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Procedia CIRP 146 (2026) 667–671

www.elsevier.com/locate/procedia

CIRP Conference on Manufacturing Systems (CIRP CMS)

Rethinking Scrap: A holistic terminology for component disposal categories to precisely assess the performance of remanufacturing systems

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Abstract

Remanufacturing plays a central role in advancing circular economy objectives, yet the processing of end-of-life products introduces substantial uncertainty regarding component condition, compatibility, and usability. Conventional performance measurement in remanufacturing often relies on the monolithic concept of scrap, which aggregates all disposed components into a single metric. As a result, critical information about the distinct causes of component non-use is lost, limiting the ability to understand system behaviour, identify improvement potentials, and design effective interventions. This paper introduces a holistic terminology that differentiates disposed components into four non-use categories: outdated, irrecoverable, misprocessed and discarded. These categories capture conditions ranging from core-quality-related failures and process-induced losses to design-related incompatibilities and deliberate control decisions. Based on this terminology, four dedicated key performance indicators are defined, allowing for a transparent evaluation of each disposal category and its impact on overall system performance. The proposed framework is validated through four illustrative scenarios that exhibit identical conventional scrap ratios but differ fundamentally in their underlying disposal profiles. The results demonstrate that the differentiated categorization and the associated key performance indicators provide a substantially more precise and actionable assessment of performance losses in remanufacturing systems, particularly in cross-generational contexts where product upgrades and design changes introduce additional complexity. The framework enables a structured, data-driven basis for monitoring, diagnosis, and continuous improvement in remanufacturing operations.

Keywords: Remanufacturing; Scrap; Quality; Key Performance Indicators; Taxonomy

1. Motivation

Remanufacturing has garnered substantial attention in recent years, as it offers a viable response to the growing need for a transition towards a circular economy [1, 2]. It is understood as an industrial production process in which used products or parts, commonly referred to as cores, are restored to a condition that meets or exceeds the performance and quality of the original product [3]. This process typically involves the systematic disassembly of cores, the reprocessing of components and subassemblies, and their subsequent reassembly into products that enter a further use phase [4]. Remanufacturing can also occur across different product generations, further increasing operational complexity as cores from older generations are transformed into products that meet the requirements of the newest generation [5].

Processing end-of-life products introduces a high degree of inherent uncertainty, which makes remanufacturing processes less deterministic and more unstable than classical production processes [6]. As a result, many components are disposed of during inspection, disassembly, and reprocessing.

The reasons for component disposal are diverse, and the required measures to improve system performance differ accordingly. However, the standard and highly general definition of *scrap* in classical production systems does not reflect this diversity and therefore does not support an appropriate and targeted response. This challenge becomes even more pronounced in complex remanufacturing systems that operate across multiple product generations, where additional incompatibilities and design variations further increase the variety of reasons for discarding products.

For this reason, a holistic and precise terminology for component disposal categories in remanufacturing systems is in-

10.1016/j.procir.2026.03.302

troduced. It is complemented by key performance indicators that support the accurate identification of problems within running remanufacturing operations. Section 2 presents related literature and outlines existing distinctions of scrap components. Section 3 introduces the proposed terminology and corresponding key performance indicators, which are then validated through example scenarios in Section 4. Finally, Section 5 provides concluding remarks.

2. Related Work

This section provides an overview of the relevant literature in the field of remanufacturing with a particular focus on the definition and differentiation of components that are not reassembled into final products and are instead removed from the remanufacturing system. While a clear and unambiguous definition of *scrap* exists in linear production according to [7], comparable clarity is missing in remanufacturing contexts. Across existing literature, foundational terms describing material removal from the system are used with substantial conceptual inconsistency.

