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Key performance indicators for sustainable remanufacturing: A literature review and methodological framework

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ABSTRACT

Remanufacturing is a key strategy in the circular economy to support sustainability and address climate change. Its adoption is a challenging process that requires analyzing several factors about products, processes, and the supply chain. Furthermore, when considering the three pillars of sustainability— economic, environmental, and social—for the integration of remanufacturing practices, the difficulty for decision-makers increases significantly. Hence, practitioners and academics have invested considerable effort in developing various key performance indicators (KPIs) to evaluate remanufacturing, circular economy strategies, and sustainability. However, a concurrent focus on sustainable remanufacturing (SR) is still lacking. This study employs a systematic literature review (SLR) to define sustainable remanufacturing, identify KPIs, and provide practical application guidance. The developed SLR, based on 106 Scopus documents, identified a total of 1021 KPIs related to SR. Among these indicators, 32 economic, 16 environmental, and 3 social indicators were the most frequently referenced in the literature. The SLR also identified six frequent fields of use or application for the KPIs, along with their links to smart sustainable remanufacturing. This study also presents a methodological framework focused on assessing products from disassembly, recycling, and remanufacturing in a sustainable manner, to guide decision-makers in using KPIs in the transition to SR.

1. Introduction

Remanufacturing stands out among circular economy (CE) strategies for combating material depletion and global warming by reducing material and energy consumption (Russell & Nasr, 2019). Indeed, through remanufacturing, the expected end-of-life (EoL) of a used item can be prolonged, thereby initiating a new full-service cycle (Ingarao, 2017; Mejía-Moncayo et al., 2023). Through remanufacturing operations, the product's functionalities are restored to their original, as-new levels. This process enables the extension of the product's lifespan beyond its EoL. As a result, it offers a new full-service cycle and reduces materials and energy consumption compared to manufacturing new products (Russell & Nasr, 2023).

Despite its advantages, the adoption of remanufacturing is a challenging process, and there is currently a growing demand to address CE strategies sustainably (Fatimah & Aman, 2018). Companies face significant challenges in balancing environmental and economic goals, often prioritizing environmentally friendly practices only when they offer economic advantages (Gusmerotti et al., 2019; Lieder et al., 2017). Additionally, CE implementations often overlook social impacts, prioritizing only environmental and economic criteria (Kaya et al., 2022; Tsalis et al., 2022). This raises concerns about its impacts, as it should be rational for CE implementations to be conducted in a sustainable manner.

Key performance indicators (KPIs) are essential tools for guiding decisions and measuring business performance. In the process of transitioning to sustainable remanufacturing (SR), KPIs are crucial at various stages (Mejía-Moncayo et al., 2025). Different literature reviews present a considerable number of KPIs to assess sustainability and CE strategies. Some of them are described in the following paragraph. Mengistu & Panizzolo (2023) identified 1041 KPIs (290 economic, 410 environmental, and 341 social) to measure industrial sustainability. These KPIs can evaluate the sustainable performance of products, processes, raw materials, suppliers, or companies. Contini & Peruzzini (2022) presented 117 KPIs for the same purpose. Joung et al. (2013) categorized the quantifiable indicators related to sustainable manufacturing, while

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Table 1
Focus of current literature reviews on remanufacturing or sustainability KPIs.

Authors	Economic Sustainability	Environmental Sustainability	Social Sustainability	Circularity	Remanufacturability	Disassembly	Product Design	Closed-loop supply chains
Ansari et al. (2022)						✓	✓	✓
Contini & Peruzzini (2022)	✓	✓	✓					
Halter et al., (2025)	✓	✓	✓	✓				
Henao et al. (2021)			✓					
Hernandez Marquina et al., (2022)	✓	✓	✓	✓				✓
Joung et al. (2013)	✓	✓	✓					
Kristensen & Mosgaard (2020)	✓	✓	✓	✓	✓	✓		
Kurt et al. (2021)		✓		✓				✓
Mesa et al., (2024)	✓	✓		✓				
Matos et al. (2023)	✓	✓	✓	✓	✓	✓		
Mengistu & Panizzolo (2023)	✓	✓	✓					
Priyono et al. (2016)	✓	✓				✓	✓	
Saidani et al. (2019)				✓	✓	✓	✓	
This study	✓	✓	✓	✓	✓	✓	✓	✓

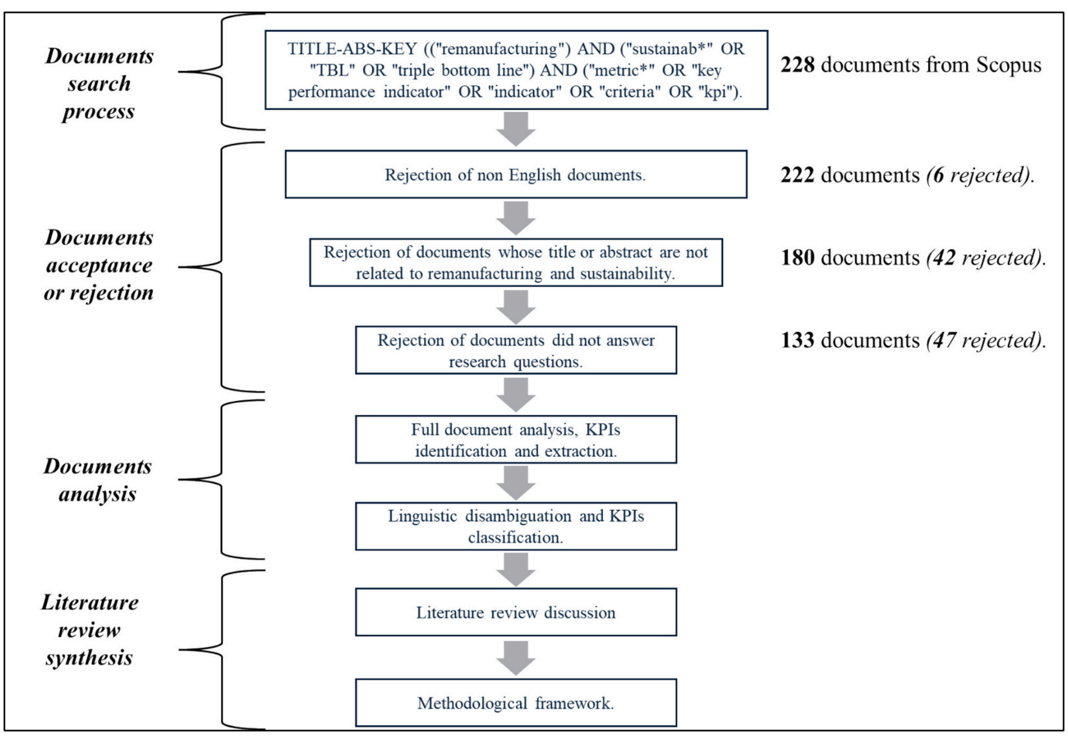

Fig. 1. Systematic Literature Review methodology steps implemented in this study.

Henao et al. (2021) focused their study on social performance indicators for sustainable manufacturing.

Similar studies have been conducted on the CE; Saidani et al. (2019) synthesized and classified 55 KPIs to assess circularity at various levels and for different CE strategies. Halter et al. (2025) provided a comprehensive techno-sustainable analysis of 67 CE KPIs at the micro (company) and nano (product) levels. Kristensen & Mosgaard (2020) and Matos et al. (2023) focused their studies on micro-level indicators for the CE. Kurt et al. (2021) introduced a classification tool for circular supply chain indicators. Mesa et al. (2024) performed a critical review and assessment of indicators for circular bioeconomy. Priyono et al. (2016) addressed disassembly for remanufacturing from a strategic perspective. Hernandez Marquina et al. (2022) analyzed the sustainable performance of circular supply chains, while Ansari et al. (2022) identified and evaluated KPIs for the remanufacturing supply chain.

Table 1 summarizes the focus addressed by the literature review

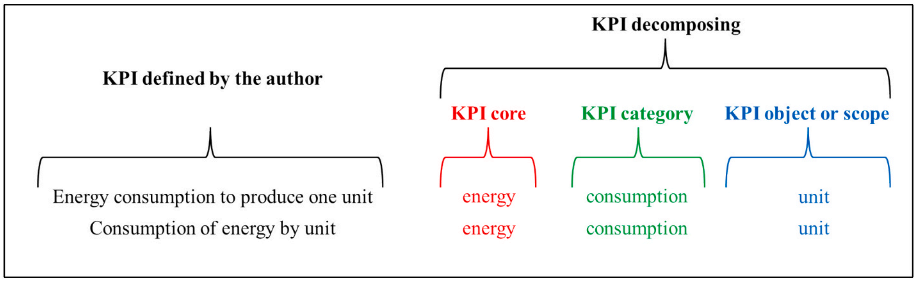

Fig. 2. Example of a key performance indicator decomposing for the disambiguation process.

studies mentioned above. These studies encompass KPIs, metrics, or indices related to economic, environmental, and social sustainability, as well as circularity, remanufacturability, disassembly, product design, and closed-loop supply chains (CLSC). The broad range of KPIs demonstrates the interest and engagement of both academia and industry in assessing sustainability and CE strategies in the industrial sector. However, the extensive range of KPIs makes it challenging to identify the most appropriate ones to use in a specific case or situation. Table 1 also shows that sustainability and CE indicators are frequently studied as separate or partially interrelated entities. This study conducts a systematic literature review (SLR) to address the distinct categories described in Table 1. The aim is to provide a holistic overview of KPIs in SR, along with their fields of application and methodological implementation. Indeed, this SLR seeks to answer the following research questions (RQ):

RQ1: What are the main KPIs reported in the literature related to SR?

RQ2: What are the main fields of application of the KPIs identified in **RQ1**?

RQ3: How to define SR?

RQ4: How to guide decision-makers in using the KPIs identified in the previous research questions?

The first question refers to identifying the main KPIs across the three dimensions of sustainability in remanufacturing. The second question enables the determination of the fields of application of KPIs in SR. The third question builds upon the previous ones and aims to deepen the understanding of SR. The fourth question addresses the practical implementation of the identified KPIs to support decision-makers in the transition to SR. The developed SLR also aims to contribute to the academic discussion by identifying research gaps and opportunities in sustainable remanufacturing.

The presented study is organized as follows: Section 2 describes the research methodology. Section 3 presents the main KPIs for sustainable remanufacturing. Section 4 addresses, through a literature review, the principal fields of application of the KPIs, and their links with smart sustainable remanufacturing. Section 5 presents the analysis and discussion of the literature review. Section 6 introduces a proposed methodological framework. Finally, section 7 presents the conclusions.

2. Research methodology

In this study, a SLR was conducted to determine the main KPIs in SR. Following the methodology outlined by Tranfield et al. (2003), this process was formulated to answer four research questions (RQ1–RQ4, introduced in section 1). A detailed overview of the methodology used in this study is provided in Fig. 1. This figure outlines the methodological steps involved, including the document search process, criteria for acceptance or rejection of documents, document analysis, and synthesis of the literature review.

The methodology starts by conducting a document search process, which is performed using the Scopus database as a primary source of information. The search process encompasses journal articles, conference papers, and book chapters to cover a broad range of relevant documents that address the research questions. The documents included in this study must be written in English and span the period from 2000 to 2025, including all areas treated by Scopus. The search process used a combination of keywords that integrates remanufacturing and various synonyms of sustainability ("sustainab*", "triple bottom line" or "TBL") and KPIs ("metric*", "key performance indicator", "indicator", "criteria", or "kpi"), Fig. 1 describes the search string used in Scopus.

