique des produits et modèles économiques (*voir Fig. 14*).

Pour la première question de recherche (**QR_1)**, deux hypothèses sont posées à savoir **H1** et **H2** concernent respectivement **RQ_1.1** et **RQ_1.2**. La première **(H1)** postule que la détermination du moment optimal de reprise d'un produit en fin d'usage doit intégrer conjointement des critères techniques, économiques et environnementaux afin de définir une stratégie circulaire réaliste. Cette première hypothèse concerne principalement la question de recherche **QR_1.1.** La seconde hypothèse **(H2)** suppose que l'utilisation de seuils d'état de santé dans des arbres de décision permet de sélectionner de manière robuste la stratégie de valorisation la plus pertinente parmi les options de réparation, reconditionnement, remanufacturation ou recyclage. Cette hypothèse concernen la question de recherche **QR_1.2**

Pour les deux deuxièmes questions de recherche, la thèse émet l'hypothèse **(H3)** qu'une évaluation hybride de l'état de santé, combinant modèles physiques et approches fondées sur les données, constitue une voie pertinente pour appuyer la circularité. Cete hypothèse concerne la question **QR_2.1.** La thèse postule également en **(H4)** que l'indice de réparabilité peut servir d'indicateur de conception clé pour estimer le potentiel d'extension de durée de vie des produits et guider les choix d'écoconception. H4 concerne la question **QR_2.2.**

Enfin, pour la troisième question de recherche (**QR_3)**, il est supposé en **(H4)** que l'adéquation entre les exigences des modèles économiques circulaires, en particulier les modèles Product-as-a-Service (PaaS), et en **(H5)** que les capacités internes des entreprises peuvent être structurée au moyen d'un cadre morphologique inspiré des canevas de modèles d'affaires circulaires.

Sur le plan méthodologique, la thèse combine revues systématiques de littérature selon le protocole PRISMA, approches fondées sur l'expertise industrielle et académique, entretiens semi-directifs, ateliers participatifs et méthodes multicritères d'aide à la décision. Les revues de littérature ont permis d'identifier les méthodes existantes relatives au choix des stratégies circulaires, à l'évaluation du SoH, à la réparabilité et aux modèles Product-as-a-Service. Les entretiens d'experts et les ateliers ont servi

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à adapter ces méthodes à des contextes industriels concrets, à sélectionner des critères pertinents selon les profils d'acteurs et à pondérer ces critères au moyen de techniques telles que l'Analytic Hierarchy Process.

Des outils d'optimisation multicritère ont été mobilisés pour calculer des temps de reprise optimaux des produits, intégrer des seuils de SoH dans des arbres de décision et tester la robustesse des modèles par analyses de sensibilité. Enfin, une matrice morphologique a été développée et validée en atelier afin de relier de manière systématique les caractéristiques des modèles Product-as-a-Service aux capacités organisationnelles des entreprises.

Cette combinaison méthodologique vise à produire des cadres opérationnels, applicables en contexte industriel réel, pour appuyer la conception et le déploiement de stratégies et de modèles d'affaires circulaires.

4. Apports de la thèse

Les apports s'inscrivent dans une méthode globale en cinq étapes (*Fig. 15*). Il s'agit d'une méthode d'aide à la décision structurée en cinq étapes couvrant l'ensemble du processus de transition vers la circularité. La première étape consiste à définir le produit existant le plus approprié pour une étude de circularité. Il s'agit d'un produit avec un fort potentiel d'extension de durée de vie. La deuxième étape porte sur la caractérisation du produit définit, ses composants critiques et les boucles circulaires envisageables selon les logiques de fermeture. Elle consiste à définir la stratégie circulaire la plus approprié pour le produit en prenant en compte les composantes économique et environnementaux. Il s'agit ainsi du choix du moment optimal de reprise d'un rpoduit et de la stratégie de valorisation associée. La troisième étape conciiste à affiner les mod-les élaboré en étape 2 avec des données plus précises tout en intégrant des techologie de process de plus en plus adapté à l'activité de l'entreprise. La quatrième étape vise à intégrer la valorisation économique de la chaine circulaire concu à la stratégie commerciale de l'entreprise. Elle permet de sélectionner le modèle économique circulaire, en particulier les configurations Product-as-a-Service, le mieux aligné avec les capacités de l'entreprise pour assurer la viabilité de la boucle circulaire. La cinquième étape consiste à reconcevoir le produit de facon à ce qu'il supporte la strategie de circulairté définie pour ainsi assurer une rentabilité économique à l'entreprise et une réduction considérable de son impact environnement.

Les apports de la thèse s'intègrent aux étapes 2, 4 et 5.

A la deuxième étape, nous avons deux apports :

- Le premier apport (A1) est une méthode d'aide à la décision pour sélectionner la stratégie circulaire optimale d'un produit en fonction du temps de reprise, en combinant critères techniques (état de santé), environnementaux et économiques dans un arbre de décision couplé à un algorithme d'arbitrage. Cet apport est implémenté dans un outil générique en Excel, et est ainsi applicable à différents types de produits. Appliquée à un disjoncteur de puissance du partenaire industriel 1, il a permis d'identifier des temps de reprise optimaux conduisant à une remanufacturation réduisant les émissions de CO_2 de 4–5 % et augmentant les profits de 22 %. Cet apport (A1) répond aux questions de QR_1.1 et QR_1.2. Il est valorisé dans l'article 1 ainsi que dans les articles de conference 1 et 2. Ses limites concernent notamment la modélisation des cycles multiples, l'absence de perspectives clients et la prise en compte partielle du redesign produit.