For instance, [8] define scrap as entire end-of-life products, whereas other authors apply the term to used products or components that fail remanufacturing criteria. In [9], scrap describes products that, after inspection or disassembly, are not considered remanufacturable and are consequently removed from the system. Similarly, [10] distinguish between components that exit the use phase as cores or as scrap, where scrap is directed into recycling rather than remanufacturing. In contrast, [11] explicitly state that a core is not scrap, thereby decoupling the notion of scrap from remanufacturing inputs altogether. The terminology surrounding waste shows a similarly heterogeneous pattern. Waste is often used synonymously, as in [9], which characterise waste as products that are no longer useful. Likewise, [12] examine waste streams and identify many reasons for disposing of cores, yet still refer to all of them collectively as waste. A more process-oriented view is taken in [13] and [14],where waste is defined as the difference in material quantities between system input and output. The term *disposal* is used in [15] to describe the final treatment option in circular supply chains when products can no longer be reused, remanufactured, or recycled. Taken together, these sources demonstrate that scrap and waste are applied to structurally different categories of material flows and product conditions, which reveals a lack of definitional consensus across the field.
At a more general level, many publications examine disposed components to assess remanufacturing system performance. In [14] a Core Disposal Rate is introduced that captures the share of returned cores ultimately treated as waste, defined as the difference between the mass of incoming cores and the mass of invoiced goods, with a similar approach in [16]. A Circular Economy Index is proposed in [17], based on the ratio between the material value recovered from end of life products and the material value required to reproduce them. Although such metrics quantify the total amount of disposed components, they do not differentiate the specific causes that lead to component removal.
Several studies also examine the quality of returned products and its influence on remanufacturing outcomes. A quantitative model is presented in [18] that assesses the environmental benefits of remanufacturing based on the quality of returned items, represented by a quality coefficient. Similarly, [19] identify variability in product quality as a major source of uncertainty in remanufacturing costs. These contributions highlight the relevance of evaluating and monitoring the condition of incoming cores. However, they do not establish a consistent terminology or a holistic metric that positions quality related rejects in relation to other reasons for component discarding.

A limited number of approaches explicitly consider process related component removal in performance measurement. In [20], functional requirements for remanufacturing production planning and control are derived alongside relevant performance indicators, distinguishing between uncertainty in core quality and random failures of cores and components during processing. In a review of remanufacturing in the automotive aftermarket, [21] introduces the concept of Regeneration Rates, defined as the ratio of process output to process input at each step of the remanufacturing process. This distinction separates the general capability of the remanufacturing processes from the quality of incoming cores. Although these approaches acknowledge different categories of component removal, they do not account for remanufacturing systems that operate across product generations. Consequently, an increasingly relevant category of component non-use remains unaddressed.

Overall, existing approaches do not sufficiently capture the full range of reasons why components are removed from remanufacturing processes. In particular, they overlook cases in which undamaged components are not reused due to strategic decisions, such as disposing of components for which demand is low and inventory costs dominate. They also do not consider situations in which components become incompatible because of cross-generational remanufacturing requirements. To our knowledge, no comprehensive terminology currently exists that clearly differentiates between these diverse categories of component removal.

3. Approach

As discussed in Section 2, the established monolithic concept of *scrap* and corresponding production indicators, such as scrap rates, have been directly applied to remanufacturing systems. However, the reasons for disposing of components are far more diverse in remanufacturing than in classical production, because end-of-life products exhibit heterogeneous conditions, design variations, and uncertain histories. Relying on a single aggregated term obscures essential information about the underlying causes of system inefficiencies and limits the ability to derive targeted improvement measures. For this reason, we introduce a differentiated terminology that captures distinct categories of component disposal within remanufacturing operations. An overview of the proposed categories is provided in Figure 1.

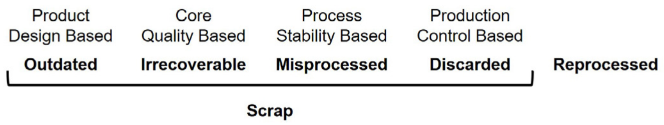

Fig. 1. Overview of different disposal categories

In cross-generational remanufacturing systems, where incoming cores are transformed into the newest product generation and may require selective component upgrades, the categorisation of *outdated* components becomes relevant. Not all components from older generations can be reprocessed or transformed to be reassembled into the newest product generation due to design changes, altered specifications, or updated functional requirements, and are therefore disposed. To minimize the amount of *outdated* components, products have to be designed in a cross-generational manner as the production system has minimal leverage on minimizing this category of scrap.

If components are compatible with the current product generation, the quality state of the disassembled component becomes a relevant factor. While the majority of components exhibit a degraded condition, a subset is in such poor condition that they must be classified as *irrecoverable*. These components cannot be reprocessed with reasonable effort and are consequently disposed of from the remanufacturing system. As with *outdated* components, *irrecoverable* components cannot be fully avoided through improvements within the remanufacturing processes themselves. The only effective leverage to reduce their occurrence lies in increasing the quality of incoming cores. This may be achieved by applying stricter acceptance criteria for end-of-use products or by sourcing higher-quality cores from external core suppliers.