Once the document search process was finished, the acceptance or rejection of documents was conducted in a second step, as described in Fig. 1. A total of 228 documents were obtained through the search process. The documents' acceptance or rejection was based on considerations of language and relevance to SR and the research questions. During the initial classification phase, 6 documents non-written in English were rejected based on language: 3 in Chinese, 2 in German, and 1 in Portuguese. Based on the examination of the title and abstract of the documents, 47 documents were rejected. Indeed, these documents were not directly related to remanufacturing and sustainability. After reading and analyzing the documents, 42 of them were rejected because they did not contribute to answering the research questions. As a result of these steps, a final set of 133 documents was compiled, which were then used for the analysis performed in this study. The distribution of documents at the acceptance and rejection stages is depicted in Fig. 1.

A comprehensive assessment of each document entails a complete analysis of the document, including KPI identification and extraction, as well as the linguistic disambiguation of the identified KPIs. The complete document analysis revealed six primary fields of application for the KPIs in the analyzed literature. These include: 1) the sustainability assessment of remanufacturing products, processes, or companies, 2) the design of products for remanufacturing, 3) product disassembly assessment, 4) product remanufacturability assessment, 5) remanufacturing circularity assessment, and 6) design, planning, or optimization of closed-loop supply chains for remanufacturing. These categories were also used to group the documents during the analysis and presentation of the results.

The KPIs identified in the documents were extracted and consolidated into a Microsoft Excel database, allowing for easy access and analysis. The database contains various metadata, including the authors, title, source or journal name, publication year, and country of origin of the document. It also includes the KPIs, its classification as economic, environmental, or social indicators, its primary use/application field, and the document's main theme.

Once the database compilation was completed, a linguistic disambiguation process was implemented to account for the diverse ways in which authors may mention the same indicator. The process involved decomposing each KPI into its core, *category*, and the *object or scope* of its application field. An example of this process is illustrated in Fig. 2, where two authors wrote the same KPI differently. They share the same KPI core (energy), KPI category (consumption), and KPI object or scope (unit). KPI decomposition allows for grouping, classification, and establishing the frequency of use of the KPI, along with the literature analyzed.

After completing this process, a literature review synthesis was conducted to classify and analyze the KPIs, summarize the contributions of each document, and propose a methodological framework based on

Table 2
Distribution of economic key performance indicators identified in the literature in four or more documents across their main fields of application (Table criteria: SA-Sustainability assessment, **RCLSCs** - Remanufacturing CLSCs, **RCir** - Remanufacturing circularity assessment, **Rem** - Remanufacturability, **Dis** - Product disassembly assessment for remanufacturing, **PDRem** - Product design for remanufacturing**).**

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
Transport cost	15		✓	✓	✓		✓	(S. S. Ali et al., 2020; Alkhayyal, 2018; Chirumalla et al., 2023; K. Das, 2020; K. Das & Mehta, 2015; K. Das & Rao Posinasetti, 2015; Grosse Erdmann et al., 2023; Inoue et al., 2020; Miyajima et al., 2019; Mohamed Noor et al., 2018; Schau et al., 2012; Taleizadeh et al., 2019; Yu & Solvang, 2017; Zarbakhshnia et al., 2018)
Remanufacturing cost	13	✓	✓	✓	✓	✓	✓	(Abdullah, 2024; S. S. Ali et al., 2020; Aydin et al., 2014; Chirumalla et al., 2023; Choudhary et al., 2022; Mohamed Noor et al., 2018; Priyono et al., 2016; Taleizadeh et al., 2019; Tian et al., 2017; Wenyuan Wang & Tseng, 2010; Zhang et al., 2021b; Zhao & Zhou, 2023)
Disassembly Time	13	✓		✓	✓	✓	✓	(A. Ali et al., 2021; Ansari et al., 2022; Aydin et al., 2014; S. K. Das et al., 2000; Favi et al., 2021; Kazancoglu & Ozkan-Ozen, 2020; Mandolini et al., 2018; Marconi et al., 2019; A. Mishra et al., 2022; Ren et al., 2021; Shrivastava et al., 2005; Vanegas et al., 2018; Zhang et al., 2022a)
Disassembly cost	11	✓	✓	✓	✓	✓	✓	(S. S. Ali et al., 2020; Amaitik et al., 2023; Ansari et al., 2022; Favi et al., 2021; Jeng & Lin, 2017; Ren et al., 2021; Shrivastava et al., 2005; Tchertchian et al., 2013; van Loon & Van Wassenhove, 2018; Wenyuan Wang & Tseng, 2010; Zhang et al., 2022a)
Labour cost	8		✓	✓	✓	✓		(A. Ali et al., 2021; Alkhayyal, 2018; Inoue et al., 2020; Miyajima et al., 2019; Mohamed Noor et al., 2018; Mota et al., 2018; Ren et al., 2021; Schau et al., 2012)
Disposal cost	8		✓	✓	✓			(S. S. Ali et al., 2020; Ansari et al., 2022; Choudhary et al., 2022; Kazancoglu & Ozkan-Ozen, 2020; Li et al., 2018; Mohamed Noor et al., 2018; Taleizadeh et al., 2019; Yu & Solvang, 2017)
Fixed cost	7		✓					(S. S. Ali et al., 2020; K. Das, 2020; K. Das & Mehta, 2015; Li et al., 2018; Mota et al., 2018; Taleizadeh et al., 2019; Yu & Solvang, 2017)
Recycling cost	7	✓	✓			✓	✓	(S. S. Ali et al., 2020; Aydin et al., 2014; Choudhary et al., 2022; Jeng & Lin, 2017; Li et al., 2018; Taleizadeh et al., 2019; van Loon & Van Wassenhove, 2018)
Total cost	7	✓	✓		✓			(Arredondo-Soto et al., 2018; Boyer et al., 2021; Inoue et al., 2020; Jeng & Lin, 2017; A. R. Mishra et al., 2023; Zarbakhshnia et al., 2018; Zhang et al., 2021c)
Recovery cost	6		✓		✓	✓		(Aydin et al., 2014; K. Das, 2020; K. Das & Mehta, 2015; K. Das & Rao Posinasetti, 2015; Ren et al., 2021; Taleizadeh et al., 2019)
Products price	6	✓	✓		✓			(K. Das, 2020; K. Das & Mehta, 2015; Goepp et al., 2014; Taleizadeh et al., 2019; Yang et al., 2019; Zhao & Zhou, 2023)
Production cost	6	✓	✓				✓	(K. Das, 2020; K. Das & Mehta, 2015; K. Das & Rao Posinasetti, 2015; Fatimah & Aman, 2018; Vicente Abellan-Nebot et al., 2024; Zhao & Zhou, 2023)
Materials cost	6	✓	✓	✓	✓		✓	(Chirumalla et al., 2023; K. Das & Mehta, 2015; Fatimah & Aman, 2018; Inoue et al., 2020; Sarwar et al., 2021; Shrivastava et al., 2005)
Market Share	6	✓	✓	✓				(Ansari et al., 2022; Chirumalla et al., 2023; Govindan et al., 2019; Li et al., 2018; Prajapati et al., 2021; Sethanan et al., 2019)
Core quality condition	5		✓		✓	✓	✓	(A. Ali et al., 2021; Aydin et al., 2014; Kazancoglu & Ozkan-Ozen, 2020; A. Mishra et al., 2022; Taleizadeh et al., 2019)
Warehouse Capacity	5		✓					(Alkhayyal, 2018; K. Das, 2020; K. Das & Mehta, 2015; Li et al., 2018; Prajapati et al., 2021)
Energy cost	5	✓	✓	✓	✓		✓	(Alkhayyal, 2018; Fatimah & Aman, 2018; Sarwar et al., 2021; Schau et al., 2012; Yu & Solvang, 2017)
Distribution cost	5		✓		✓			(K. Das, 2020; K. Das & Mehta, 2015; Li et al., 2018; van Loon & Van Wassenhove, 2018; Yang et al., 2019)
Cleaning cost	5		✓		✓			(A. Ali et al., 2021; Amaitik et al., 2023; Ansari et al., 2022; Jeng & Lin, 2017; Mohamed Noor et al., 2018)
Operational cost	5		✓		✓		✓	(Deveci et al., 2021; Jindal & Singh Sangwan, 2016; Mota et al., 2018; Tian et al., 2017; Zhang et al., 2021a)
Reliability	5	✓					✓	(Abdullah, 2024; Aziz et al., 2017; Fatimah et al., 2013; Tchertchian et al., 2013; Vimal et al., 2021)
Revenue of Recycled	5	✓	✓	✓	✓		✓	(Aydin et al., 2014; Goepp et al., 2014; Jeng & Lin, 2017; Li et al., 2018; Zwolinski et al., 2006)
Investment cost	4	✓	✓	✓				(Deveci et al., 2021; Mejía-Moncayo et al., 2024; Mota et al., 2018; Peng et al., 2019)
Refurbishment cost	4		✓					(Choudhary et al., 2022; Goepp et al., 2014; van Loon & Van Wassenhove, 2018; Zwolinski et al., 2006)
Waste cost	4		✓		✓		✓	(Fatimah & Aman, 2018; Jeng & Lin, 2017; Prajapati et al., 2021; Sarwar et al., 2021)
Quality	4			✓	✓		✓	(Inoue et al., 2020; Justham et al., 2013; A. R. Mishra et al., 2023; Zarbakhshnia et al., 2018)
Distance to collection centre	4		✓		✓			(S. S. Ali et al., 2020; Chakraborty et al., 2017; Mandolini et al., 2018; Wenyuan Wang & Tseng, 2010)
Total number of Components	4		✓		✓		✓	(A. Ali et al., 2021; Chakraborty et al., 2017; Mandolini et al., 2018; Wenyuan Wang & Tseng, 2010)
Remanufactured product price	4		✓		✓	✓	✓	(S. S. Ali et al., 2020; Aydin et al., 2014; Priyono et al., 2016; Zwolinski et al., 2006)
Inspection cost	4		✓					(S. S. Ali et al., 2020; Amaitik et al., 2023; Jeng & Lin, 2017; A. Mishra et al., 2022)
Production capacity	4		✓	✓				(K. Das, 2020; K. Das & Mehta, 2015; Mota et al., 2018; Taleizadeh et al., 2019)
Products Weight	4		✓			✓		(Alkhayyal, 2018; Mandolini et al., 2018; Mota et al., 2018; Ren et al., 2021)

Table 3
Distribution of environmental key performance indicators identified in the literature in four or more documents across their main fields of application (Table criteria: SA-Sustainability assessment, RCLSCs - Remanufacturing CLSCs, RCir - Remanufacturing circularity assessment, Rem - Remanufacturability, Dis - Product disassembly assessment for remanufacturing, PDRem - Product design for remanufacturing).