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- Le deuxième apport (A2) est soutenu par un cadre générique d'évaluation du l'état de santé combinant analyses de criticité, méthodes de prognostic et de santé des systèmes et arbres de décision fondés sur des seuils. Cet apport répond partiellement à la question de recherche QR_2.1 et a été valorisée dans les articles de conference 2 et 3. Son application industrielle reste limitée, bien que les seuils aient été exploités dans l'étude de cas du disjoncteur électrique développée dans l'apport 1 (A1).

A La quatrième étape de la méthode globale en Fig. 5 nous avons proposé une méthode d'évaluation de la faisabilité de replication d'un modèle éconmique circulaire dit d'économie de la fonctionalité (spécifiquement le cas du modèle de paiement à l'usage). Cette méthode est l'apport 4 (A4) de la thèse.

- L'apport 4 à une méthode qualitative d'évaluation des modèles économiques circulaires fondée sur une boîte morphologique reliant les capacités organisationnelles aux archétypes Product-as-a-Service. Appliquée au département "eau" du partenaire industriel 3, elle a permis d'identifier les modèles pay-per-service-unit et functional result comme les plus adaptés, tout en mettant en évidence les capacités à renforcer pour leur mise en œuvre. Cette contribution répond entièrement à la question QR_3. L'apport 4 a été valorisée dans l'article 4 ainsi que dans les articles de conference 5 et 6.

Finalement, à la cinquième étape, nous avons proposé une méthode d'évaluation de l'indice de réparabilité centré profils d'usagers, nommé RIUP. La méthode est implémentée en outil Excel et consitue ainsi l'apport 3 (A3) de la thèse.

- La méthode RIUP propose une évaluation de la réparabilité tenant compte des profils de conception, de maintenance et de réparation indépendante, ainsi qu'une estimation de son évolution au cours du cycle de vie. Testée sur plusieurs produits et appliquée notamment à une machine de thermoscellage du partenaire industriel 2, elle révèle des écarts significatifs entre profils (8,4/10 pour le design, 8,1/10 pour l'utilisateur final, −17 % pour la maintenance). Cet apport répond partiellement à la question QR_2.2. Cet apport de la thèse (A3) a été diffusée dans l'article 2, l'article 3 (en collaboration avec un autre laboratoire) et l'article de conference 4.

5. Les limitations

Les quatre apports de la thèse sont intégrés dans une méthodologie globale en cinq étapes visant à accompagner les entreprises dans leur transition vers l'économie circulaire, depuis la fermeture et l'amélioration des boucles au niveau produit jusqu'à leur monétisation au niveau de l'entreprise.

Toutefois, certaines étapes restent partiellement couvertes. La sélection initiale des produits à fort potentiel circulaire (*Fig. 15, étape 1*) repose encore sur l'expertise industrielle et non sur des indicateurs standardisés, tandis que la définition détaillée des procédés industriels associés aux stratégies de circularité (*Fig. 15, étape 3*) demeure limitée à un niveau macro. De plus, les évaluations techniques et environnementales mobilisent encore des hypothèses, ce qui souligne la nécessité de validations industrielles à plus grande échelle.

Concernant la phase de fermeture et d'amélioration des boucles (*Fig. 15, étape 2*), plusieurs perspectives se dégagent. L'intégration des préférences et de l'acceptabilité clients dans les décisions, notamment par des approches issues de la théorie des jeux, constitue un prolongement essentiel. Le développement de méthodes normalisées pour prioriser les produits à circulariser, l'usage de l'indice

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de réparabilité comme proxy de l'état de santé lorsque les données sont rares, ainsi que la formalisation de cartographies technologiques détaillées pour chaque stratégie circulaire figurent parmi les axes majeurs de recherche future.

Dans la phase de monétisation des boucles (*Fig. 15, étape 4*), la thèse met en évidence l'importance stratégique des modèles économiques circulaires pour assurer le déploiement à grande échelle des solutions techniques. Si la méthode qualitative d'évaluation de la faisabilité de replication des modèles économiques circulaires permet d'identifier les modèles PaaS les plus adaptés aux capacités des entreprises, la conception quantitative complète des chaînes de valeur et l'évaluation multicritère de leurs performances économiques, environnementales, techniques et sociales restent à approfondir.

Les perspectives incluent ainsi le développement d'outils intégrés combinant simulations d'analyse de cycle de coûts (ACC) et d'analyse de cycle de vie (ACV), indicateurs techniques issus de l'état de santé ou de la réparabilité, et critères sociaux liés à l'acceptation client, afin de fournir un cadre décisionnel robuste pour comparer et déployer des modèles Product-as-a-Service en conditions réelles.

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