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
GHG emissions	23	✓	✓	✓			✓	(Alamerew et al., 2020; S. S. Ali et al., 2020; Alkhayyal, 2018; K. Das, 2020; K. Das & Mehta, 2015; K. Das & Rao Posinasetti, 2015; Fatimah et al., 2013; Golinska et al., 2015; Golinska & Kuebler, 2014; Golinska-Dawson & Pawlewski, 2015; Govindan et al., 2019; Grosse Erdmann et al., 2023; Inoue et al., 2020; Jayakrishna & Vinodh, 2017; Jensen et al., 2019; Miyajima et al., 2019; Prajapati et al., 2021; Russell & Nasr, 2023; Shakourloo, 2017; Taleizadeh et al., 2019; Vimal et al., 2021; Yadav et al., 2020; Yanikara et al., 2014)
Energy Consumption	20	✓	✓	✓	✓	✓	✓	(Chen et al., 2023; K. Das, 2020; K. Das & Mehta, 2015; K. Das & Rao Posinasetti, 2015; Favi et al., 2021; Golinska et al., 2015; Golinska-Dawson & Pawlewski, 2015; Govindan et al., 2019; Jayakrishna & Vinodh, 2017; Kazancoglu & Ozkan-Ozen, 2020; Kurt et al., 2021; Lu et al., 2020; Prajapati et al., 2021; Ren et al., 2021; Russell & Nasr, 2023; Sarwar et al., 2021; Shakourloo, 2017; Taleizadeh et al., 2019; Vimal et al., 2021; Yu & Solvang, 2017)
Environmental Impact	13	✓	✓	✓	✓		✓	(Abdullah, 2024; Aydin et al., 2014; Bhatia et al., 2019; Goodall et al., 2014; Hummen & Wege, 2021; Jensen et al., 2019; Jindal & Singh Sangwan, 2016; Lampón, 2023; Mota et al., 2018; Shrivastava et al., 2005; Tchertchian et al., 2013; van Loon & Van Wassenhove, 2018; Yang et al., 2019)
Recycling	6	✓	✓				✓	(Boorsma et al., 2022; Golinska & Kuebler, 2014; Govindan et al., 2019; Sarwar et al., 2021; Yu & Solvang, 2017; Zarbakhshnia et al., 2018)
Remanufactured Parts	5		✓		✓		✓	(S. S. Ali et al., 2020; Aydin et al., 2014; Goepp et al., 2014; Justham et al., 2013; Zwolinski et al., 2006)
Disposal	5	✓	✓		✓			(Aydin et al., 2014; Golinska & Kuebler, 2014; Govindan et al., 2019; Justham et al., 2013; Zarbakhshnia et al., 2018)
Acidification potential	5			✓	✓		✓	(Alamerew et al., 2020; Jannone Da Silva et al., 2012; Schau et al., 2012; Spreafico, 2022; Vogtlander et al., 2017)
Global Warming Potential	5				✓		✓	(De Barba et al., 2013; Favi et al., 2021; Jannone Da Silva et al., 2012; Schau et al., 2012; Spreafico, 2022)
Solid Waste	4	✓			✓	✓		(Jiang et al., 2011; Kazancoglu & Ozkan-Ozen, 2020; Pan & Liu, 2009; Zhang et al., 2021c)
Remanufacturing	4		✓		✓		✓	(Boorsma et al., 2022; Govindan et al., 2019; Zarbakhshnia et al., 2018; Zhang et al., 2021d)
Remanufactured Products	4	✓	✓				✓	(Ansari et al., 2022; Goepp et al., 2014; Yu & Solvang, 2017; Zwolinski et al., 2006)
Eutrophication potential	4			✓	✓		✓	(Alamerew et al., 2020; Goepp et al., 2014; Yu & Solvang, 2017; Zwolinski et al., 2006)
Number of parts	4		✓		✓		✓	(S. S. Ali et al., 2020; Aydin et al., 2014; Goepp et al., 2014; Zwolinski et al., 2006)
Reused Parts	3		✓				✓	(S. S. Ali et al., 2020; Goepp et al., 2014; Zwolinski et al., 2006)
Energy Saved	3					✓	✓	(Goepp et al., 2014; Ren et al., 2021; Zwolinski et al., 2006)
Energy Embodied	3	✓			✓	✓		(Justham et al., 2013; Ren et al., 2021; Russell & Nasr, 2023)

Table 4
Distribution of social key performance indicators identified in the literature in three or more documents across their main fields of application (Table criteria: SA-Sustainability assessment, RCLSCs - Remanufacturing CLSCs, RCir - Remanufacturing circularity assessment, Rem - Remanufacturability, Dis - Product disassembly assessment for remanufacturing, PDRem - Product design for remanufacturing).

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
Health and safety	17	✓	✓	✓	✓	✓	✓	(Alkouh et al., 2023; Aziz et al., 2017; Deveci et al., 2021; Golinska et al., 2015; Govindan et al., 2019; Kazancoglu & Ozkan-Ozen, 2020; A. Mishra et al., 2022; A. R. Mishra et al., 2023; Mouflih et al., 2023; Sarwar et al., 2021; Sethanan et al., 2019; Taleizadeh et al., 2019; Ullah et al., 2016; Vimal et al., 2021; Vogtlander et al., 2017; Zarbakhshnia et al., 2018; Zhang et al., 2021c)
Job Creation	3	✓	✓	✓				(Alamerew et al., 2020; Fatimah & Aman, 2018; Taleizadeh et al., 2019)
Employment Stability	3		✓					(Li et al., 2018; Prajapati et al., 2021; Zarbakhshnia et al., 2018)

the findings of the systematic literature review (SLR) process. The following sections will present the main KPIs related to sustainability performance in remanufacturing.

3. Key performance indicators for sustainable remanufacturing

The SLR conducted in this study resulted in the identification of 1021 KPIs in SR, extracted from 1616 records obtained from the analysis of 106 documents. The KPIs are distributed across three sustainable dimensions, comprising 643 economic indicators, 273 environmental indicators, and 105 social indicators. Tables 2, 3, and 4 summarize the most frequently referenced KPIs in the literature: 32 economic, 16 environmental, and 3 social indicators. These tables also include the document counts and the distribution of KPIs, along with their fields of use or application (as detailed in sections 4.1 to 4.6 of the literature review). These applications encompass areas such as sustainability assessment, product design, disassembly, remanufacturability, remanufacturing circularity, and closed-loop supply chains.

The different KPIs in Tables 2 to 4 present a multidimensional approach to SR that extends beyond the sustainable manufacturing KPIs described by Mengistu & Panizzolo (2023). SR also requires considering technical and CE KPIs related to disassembly, remanufacturability, circularity, CLSC, and even product design. This provides decision-makers with a comprehensive understanding of which KPIs to consider when evaluating the adoption, transition, or operation of SR systems or their CLSC. Regarding the distribution of the KPIs in Tables 2 to 4, the greater number of economic KPIs reveals its prominent position as a driver of SR, outshining the environmental and social dimensions. Economic KPIs provide an exhaustive overview of the main concerns regarding remanufacturing and CLSC operations. Transport cost emerges as the most frequent KPI, followed by remanufacturing cost, disassembly time, disassembly cost, and labor cost. Disassembly is a technical enabler of remanufacturing, as it is commonly used to evaluate a product's complexity and remanufacturability. CE strategies, such as recycling, reuse, and refurbishing, represent other cost categories. Most of the KPIs described are related to CLSC. This shows the main role of remanufacturing in the CLSC.

Greenhouse gas (GHG) emissions, energy consump,tion, and environmental impact are the primary driving factors behind the environmental KPIs, followed by CE practices such as recycling materials, remanufacturing and the reuse of parts. The literature identifies several commonly used KPIs in life cycle assessment (LCA). These include acidification potential, disposal of materials, global warming potential, solid waste, and eutrophication potential within the environmental category.

The social dimension places significant emphasis on strategic KPIs, including but not limited to health and safety measures for both employees and users. The actors involved in the CLSC also consider factors like job creation and employment stability. Unfortunately, social KPIs are less considered in comparison with the other dimensions.

Some KPIs, such as transportation costs, transportation distance, fixed costs, and investment costs among others, play a crucial role in CLSC network design. This is because the proximity to customers and suppliers reduces energy consumption, operational costs, and environmental impacts. This also emphasizes the importance of supporting local or regional supply chains, which helps minimize the environmental effects of long-distance transportation.

The price of new products is used as a reference for remanufactured products. Reverse logistics demands consideration of collection costs, distance to the collection centre, storage capacity, and employment stability. The inspection operation assesses the quality conditions of the core or used product. Quality conditions can be assessed by evaluating various factors, including product deterioration, technical standards, regulatory requirements, maintenance data, as well as an organization's experience and expertise. Depending on the types of materials and their conditions, the disposal process and its cost are established.

The disassembly time is directly proportional to the complexity of the operation, thereby impacting its cost. When assessing remanufacturing operations, it is important to consider various KPIs, including remanufacturing costs, cleaning costs, the price of remanufactured products, and production capacity. The energy saved and embodied in the product plays a crucial role in determining the overall energy savings achieved through remanufacturing. The assessment also examines the quantity of reused and remanufactured parts and their effects on acidification, eutrophication, and global warming. Each of these indicators plays a role in assessing the feasibility of remanufacturing. The costs and revenue in the recycling operation are strongly influenced by the recycled materials and the energy they contain. When evaluating energy savings for subsequent transformation processes, it is essential to consider this energy as a determining factor. In the following sections, a descriptive analysis of each field of application will be exposed. The different approaches identified in the literature are described and analyzed in the next section.

4. Literature review

The following sections will provide an in-depth analysis of the six different application fields of use for the KPIs and their relationship with smart technologies identified through the SLR. This will be accompanied by a thorough examination of the scope of the reviewed literature.

4.1. Sustainability assessment in remanufacturing

The three dimensions of sustainability (economic, environmental, and social) are part of the concerns of remanufacturing companies. The development of indicators to assess environmental performance is a concern in various studies, including those by Pan & Liu (2009), Tsiliyannis (2014), and Haupt & Hellweg (2019). Pan & Liu (2009) developed a system of environmental indicators for the automotive remanufacturing industry in China. This system encompasses aspects such as durability, environmental policies, green technology, environmental development, utilization, standard authentication systems, and noise ranking, among others. Tsiliyannis (2014) presented the cycle rate as a method for achieving environmental improvement. This method is based on three main criteria: reducing final waste, minimizing the extraction of virgin raw materials, and lowering manufacturing impacts. Haupt & Hellweg (2019) proposed the concept of Retained Environmental Value in response to the fact that mass-based indicators, such as recycling rates, cannot fully capture the environmental perspective. This indicator measures the proportion of environmental impact that is retained in products and materials through reuse, remanufacturing, repair, or recycling. Yadav et al. (2020) identify and analyze several indicators that influence the adoption of CE. They include strategic, management, informational, technological, supply chain, and organizational indicators. Its results show that strategic and management indicators have the most significant influence on the development of other indicators. Ansari et al. (2022) assessed the KPIs of the remanufacturing supply chain using the Supply Chain Operations Reference Model.

The sustainability of remanufactured products in Indonesian small and medium-sized enterprises (SMEs) was analyzed by Fatimah et al. (2013). Its proposal introduces a framework that considers life cycle costs, reliability, warranty, sales, GHG emissions, solid waste, and employment opportunities. Fatimah & Aman (2018) introduce remanufacturing sustainability indicators, a guide for measuring the sustainability of SMEs in Indonesia. It aims to help SMEs understand and evaluate their economic, social, and environmental performance. Sethanan et al. (2019) developed a set of sustainability indicators for remanufacturing in small and medium-sized enterprises (SMEs). These indicators serve as guidelines for creating a sustainable measurement system that is adaptable to different company sizes and types of products.

Golinska & Kuebler (2014) presented a method for assessing the sustainability maturity of remanufacturing companies and identifying areas that require improvement. Golinska et al. (2015) introduced a set of indicators to classify the level of sustainability of remanufacturing companies. Golinska-Dawson & Pawlewski (2015) assessed environmental issues in remanufacturing supply chains using simulation.

Arredondo-Soto et al. (2018) analyzed the current state of remanufacturing in Mexico. The study identifies the elements of the productive systems of companies and compares them to identify similarities, differences, advantages, and disadvantages. Russell & Nasr (2023) proposed a methodology for assessing the environmental and economic impacts of value-retention processes, including reuse, repair, refurbishment, and remanufacturing. This study demonstrates that these processes have different forms of value and varying degrees of environmental and economic impact. Jensen et al. (2019) examined remanufacturing as a strategy for circular business models, emphasizing its value. They also highlighted the importance of considering social, environmental, and profitability perspectives while ensuring market protection.

Price and service competition in remanufacturing systems is addressed by Yang et al. (2019). Their study examines various aspects, including demand uncertainty, recycling efforts, channel structure, sustainability analysis, pricing and marketing strategies, supplier

Table 5
Design frameworks focused on remanufacturing.

Framework	Objective of the framework
Remanufacturing Product Profiles (REPRO2) (Zwolinski et al., 2006)	Support the initial stages of the design process with product profiles.
Design framework (Yang et al., 2017)	Material selection for parts to be remanufactured
Remanufacturing quality function deployment (RQFD) (Vimal et al., 2021)	RQFD integrates sustainability and remanufacturing strategies into product design, considering the voice of the customer.
Life Cycle Commonality Metrics (LCCM) (Wenyuan Wang & Tseng 2010)	LCCM measures the product design's ability and convenience for implementing end-of-life strategies such as reuse, remanufacturing, and recycling.
Design framework based on eco-design (Favi et al., 2021)	This framework guides companies in using eco-design methods and tools towards eco-sustainability and CE.
Fuzzy Axiomatic Design (FAD) (Chakraborty et al., 2017)	FAD helps to evaluate and rank product design alternatives for remanufacturing.
Circular Product Readiness (CPR) (Boorsma et al., 2022)	CPR helps designers to monitor the implementation level when designing a circular product or service.
Modular design method. (Miyajima et al., 2019)	This modular design method utilizes a design structure matrix to generate supply chain-based modular architectures that consider environmental load, cost, quality, and lead time.
Modular design strategy. (Inoue et al., 2020)	This strategy enables the design and evaluation of modular product architectures from a supply chain management perspective, considering sustainability factors alongside traditional metrics.
The modular grouping explorer (MGE) tool (Tchertchian et al., 2013)	MGE tool helps designers modify product architecture to optimize end-of-life strategies.
Joint Complexity Index (JCI) (Mesa et al., 2018)	JCI provides a holistic measurement of the complexity involved in the assembly and disassembly tasks of mechanical joints for open-architecture products.
Design for Upgradability (DfU) (Aziz et al., 2017)	DfU enhances the remanufacturing features of a product by incorporating upgrade strategies at the design stage.

relationships, emissions regulation, and more. Competitiveness and the interplay between greening and remanufacturing strategies in supply chains were examined by Zhao & Zhou, (2023). Their study considers the uncertainty of performance and the behaviour of risk-averse manufacturers.

Over the past two decades, there has been a notable interest in quantifying the sustainable performance of remanufacturing, as evidenced by the approaches presented in this section. These studies have focused on providing insights from a sustainability standpoint regarding remanufacturing products, processes, companies, supply chains, and industries. They also emphasize the various interactions that remanufacturing entails within CLSCs. The subsequent section analyzes product design for remanufacturing.

4.2. Product design for remanufacturing

Product design plays a crucial role in remanufacturing, as its shape, dimensions, materials, joining processes, and other characteristics significantly determine the remanufacturability and sustainability of products. Therefore, it is essential to analyze the different approaches towards design in remanufacturing, as presented below.

Environmental impact assessment has become an essential criterion for evaluating design in remanufacturing, as demonstrated by approaches such as those of Jannone Da Silva et al. (2012). Their study detailed a meticulous design of a grinding machine, including an environmental assessment and a discussion of product monitoring and maintenance. Spreafico (2022) analyzed design strategies for CE using LCA. This study examined the environmental impacts of design solutions that incorporate reuse, waste management, and remanufacturing compared to those that do not account for a CE strategy.

Design frameworks for remanufacturing have been developed to support the design process; some of them are listed in Table 5 and are explained as follows. Remanufacturing Product Profiles (REPRO2) (Zwolinski et al., 2006) emerge as a tool to assist designers in the initial stages of the design process. This process involves analyzing the project context and identifying remanufacturable product profiles (RPPs) to help designers create products suited for remanufacturing. Goepp et al. (2014) adopted this strategy by integrating eco-design approaches based on product LCA.

Other frameworks address different remanufacturing edges, such as material selection (Yang et al., 2017), product development regarding sustainability and customers requirements (Vimal et al., 2021), or performing economic analysis into product design to achieve sustainability (Wenyuan Wang & Tseng, 2010). Also, Yang et al. (2017) addressed durability, cleanability, and restorability/upgradability. Here, durability involves extending the service life and minimizing deterioration during usage. Cleanability pertains to the effortless elimination of impurities. Restorability and upgradability refer to the ability to recover and enhance the properties or features of a part through various processes. Favi et al. (2021) presented a design-based eco-design framework for disassembly and modular components to facilitate remanufacturing and recycling. Chakraborty et al. (2017) analyzed the design characteristics of products for enhancing remanufacturability using a combination of axiomatic design and analytical hierarchy process (AHP). Boorsma et al. (2022) introduced the Circular Product Readiness (CPR) approach, a tool designed to evaluate the circularity of product designs.

Modular architectures integrate standardized, upgradable modules, which, thanks to effective supply chain management, enable products to be developed with interchangeable and upgradable components. Examples of such architectures in computer production are discussed in the work of Miyajima et al. (2019) and Inoue et al. (2020). Miyajima et al. (2019) presented a modular design and evaluation method for supply chain management. Inoue et al. (2020) propose a modular design strategy that considers sustainability and supplier selection in the initial design phase. The aim is to design products and their components with reuse, remanufacturing, and future updating in mind. Tchertchian et al. (2013) analyzed the Modular Grouping Explorer (MGE) tool, which helps to identify and modify module limits in product design to increase remanufacturability and recyclability. Jayakrishna & Vinodh (2017) described the application of gray relational analysis for material selection and end-of-life (EoL) strategy selection in the automotive industry. Lampón (2023) examined the implementation of modular electric vehicle platforms in the automotive industry to achieve their sustainable development goals. Aziz et al. (2017) introduce design for upgradability, considering KPIs, such as durability, ease of reprocessing, safety, interface between components, lifecycle similarities, useful lifetime, performance, reliability and technology cycles.

Design for X enhances remanufacturing by improving service functionalities, circularity, and supporting design decisions and knowledge management (Sassanelli et al., 2020). Mesa et al. (2018) introduced the Joint Complexity Index (JCI) to assess the complexity of assembly and disassembly tasks in mechanical joints. This index evaluates various joining methods based on their functional characteristics and overall complexity. While Mohamed Noor et al. (2018) addressed economic decision-making in the selection of the best alternative design for remanufacturing.

The reviewed literature suggests that design for remanufacturing includes multiple dimensions. This necessitates a concurrent approach encompassing manufacturing, assembly, and disassembly to enhance performance, conserve materials, and reduce costs. Modular design emerges as an option that contributes to this purpose. Modularization refers to the process of breaking down products into their fundamental functions to create modules that are interchangeable and upgradable

(Chavanel-Precloux et al. 2025). This approach facilitates subsequent remanufacturing and recycling, as seen in components for industries like automotive and computing. This requires the comprehensive development of standards that enable component interchangeability, quality control, and the integration of a comprehensive supply chain. Remanufacturing design requires a complete product lifecycle analysis, regardless of the chosen method (Shahhoseini et al., 2023). This requires capturing, managing, and securing the traceability of product lifecycle information (Sassanelli et al., 2020). This highlights the crucial role of technology in facilitating this task. Disassembly enables remanufacturability and represents a vital factor for product design for remanufacturing, as outlined in the next section.

4.3. Product disassembly assessment for remanufacturing

Disassembly is an essential step in remanufacturing, as the subsequent stages of the process—cleaning, repair, reconditioning, and assembly—depend on it. Thus, their assessment is crucial in determining the feasibility of remanufacturing or the level of remanufacturability. KPIs have been developed to evaluate the feasibility of disassembly through an analysis that considers operational time, disassembly sequence, and product complexity. Some of these KPIs are listed here: Ease of Disassembly Metric (eDiM) (Vanegas et al., 2018), Effective Disassembly Time (EDT) (Mandolini et al., 2018; Marconi et al., 2019), Disassembly Effort Index (DEI) (Das et al., 2000), and Joint Complexity Index (JCI) (Mesa et al., 2018).

The Ease of Disassembly Metric (eDiM) (Vanegas et al., 2018) provides a systematic and quantitative approach to estimating disassembly time and assessing its ease. This process involves classifying tasks into six categories: tool change, identification, manipulation, positioning, disconnection, and removal. Erdmann et al. (2023) presented an adaptation of eDiM to evaluate the ease of disassembly of five e-bike motors. Effective Disassembly Time (EDT) (Mandolini et al., 2018; Marconi et al., 2019) helps determine the sequence and time of component disassembly in complex products. The Disassembly Effort Index (DEI) (Das et al., 2000) calculates a score that considers factors such as fixation, access, instruction, hazard, and force requirements.

Sustainability has become a key focus in evaluating dismantling performance. Kazancoglu & Ozkan-Ozen (2020) analyzed the concept of sustainable balance of the disassembly line. Lu et al. (2020) examined energy efficiency in disassembly. Ren et al. (2021) concentrated on optimizing value recovery and energy conservation in the disassembly of electronic products.

Operations research and optimization-based approaches are commonly employed in disassembly. Lu et al. (2020) introduced a hybrid *meta*-heuristic algorithm to solve the problem of for-profit and energy-efficient disassembly sequencing. Ren et al. (2021) presented a multi-objective disassembly planning approach for end-of-life products to maximize value recovery and energy conservation. Zhang et al. (2022b) proposed a multi-objective optimization model for balancing bilateral disassembly lines in automotive engine remanufacturing. Zhang et al. (2022a) presented a selective parallel disassembly sequence planning methodology. Priyono et al. (2016) examined the factors that affect the disassembly process, including organizational characteristics, process choices, and product attributes.

Disassembly time emerges as the primary metric for evaluating disassembly performance, as it provides a quantitative assessment of its complexity. However, to achieve a successful process, it is necessary to consider simultaneously both the disassembly sequence and the complexity of the product. Indeed, Industry 4.0 (I4.0) technologies can contribute to simplifying dismantling operations and promoting the integration of sustainability criteria into processes. The following section will examine the concept of remanufacturability.

4.4. Remanufacturability assessment

The remanufacturability of a product refers to the existence of conditions that allow for its remanufacture. This requires a multi-criteria focus analysis of the problem, which extends beyond the product's borders (Tian et al., 2017). This concept requires the simultaneous harmonization of economic, environmental, social, and technical factors, as described by (Zhang et al., 2021b). Their study also highlights the importance of assessing remanufacturing feasibility and the need to improve the required methods for deployment.

Shrivastava et al. (2005) proposed a decision support system that provides information on optimal disassembly methods, material composition, and environmental impact assessment of electronic products. This system enables the evaluation of various parameters, including dismantling analysis, product recycling, material evaluation, and environmental impact assessment. Jiang et al. (2011) presented a multi-criteria decision-making model for selecting remanufacturing technologies using the AHP.

The sustainability of remanufactured alternators, assessed using a life-cycle approach, was evaluated by Schau et al. (2012). According to their results, remanufacturing exhibits lower emissions and costs when compared to the production of new parts, and the conventional alternator design excels in all aspects. De Barba et al. (2013) suggested considering the voice of the customer in conjunction with technical, economic, and environmental assessments.

Goodall et al. (2014) examined the tools and techniques used to assess remanufacturability. They found that while decision factors are adequately covered, operational tools and consideration of uncertainty are often overlooked. This approach is also shared by Justham et al. (2013), who proposed a knowledge-based framework for assessing remanufacturability of products in a supply chain. Aydin et al. (2014) proposed a lifecycle-based methodology to determine the recoverability, reusability, remanufacturability, and recyclability of end-of-life products.

Ullah et al. (2016) aimed to find a standardized and efficient approach for decision-making in remanufacturing. This approach offers a systematic and effective method for determining the optimal strategy for remanufacturing machine tools. Jindal & Singh Sangwan (2016) proposed a fuzzy framework for selecting the best recovery alternative among five recovery processes: repair, refurbishing, remanufacturing, cannibalizing, and recycling. Vogtlander et al. (2017) analyzed the costs, market value, and ecological costs of remanufactured products.

Peng et al. (2019) addressed the problem of selecting restoration technologies to recover the original dimensions of engine parts. (Zhang et al., 2021d) investigated the impact of remanufacturing on reducing material losses in vehicle engines throughout their lifecycles. Zhang et al. (2021c) presented a model for assessing the sustainability of retired machinery. Hummen & Wege (2021) presented the Circular Economy Remanufacturing Indicator (CERI) to compare the environmental impacts and cost of new and remanufactured products.

Ali et al. (2021) analyzed the quantitative assessment of products to develop an EoL product remanufacturability index. Its methodology considers factors such as the complexity of the product design, the technological capability of the process, and the incoming quality. Chen et al. (2023) evaluate the environmental impacts, recycling technologies, and sustainability of lithium-ion batteries (LIBs) used in electric vehicles (EVs). Chirumalla et al. (2023) analyzed the economic feasibility of remanufacturing, repurposing, and reusing Li-ion batteries for their second life in the heavy-duty vehicle industry.

In 2021, the French government (Ministères Territoires Écologie Logement, 2021) introduced the "reparability index" to promote CE and reduce waste in five product categories: smartphones, laptops, televisions, lawn mowers, and front-loading washing machines. The repairability index contributes to addressing planned obsolescence by raising consumer awareness to buy products that are more easily repaired. Canada is also exploring to implement a similar index based on the

French experience (Équiterre, 2024). Alkouh et al. (2023) presented the Repairability Index (IOR) as a mathematical score to assess the ease of repair of electronic equipment.

Different perspectives on the analysis of remanufacturability are presented in the aforementioned studies. In these approaches, economic and environmental criteria prevail, with a lesser presence of social ones. Both internal and external product factors are considered in these analyses. Internal factors are directly related to the product, its components, materials, geometry, deteriorating condition, and the processes necessary for their remanufacturing. Product's repairability also emerges as an internal factor when pursuing remanufacturability. External factors analyze the remanufacturability of products within their specific context. This means conducting an economic, environmental, and social evaluation of the product. This is achieved by considering its impacts not only on remanufacturing, but also on the performance of the product in operation compared to new products. Section 4.5 examines circularity, with a particular focus on remanufacturing.

4.5. Remanufacturing circularity assessment

Assessing circularity in terms of sustainability requires KPIs that facilitate this task. Saidani et al. (2019) presented a comprehensive taxonomy of circularity indicators that considers implementation levels, types of CE strategies, performance, circularity perspective, and degree of transversality. Kristensen & Mosgaard (2020) and Matos et al. (2023) explored and categorized CE micro-level indicators in the existing literature. Their findings show that indicators concentrate mainly on environmental and economic aspects while paying less attention to the social dimension. Their study also provides practical guidelines for selecting and applying such KPIs.

The Product-Level Circularity Metric (PLCM), proposed by Linder et al. (2017), is a metric that evaluates the ratio between recirculated economic value and the product's total value. The Decision Support Tool for Remanufacturing (DSTR) (van Loon & Van Wassenhove, 2018) evaluates the economic and environmental viability of remanufacturing in comparison to the production of new components. Current approaches present new indicators, such as those proposed by Bobba et al. (2023), who introduced the Circular Input Rate (CIR). This indicator is described as the relationship between material flows from reused, remanufactured, and recycled products or components and sector-specific demand for materials. Mishra et al. (2022) presented a quality indicator (QI) oriented to CE for the evaluation and categorization of various basic types in recycling and remanufacturing procedures.

Other approaches, as proposed by Alamerew et al. (2020), include a multi-criteria assessment method to evaluate circularity strategies at the product level. Benini et al. (2022) introduced a model to promote circular practices in the remanufacturing of EoL products and parts. Figge et al. (2018) introduced measures for both resource circularity and resource longevity. Kurt et al. (2021) introduced a classification tool for circular supply chain indicators, aiming to evaluate the circularity of supply chains at a strategic level. Boyer et al. (2021) contributed to the understanding of circularity through a three-dimensional framework that considers material recirculation, utilization, and durability.

The different approaches to analyzing circularity depend strongly on the CE strategies under consideration. In the case of remanufacturing, it is necessary to consider simultaneously the three dimensions of circularity from a product-focused perspective. In practical terms, it is recommended to consider the KPIs previously described (PLCM, DSTR, CIR, or QI), which provide different perspectives on remanufacturing circularity. In the following section, the KPIs for closed-loop supply chains in remanufacturing will be analyzed.

4.6. Closed-loop supply chains KPIs for remanufacturing

The various approaches identified in the literature regarding the CLSC for remanufacturing are presented in this section. These include the design of reverse logistics (RL) networks, sustainable supply chain planning, remanufacturing planning, RL supplier selection, and logistics performance. Each of these aspects contributes to understanding the different approaches to consider throughout the CLSC of SR, including its main KPIs.

4.6.1. Design of reverse logistics networks

RL networks play a fundamental role in the collection of used products, connecting users and collection centers with facilities for disassembly, recycling, remanufacturing, and final disposal. The design of these networks presents challenges, such as uncertainty in product returns, as discussed by Yanikara et al. (2014). This study proposes a simulation-based methodology to evaluate different network configurations based on sustainability and productivity metrics. Performance metrics include total travel distance, GHG emissions, time in the system, and work in process. Yu & Solvang (2017) addressed the design of a RL network to capture the value of products at the end of their useful life. They proposed a stochastic, multi-product, multi-step optimization model that integrates carbon restriction for the design of a RL network.

Alkhayyal (2018) proposed a multi-criteria decision-making approach for designing a reverse supply chain in a carbon trading environment. This study optimizes part flow for remanufacturing, considering profit and GHG emissions. Ali et al. (2020) presented a model that evaluates four return strategies (reuse, remanufacturing, recycling, and disposal), considering customer satisfaction, increasing market share, reducing costs, and adding value to the logistics chain.

Facility location is a sensitive decision for CLSC, addressed in various studies. Bhatia et al. (2019) proposed a framework for evaluating the ideal location of a remanufacturing plant. This approach considers initial investment, transportation costs, proximity to customers, availability of renewable energy, and availability of skilled labour. Mota et al. (2018) optimize supply chain design using a multi-objective mixed-integer linear programming model that integrates facility location and capacity determination, supplier selection, and purchase levels definition, technology selection and allocation, transportation network definition (including both unimodal and intermodal options), supply planning, product recovery, and remanufacturing.

Deveci et al. (2021) proposed an integrated neutrosophic decision-making model to select the best location for an automotive lithium-ion battery remanufacturing facility. Grosse Erdmann et al. (2023) proposed a multi-method simulation model for the design of product-service system (PSS) reverse supply chain networks. The model determines the optimal infrastructure and locations for storing, remanufacturing, and repairing used products in the reverse supply chain.

The design of remanufacturing facilities is also analyzed by Mejía-Moncayo et al. (2021). They introduced a hybrid manufacturing architecture that integrates cellular and reconfigurable manufacturing features. Mejía-Moncayo et al. (2024) presented a multi-objective approach to the design of a productive architecture for a smart sustainable remanufacturing system. The proposed architecture integrates reconfigurable features based on I4.0 that mitigate the negative effects of uncertainty on the quality, quantity, and return time of used products. This study also highlighted the need to integrate productive architecture with smart architecture and a business model to achieve sustainable system performance.

4.6.2. Sustainable supply chain planning

Environmental concerns in the design and planning of the CLSC are addressed by Das & Rao Posinasetti (2015) to improve sustainability and business performance. Their proposal includes a system for collecting EoL products and managing customer returns, along with refurbishment, recovery, and repair operations, all of which are managed by service providers. They emphasized the importance of green modular design in product architecture as a facilitator of product recovery processes, environmental sustainability, and cost-effectiveness in CLSC operations. Das & Mehta (2015) presented a model that integrates

Table 6
Distribution of Economic, environmental, and social key performance indicators identified in the literature in three or more documents, along with the main fields of application in remanufacturing closed-loop supply chains.

Performance indicator	Documents	Design of reverse logistics networks	Sustainable Supply Chain Planning	Remanufacturing Planning	Selection of reverse logistics providers	Logistics performance	References
Economic							
Transport cost	10	✓	✓		✓		(S. S. Ali et al., 2020; Alkhayyal, 2018; K. Das, 2020; K. Das & Mehta, 2015; K. Das & Rao Posinasetti, 2015; Grosse Erdmann et al., 2023; Taleizadeh et al., 2019; Yu & Solvang, 2017; Zarbakhshnia et al., 2018)
Fixed cost	7	✓	✓		✓		(S. S. Ali et al., 2020; K. Das, 2020; K. Das & Mehta, 2015; Li et al., 2018; Mota et al., 2018; Taleizadeh et al., 2019; Yu & Solvang, 2017)
Warehouse Capacity	5	✓	✓		✓	✓	(Alkhayyal, 2018; K. Das, 2020; K. Das & Mehta, 2015; Li et al., 2018; Prajapati et al., 2021)
Recycling cost	5	✓	✓	✓	✓		(S. S. Ali et al., 2020; Aydin et al., 2014; Choudhary et al., 2022; Jeng & Lin, 2017; Li et al., 2018; Taleizadeh et al., 2019)
Disposal cost	5	✓	✓	✓	✓		(S. S. Ali et al., 2020; Ansari et al., 2022; Choudhary et al., 2022; Li et al., 2018; Taleizadeh et al., 2019; Yu & Solvang, 2017)
Recovery cost	4		✓				(K. Das, 2020; K. Das & Mehta, 2015; K. Das & Rao Posinasetti, 2015; Taleizadeh et al., 2019)
Distance to Collection centre	4	✓	✓				(S. S. Ali et al., 2020; Chakraborty et al., 2017; Mandolini et al., 2018; Wenyuan Wang & Tseng, 2010)
Production Capacity	4	✓	✓				(K. Das, 2020; K. Das & Mehta, 2015; Mota et al., 2018; Taleizadeh et al., 2019)
Energy cost	3	✓				✓	(Alkhayyal, 2018; Sarwar et al., 2021; Yu & Solvang, 2017)
Investment cost	3	✓					(Deveci et al., 2021; Mejía-Moncayo et al., 2024; Mota et al., 2018)
Transport Distance	3	✓	✓				(K. Das, 2020; K. Das & Mehta, 2015; Yanikara et al., 2014)
Products Demand	3	✓	✓				(Alkhayyal, 2018; K. Das, 2020; K. Das & Mehta, 2015)
Waste Cost	3			✓		✓	(Jeng & Lin, 2017; Prajapati et al., 2021; Sarwar et al., 2021)
Distribution Cost	3		✓		✓		(K. Das, 2020; K. Das & Mehta, 2015; Li et al., 2018)
Market Share	3				✓	✓	(Govindan et al., 2019; Li et al., 2018; Prajapati et al., 2021)
Operational Cost	3	✓			✓		(Deveci et al., 2021; Mota et al., 2018; Zhang et al., 2021a)
Delivery	3				✓		(Govindan et al., 2019; Li et al., 2018; Zarbakhshnia et al., 2018)
Government Subsidy	3	✓				✓	(Bhatia et al., 2019; Sarwar et al., 2021; Yu & Solvang, 2017)
Products Price	3		✓				(K. Das, 2020; K. Das & Mehta, 2015; Taleizadeh et al., 2019)
Production Cost	3		✓				(K. Das, 2020; K. Das & Mehta, 2015; K. Das & Rao Posinasetti, 2015)
Remanufacturing Cost	3	✓	✓	✓			(S. S. Ali et al., 2020; Choudhary et al., 2022; Taleizadeh et al., 2019)
Total Cost	3			✓	✓		(Jeng & Lin, 2017; A. R. Mishra et al., 2023)
Environmental							
GHG emissions	11	✓	✓	✓	✓	✓	(S. S. Ali et al., 2020; Alkhayyal, 2018; K. Das, 2020; K. Das & Mehta, 2015; K. Das & Rao Posinasetti, 2015; Govindan et al., 2019; Grosse Erdmann et al., 2023; Prajapati et al., 2021; Shakourloo, 2017; Taleizadeh et al., 2019; Yanikara et al., 2014)
Energy Consumption	9	✓	✓	✓	✓	✓	(K. Das, 2020; K. Das & Mehta, 2015; K. Das & Rao Posinasetti, 2015; Govindan et al., 2019; Prajapati et al.,

(continued on next page)

Table 6 (*continued*)

Performance indicator	Documents	Design of reverse logistics networks	Sustainable Supply Chain Planning	Remanufacturing Planning	Selection of reverse logistics providers	Logistics performance	References
							2021; Sarwar et al., 2021; Taleizadeh et al., 2019; Yu & Solvang, 2017)
Recycling	4	✓			✓	✓	(Govindan et al., 2019; Sarwar et al., 2021; Yu & Solvang, 2017; Zarbakhshnia et al., 2018)
Collection	3		✓		✓		(K. Das, 2020; Govindan et al., 2019; Li et al., 2018)
Renewable Energy	3	✓		✓		✓	(Bhatia et al., 2019; Prajapati et al., 2021; Shakourloo, 2017)
Social							
Health and safety	6	✓	✓		✓	✓	(Deveci et al., 2021; Govindan et al., 2019; A. R. Mishra et al., 2023; Sarwar et al., 2021; Taleizadeh et al., 2019; Zarbakhshnia et al., 2018)
Employment Stability	3				✓	✓	(Li et al., 2018; Prajapati et al., 2021; Zarbakhshnia et al., 2018)

environmental and economic sustainability. Their model assesses the cost of the product, the cost of collecting returns, the cost of acquisition and recovery, the cost of transportation, distribution, and inventory, as well as the cost of energy and emissions penalties.

Taleizadeh et al. (2019) introduced a comprehensive model for planning a multi-period, multi-echelon sustainable CLSC that considers social and environmental impacts. This model also utilizes a quality-dependent discount offer to incentivize product returns and categorizes returned products by quality to inform recovery decisions. Das (2020) discussed practices and strategies to improve economic and environmental sustainability, including emissions trading schemes, sustainable transport, and supplier management. Ansari et al. (2020) evaluated and classified solutions to mitigate risks in sustainable remanufacturing supply chains.

4.6.3. *Remanufacturing planning*

Remanufacturing planning is a crucial factor in achieving reliable performance in an environment characterized by uncertainty in the conditions, quantity, and return time of used products. Jeng & Lin (2017) proposed a fuzzy cradle-to-cradle remanufacturing planning model for the recycled toner cartridge industry. Their model considers the entire product life cycle and uses fuzzy theory to define environmental laws and regulations, ecological reputation, and environmental performance indicators. Shakourloo (2017) developed a stochastic multi-objective goal programming model to optimize the sustainability and efficiency of the remanufacturing process, thereby increasing profit and reducing costs. Choudhary et al. (2022) introduce a comprehensive decision-making framework to select the optimal recovery strategy for electronics returns in India.

4.6.4. *Selection of reverse logistics providers*

The complexity of RL operations and the limited resources available to various companies make them prefer outsourcing their RL practices to a third-party reverse logistics provider (3PRLP) as a strategic approach. One of the most essential and risky processes for outsourcing RL is selecting the optimal 3PRLP among the alternatives. Several studies have addressed this issue, including Li et al. (2018). Indeed, they deployed a case study of the computer manufacturing industry to illustrate their 3PRLP approach. Zarbakhshnia et al. (2018) analyzed the evaluation and selection of a sustainable 3PRLP using a multi-attribute decision-making model applied to a case study from the automotive industry. Govindan et al. (2019) proposed a hybrid method for a case study in the Indian automobile remanufacturing industry. The study highlights the importance of incorporating sustainability criteria into supplier evaluation. (Zhang et al., 2021a) implemented an approach that integrates multi-criteria decision-making and circularity to classify remanufacturing suppliers for medium-sized engines in China. While Mishra et al. (2023) proposed a framework to select a sustainable 3PRLP, considering the economic, environmental, and social dimensions.

4.6.5. *Logistics performance*

Once the logistics network has been designed, it is necessary to measure its performance, as presented by Sagnak (2020). Their study proposes a framework for measuring logistics performance by focusing on sustainable procurement, sustainable distribution, and RL. Prajapati et al. (2021) proposed a framework to identify and prioritize performance indicators for measuring the success of RL implementation. Environmental, industrial operations, customer, financial, and social indicators are considered. Sarwar et al. (2021) analyze the impact of green supply chain management practices on the economic, environmental, and social performance of Pakistani organizations.

4.6.6. *Key performance indicators distribution along with main concerns in remanufacturing's closed-loop supply chains*

This section addresses the distribution of sustainable KPIs along remanufacturing's CLSC concerns, which include the design of RL networks, sustainable supply chain planning, remanufacturing planning, the selection of RL providers, and logistics performance. These concerns are outlined in Table 6.

Table 6 summarizes the sustainable KPIs in remanufacturing CLSCs, where the cost of transport is the most frequently adopted economic KPI. This table highlights its impact on remanufacturing and the main role of reverse logistics and distribution in SR. Similarly, fixed costs, warehouse capacity, production capacity, energy costs, investment costs, distribution costs, and operational costs. These highlight the need to consider the capacity and cost of the reverse logistics network, as different concerns share these key performance indicators (KPIs) in CLSC setting. The role of the government as an enabler of sustainable remanufacturing is evidenced by the KPI of government subsidies. The other economic KPIs in Table 6 are mainly related to remanufacturing processes.

Environmental KPIs, as outlined in Table 6, include GHG emissions, energy consumption, recycling, collection, and renewable energy. These KPIs once again reaffirm the crucial role of energy in transport and CLSC operations, as well as the need to decarbonize CLSCs. In conclusion, health and safety is the principal social KPI for all CLSC concerns and stakeholders. Employment stability is critical for maintaining the quality of services provided by the CLSC and ensuring a good quality of life for its employees.

The KPIs listed in Table 6 can be utilized by decision-makers at various stages of the CLSC network. Starting with the design of the RL network, the KPIs provide insights into the selection of criteria to

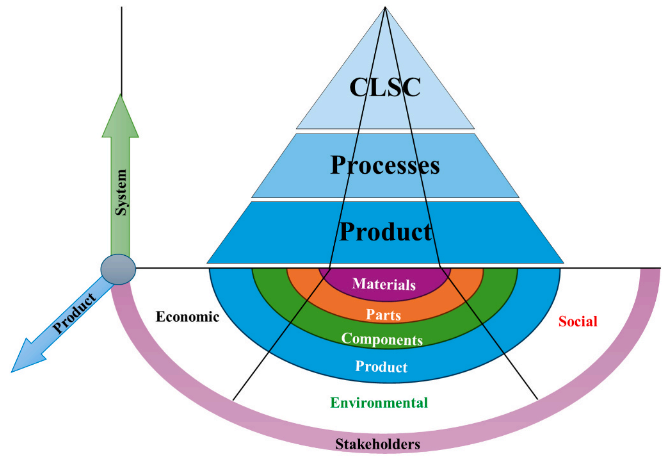

Fig. 3. Product and system layers through sustainability dimensions and stakeholders' requirements in the proposed methodological framework.

consider in these projects. Then, plan the sustainable supply chain or remanufacturing systems, assess logistics performance, or even select an RL provider. This also highlights the need to address remanufacturing, considering its interactions with other CLSC actors.

4.7. *Smart sustainable remanufacturing*

I4.0 technologies have been highlighted by various authors as enablers of sustainability and CE strategies, such as remanufacturing (Alshammari et al., 2025; Culot et al., 2020; Prajapati et al., 2025). I4.0 or smart technologies recover, process, and analyze product life cycle information (PLCI) along processes and CLSC (Taddei et al., 2022), enabling the assessment or calculation of the KPIs in SR. Quality management systems, environmental management systems, and others utilize PLCI to quantify KPIs and support decision-making processes at various organizational levels (Mejía-Moncayo et al., 2023). Remanufacturing strategies have been incorporating various technologies to streamline their operations (Kerin & Pham, 2019; Tolio et al., 2017), enhance CLSC operations (Taddei et al., 2022; Xin et al., 2022), overcome their intrinsic barriers or challenges (Bressanelli et al., 2018), and to support sustainable decision-making processes (Kerin & Pham, 2020).

The Internet of Things (IoT) enables the recovery and tracking of PLCI along CLSCs to optimize resource usage (Delpla et al., 2021), reconfigure supply chain processes, and provide data to support sustainable decision-making processes (Alam et al., 2025). This is enabled through the digitization of collection, transportation, remanufacturing, recycling, and disposal (Sun et al., 2023). Cyber-physical systems (CPS) integrate sensors, actuators, and computer algorithms to achieve efficient, reliable, flexible, or reconfigurable processes (Alshammari et al., 2025) or CLSC (Taddei et al., 2022). Cloud manufacturing technologies enable online access to data and applications (Singh et al., 2025). Big data analytics (BDA), artificial intelligence (AI), machine learning (ML), simulation, optimization, and other technologies or methodologies enable the processing and analysis of data to inform decision-making (Mejía-Moncayo et al., 2023).

Papacharalampopoulos et al. (2024) suggested that I4.0 facilitates the optimization of key performance indicators (KPIs) such as energy consumption, lead times, and material efficiency. Yannou et al. (2024) introduced the Circular Digital Cockpit, which uses IoT, simulation, and AI to monitor and optimize circularity. Prajapati et al. (2025) highlight the role of IoT, BDA, and cloud computing, in optimizing KPIs, such as resource efficiency and waste reduction. Oláh et al. (2022) affirmed the positive impact of robotics and BDA in operational efficiency. Mouflih et al. (2023) examined Virtual Reality (VR), Augmented Reality (AR), Human-Robot Collaboration (HRC), and Radio Frequency Identification (RFID) to optimize disassembly processes, addressing time efficiency, cost reduction, and operator safety. Noman et al. (2022) proposed a decision support system based on AI and ML to improve waste reduction and resource recovery. Xia et al. (2014) introduced a cloud-based remanufacturing system framework for the sustainable management of e-waste. Shahhoseini et al. (2023) emphasized the significance of PLCI in product design for remanufacturing.

Psarommatis et al. (2025) highlighted the contribution of IoT, AI, and blockchain (BCT) to enhanced traceability and predictive maintenance, impacting key performance indicators (KPIs) such as resource efficiency and life cycle longevity. Neri et al. (2025) illustrated how Digital Product Passports (DPPs) enhance traceability and lifecycle management, Digital Twins (DTs) optimize disassembly and reassembly processes, and the Internet of Everything (IoE) facilitates real-time decision-making. Eldrandaly et al. (2022) proposed a hybrid multi-criteria decision-making framework for sustainable manufacturer selection based on BCT and BDA. Govindan (2022) emphasized the potential of BCT to increase customer trust in remanufactured products by enhancing traceability throughout the product lifecycle. Bettín-Díaz et al. (2021) explored the integration of BCT to enhance quality management systems and build customers' confidence.

The transition from I4.0 to I5.0 is ongoing. In this new Industry 5.0 industrial paradigm, smart or Industry 4.0 technologies are integrated

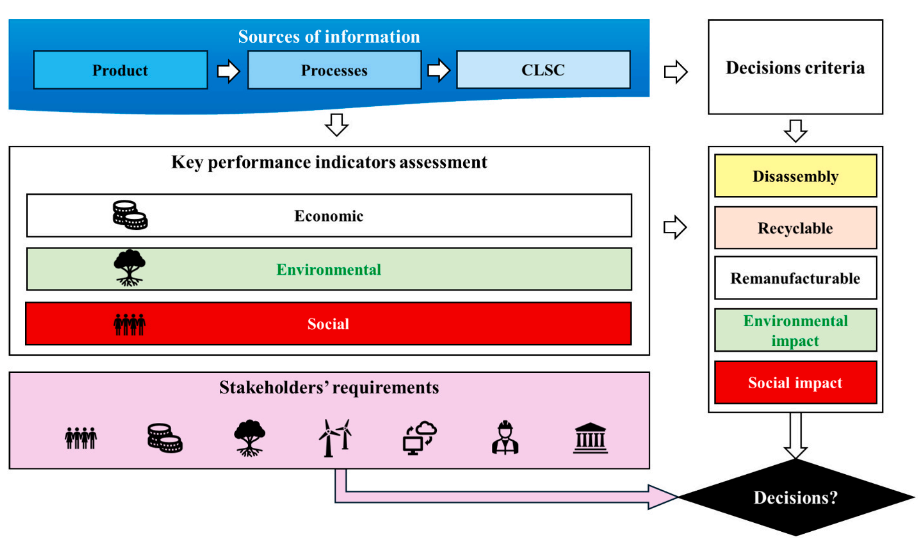

Fig. 4. Proposed methodological framework.

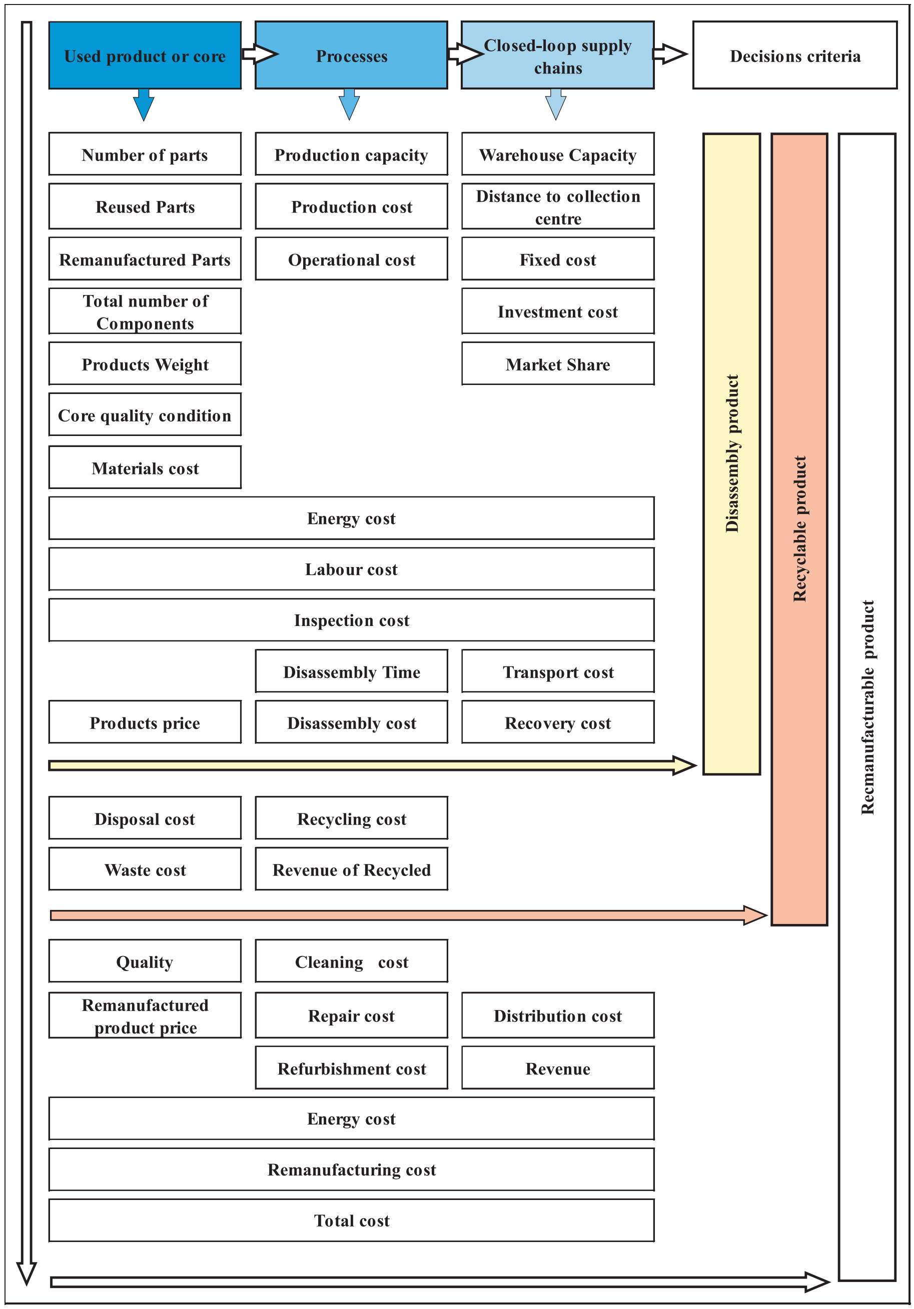

Fig. 5. Proposed methodological framework assessment sequence of economic key performance indicators to determine if the product is disassembly, recyclable, or remanufacturable.

with a sustainable, human-centric approach (Castillo et al., 2025; Yannou et al., 2024). In remanufacturing, human-robot collaborative disassembly plays a crucial role in this transition by integrating human agility with robotic capabilities (Lou et al., 2024; Yuan et al., 2025; De Simone et al., 2025). DTs are among the crucial technologies enabling I5.0 allowing to address uncertainty and improving sustainability in RL (Sun et al., 2023; Guangju et al., 2025). I5.0 also facilitates the linking of diverse analytical methods (optimization and simulation) in RL network planning for disruption mitigation (Yu & Sun, 2024).

Despite the advantages of I4.0 or I5.0 for remanufacturing, some challenges remain for their successful implementation. Papacharalampopoulos et al. (2024) revealed limitations in capturing specific I5.0 KPIs, such as human prosperity and resilience. Taddei et al. (2022) and Prajapati et al. (2025) highlighted unresolved challenges, including standardization, scalability, and social impact measurement. Oláh et al. (2022) and Psarommatis et al. (2025) identified I4.0 high costs and the shortage of skilled labour as major barriers to its implementation.

Yu & Sun (2024) suggested that, despite high initial technology investment, long-term cost and emission savings can be achieved. There are gaps in standardized sustainability metrics for disassembly (Mouflih et al., 2023) and circularity in industrial systems (Noman et al., 2022). Additionally, concerns regarding data access and availability persist (Amaitik et al., 2023), as well as issues related to data security and intellectual property (Neri et al., 2025).

The consulted literature demonstrates how remanufacturing is adopting smart systems and sustainability to achieve smart sustainable remanufacturing. The following section synthesizes the main findings of the literature review that was performed.

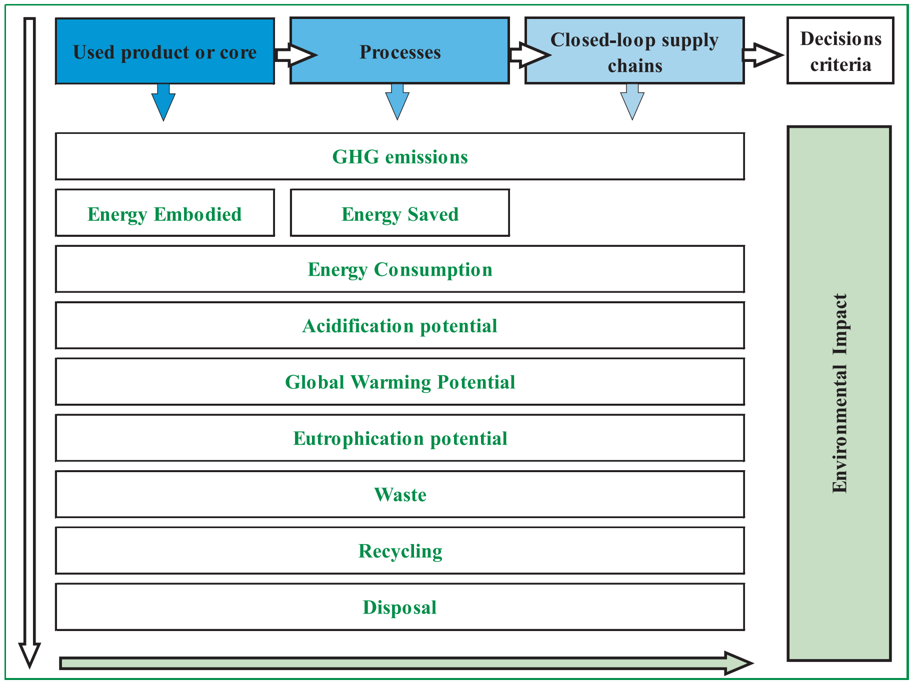

Fig. 6. Proposed methodological framework assessment sequence of environmental key performance indicators to determine the environmental impact when evaluating if the product is disassembly, recyclable, or remanufacturable.

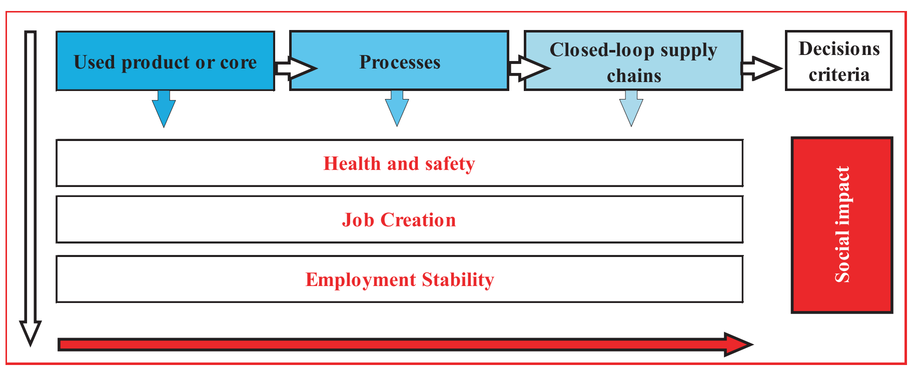

Fig. 7. Proposed methodological framework assessment sequence of social key performance indicators to determine the social impact when evaluating if the product is disassembly, recyclable, or remanufacturable.

5. Literature review analysis and discussion

The SLR conducted in this study presents a broad spectrum of KPIs in SR. Sections 3 and 4 focus on answering the first two research questions (RQ1 and RQ2) by presenting the KPIs that are most frequently referenced in the consulted documents. The identified KPIs offer a comprehensive view of sustainability in remanufacturing for decision-makers, encompassing the assessment of sustainability performance across remanufactured products, processes, companies, and CLSCs. These KPIs also highlight the multidimensional nature of SR along product dimensions (materials, parts, components, and cores), processes, CLSC, and stakeholders.

The KPIs presented in this study integrate CE and sustainable KPIs along with remanufacturing products, processes, and CLSC. This focus provides a holistic approach to understanding SR and shows the need to customize indicators directly related to the product, operation, process, company, or CLSC.

The assessment of remanufacturing sustainability relies on its precise definition within the context of the product, process, or organization that adopts or has already implemented remanufacturing. This approach is evident in the various studies that evaluate the sustainability of remanufacturing from different perspectives, as previously explained in Section 4.1. However, this focus also creates a challenge when comparing the sustainability of remanufactured products or processes in different markets.

Product design for remanufacturing (section 4.2) integrates different focuses, as the topics previously considered for sustainability assessment, remanufacturability, circularity, and CLSC concerns, along with section 4. Design frameworks for remanufacturing support this process from the early stages of new remanufacturable product design, as well as redesigning products to improve their remanufacturability or sustainability performance. Among the deployed methods, design for X stands out, with a design approach towards modular architectures that contributes to product's remanufacturability. Repairability and upgradability emerge as key topics in product design, alongside remanufacturability and circularity. Indeed, longevity also plays an important role as an alternative to the design of non-remanufacturable products.

The focus of this study on CE includes assessing disassembly, remanufacturability, and circularity. This is crucial to achieving sustainable

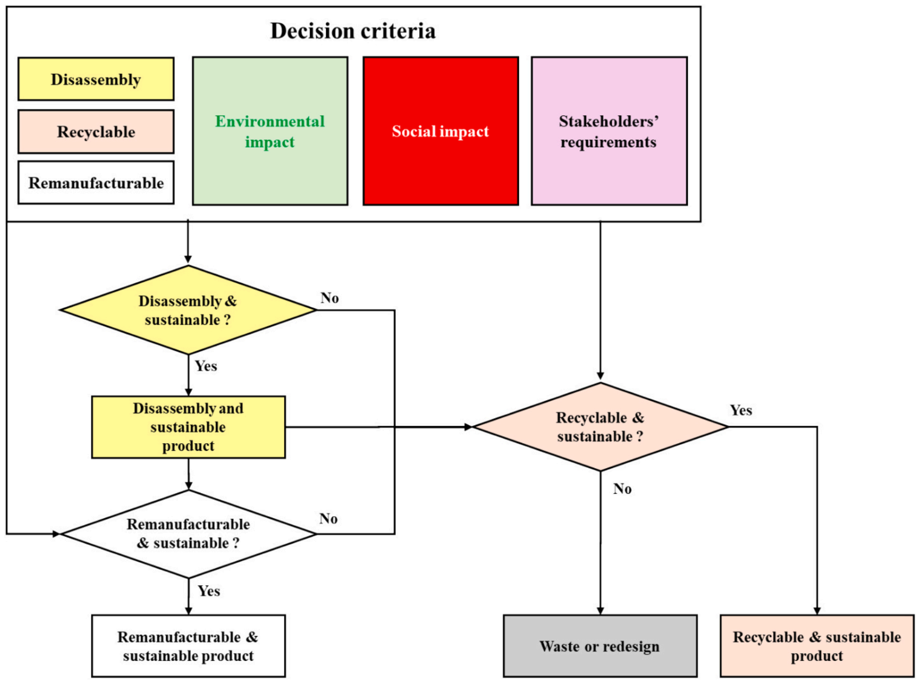

Fig. 8. Decision-making process for the methodological framework.

performance because these technical or CE KPIs contribute to measuring and improving the performance of products, processes, or operations. Disassembly and remanufacturability KPIs provide insights into the feasibility of recovering the value retained in materials, parts, components, and cores. These KPIs can be used in the early stages of remanufacturing adoption, product design, or process improvement.

This study presents a set of circularity KPIs focused on remanufacturing. These KPIs provide insight into the CE system and material loops involved in remanufacturing. Circularity is a concept that is evolving, and numerous approaches have been developed to address circularity in consideration of different CE strategies (Saidani et al., 2019). Indeed, the large number of approaches makes it complicated to perform comparisons between circularity KPIs. It would be preferable to adopt a standardized method for evaluating the circularity of products.

The significant number of studies focusing on remanufacturing CLSCs emphasizes its importance in SR. These cover the design of RL networks, sustainable supply chain planning, selection of RL providers, remanufacturing planning, and logistics performance. CLSC actors must identify which KPIs apply specifically to a use case to assess its performance, taking into account the needs of their stakeholders.

The CLSC design, operation, and optimization are crucial perspectives to achieve SR. Various studies utilize optimization models based on the KPIs identified in this research to design or improve the performance of remanufacturing operations, systems, or CLSCs. These models employ a multi-criteria approach, comprehensively addressing sustainability dimensions.

I4.0 and I5.0 technologies enable the retrieval, processing, analysis, and utilization of PLCI for KPI-based decision-making in SR. I5.0 integrates smart systems with sustainability, which aligns with SR. The advantages of I4.0 and I5.0, as described in the reviewed literature, demonstrate the need to integrate technology into the implementation of KPIs in SR. These implementations must be integrated with organizations' management systems to fully leverage their potential. Traceability is highlighted as a crucial issue in remanufacturing, where IoT, AI, CPS, BDA, and BCT play a prominent role. Some authors also express concerns regarding social sustainability and the use, security, access, and management of data.

In summary, the conducted literature review has comprehensively discussed various KPIs and concepts that have been resulted in the formulation of the following definition of SR:

> "*Sustainable remanufacturing involves performing remanufacturing and CLSC processes or operations sustainably. This comprises ensuring concurrently the disassembly, remanufacturability, and circularity of a product, its components, parts, and materials, regarding economic, environmental, and social concerns of stakeholders through the product life cycle.*".

A practical approach to supporting decision-makers will be introduced in Section 6.

6. Methodological framework for decision makers

The scope of the KPIs identified in this study is broad. Therefore, decision-makers have concerns about their selection and use. Tables 2 to 4 present the distribution of the indicators among the main fields of application reported in the literature. These can be used as a reference to select the KPIs to be implemented. However, this study seeks to provide a closer approximation to the user, enabling them to take advantage of the KPI's full potential through a methodological framework.

The proposed methodological framework jointly evaluates sustainability dimensions and the processes of product disassembly, recycling, and remanufacturing. A thorough analysis, shown in Fig. 3, is conducted across product layers (materials, parts, and components) and system layers (product, CLSC, and processes) to satisfy stakeholder requirements. This framework is applicable throughout the remanufacturing process, from initial adoption assessment to ongoing operational management and product design or redesign.

This methodological framework begins by recovering information on the product, the manufacturing processes involved, and its CLSC. Subsequently, a KPI assessment is undertaken to develop the decision-making criteria, which are then used to guide the final decision, a process illustrated in Fig. 4.

The first step of the framework recovers the information that feeds the KPIs and contributes to establish the stakeholders' requirements or objectives for each KPI. The required information could include the product's bill of materials, drawings or datasheets, material composition, CLSC information, process route, life cycle information, maintenance reports, quality reports, and stakeholders' requirements, such as governmental policies, technical standards, investors' objectives, employees and community requirements, or other relevant information sources. The recovery, process, and analysis of this information must be supported by I4.0 and I5.0 technologies, as suggested in section 4.7. The implementation of this methodological framework can be enhanced by a smart architecture that integrates technology, management systems, stakeholders and operations (Mejía-Moncayo et al., 2023).

Once the information is recovered, the KPI assessment is performed by implementing the KPIs described in Tables 2 to 4. This includes the analysis of materials, parts, components, processes, and CLSCs from product recovery to disassembly, recycling, and remanufacturing. A top-to-bottom, left-to-right KPI assessment sequence is recommended to determine decision criteria, as illustrated in Figs. 5 to 7.

Fig. 5 presents the assessment of economic KPIs to evaluate disassembly, recycling, and remanufacturing. Fig. 6 focuses on environmental KPIs, and Fig. 7 on social KPIs, to determine the environmental and social impacts of disassembly, recycling, and remanufacturing.

This suggestion encompasses the three sustainability dimensions and focuses on KPIs related to disassembly, recycling, and remanufacturing, including disassembly cost, recycling cost, remanufacturing or total cost, environmental impact, and social impact, as illustrated in Figs. 5 to 7.

The final step of the framework is the decision-making process, which concurrently determines whether a product can be sustainably disassembled, recycled, or remanufactured. This step involves comparing decision criteria with stakeholder requirements, as illustrated in Figs. 5-7, to inform decisions, as shown in Fig. 8.

The process begins with evaluating the product's disassemblability and sustainability. If the product qualifies as disassembly- and sustainability-friendly, it is then assessed for its potential to be sustainably remanufactured. Suppose the product does not meet the criteria for sustainable disassembly or remanufacturing. In that case, the next step is to evaluate its recyclability in a sustainable manner to recover the value embedded in its materials. If sustainable recycling is also not feasible, redesign or responsible disposal should be considered.

In essence, the proposed methodology aims to support the evaluation of sustainable recovery options across products, processes, or CLSC by systematically aligning with stakeholder requirements—from the initial adoption of SR strategies to the end-of-life management of remanufactured products.

7. Conclusions

This study conducts a systematic literature review to identify the primary key performance indicators in sustainable remanufacturing, determine their primary fields of application, define sustainable remanufacturing, and provide practical insights through a methodological framework. These objectives were appropriately achieved by answering the four research questions (RQ1-RQ4) introduced and discussed in sections 3 to 6.

The most referenced KPIs in SR (32 economic, 16 environmental, and 3 social) were identified by a comprehensive review process of 106 systematically selected published documents. In terms of frequency of use, the KPIs are distributed among economic, environmental, and social factors in descending order. The studies that were consulted have identified six fields of application, which include 1) the sustainability assessment, 2) product design for remanufacturing, 3) product disassembly assessment, 4) product remanufacturability assessment, 5) remanufacturing circularity assessment, and 6) closed-loop supply chains for remanufacturing, and its relationship with smart sustainable remanufacturing.

The conducted SLR presents the main KPIs in SR across the three sustainability dimensions. Economic KPIs are the costs of transport, remanufacturing, disassembly, labour, disposal, fixed and recycling, and disassembly time. Environmental KPIs include GHG emissions, energy consumption, environmental impact, recycling, remanufactured parts, materials disposal, and acidification potential. Social concerns are health and safety, job creation, and employment stability.

In summary, the KPIs included in this study enable a thorough evaluation of sustainability within remanufactured products, the processes involved in their remanufacture, the companies involved, and the closed-loop supply chain. This focus establishes a link between CE and sustainability KPIs, highlighting the multidimensional nature of SR along product dimensions (materials, parts, components, and cores), processes, CLSC, and stakeholders. This focus is developed in the proposed methodological framework, which allows a concurrent assessment of sustainable disassembly, recycling, and the remanufacturing of a generic product. The framework can also be customized by adding specific KPIs depending on the characteristics of the product, processes, or CLSC. The framework provides decision-makers with a broad and detailed perspective of SR. This enables them to consider the various challenges and opportunities associated with its adoption, implementation, and operation. The framework also suggests integrating a smart architecture to support its implementation.

Future research opportunities identified in this SLR include the identification of the obstacles hindering the integration of social considerations into SR assessments. The development of practical methodological tools to guide the implementation of KPIs in SR based on I5.0. Implementing the international standard ISO 59000 in SR, its integration into the company management system, the challenges it presents in an I5.0 context, and its integration with smart architectures. Planned obsolescence versus design for remanufacturing, considering repairability, upgradeability, and product lifespan, also must be addressed. Finally, there is a gap in the development of sustainable models for designing, planning, and controlling remanufacturing systems and their corresponding closed-loop supply chains.

This study has inherent limitations in terms of its scope, as it solely relies on documents sourced from the Scopus database and focused on SR. As a result, it may inadvertently exclude other valuable perspectives that could have contributed to a more comprehensive analysis. A lack of an empirical assessment of the methodological framework also represents a limitation of this study. It is also advisable to customize the framework according to the context of implementation and to validate the obtained results.

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

During the preparation of this work the authors used *ProWritingAid* and *ChatGPT* in order to improve document readability. After using these services, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

CRediT authorship contribution statement

Camilo Mejía-Moncayo: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Amin Chaabane:** Writing – review & editing, Validation. **Jean-Pierre Kenné:** Writing – review & editing, Validation, Supervision. **Lucas A. Hof:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization, Methodology.

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.clscn.2025.100260.

Data availability

Data will be made available on request.

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