Components that pass initial inspection enter processing within the remanufacturing system. During processing, *misprocessed* components arise when a component is irreversibly damaged as a direct result of the processing steps and consequently becomes unusable. This corresponds to the most common mechanism through which *scrap* is generated in linear production systems. In remanufacturing, however, the frequency of such occurrences is typically higher, particularly during disassembly where aged, worn, or degraded interfaces increase the risk of operational errors. The amount of scrap in this category can be reduced by stabilizing process conditions and conducting more comprehensive inspections to prevent improper operations, for example applying excessive torque to a corroded screw.

The remaining set of components, which are neither *irrecoverable*, *misprocessed* nor *outdated*, are in principle suitable for reprocessing and reassembly. However, in certain situations, the production control system may deliberately decide not to reprocess them. These components are referred to as *discarded*. This can occur when the required processing time for specific component types is disproportionately high, or when sourcing new or refurbished components through a linear supply channel proves more favorable for meeting system-level objectives. All components that are technically reprocessable but intentionally not pursued for operational or economic reasons are categorized as *discarded*. All remaining components are then forwarded to the reprocessing steps.

In addition to establishing a precise terminology for the different categories of component non-use, it is essential to define corresponding key performance indicators. These indicators enable remanufacturing systems to quantify operational effectiveness and to detect deviations between expected and actual performance. They provide a structured and data-driven basis for decision-making, supporting continuous improvement efforts. For each non-use category, a dedicated KPI is introduced to allow targeted identification of problems within that specific area.

The Compatible Component Ratio (CCR) (Equation 1) provides a measure to assess whether an excessive number of *outdated* components are entering the remanufacturing system. A distinct component is defined as a unique component type within the set of incoming cores. Each different component is considered compatible if it satisfies the design and functional requirements of the current product generation. The CCR, therefore, quantifies the proportion of incoming component types that can still be used without requiring design-related substitutions. Similar concepts have also been described in the literature, for example in [22]. However, these approaches focus primarily on detailed technical compatibility assessments and are not specifically designed to provide an aggregated and decision-relevant indicator suitable for production planning and control contexts.

$$CCR = \frac{\text{Compatible Distinct Component Types}}{\text{Distinct Component Types}} \quad (1)$$

The Core Quality Index (CQI) (Equation 2) serves to assess the quality of incoming cores. A low CQI indicates that the returned cores contain a high proportion of *irrecoverable* components, signaling quality-related issues at the point of return. This aspect is often intended to be captured through recovery rates [6]. However, recovery rates typically aggregate multiple loss mechanisms and therefore do not exclusively distinguish irrecoverable components.

$$CQI = 1 - \frac{\text{Irrecoverable Components}}{\text{Disassembled Components}} \quad (2)$$

The Quality Ratio (QR) (Equation 3) can be defined in accordance with [7], while incorporating necessary adjustments to ensure its applicability to remanufacturing contexts. The adapted QR exclusively reflects issues that arise during the actual processing of components. It therefore captures only process-induced losses and does not account for other categories of component non-use. Consequently, the QR is inherently focused on stations and resources, as it specifically reflects processing errors occurring at individual processing steps and the associated production equipment.

$$QR = 1 - \frac{\text{Misprocessed Components}}{\text{Components leaving Station}} \tag{3}$$

The Circularity Effectiveness Ratio (CER) (Equation 4) quantifies whether a remanufacturing system generates an excessive amount of *discarded* components. It expresses the share of components that are actually reprocessed relative to all elements that would, in principle, be suitable for reprocessing. The set of possible reprocessed components, therefore, consists of the sum of reprocessed and discarded components.

$$CER = \frac{\text{Reprocessed Comp.}}{\text{Reprocessed Comp. + Discarded Comp.}} \tag{4}$$

To holistically assess quality related issues within the remanufacturing system, the Reprocessed Component Ratio (RCR) (Equation 5) can be evaluated. Similarly to the conventional *Scrap Ratio* defined in [7], the RCR provides an aggregate view of system performance, but does not enable a detailed analysis of the underlying sources of quality losses. Nevertheless, it offers a meaningful overall indication of how effectively the system preserves component usability throughout processing.

$$RCR = \frac{\text{Reprocessed Components}}{\text{Disassembled Components}} \tag{5}$$

4. Validation

In this section, the proposed KPI framework is applied to an illustrative example. The analysis demonstrates the value of categorizing scrap components into four categories: discarded, outdated, misprocessed and irrecoverable components. It also highlights the relevance of the corresponding KPIs, which provide a more precise understanding of system performance and the underlying causes of component disposal.

The example consists of four scenarios that all exhibit identical overall performance when assessed with a conventional high-level scrap metric. Despite this apparent similarity, each scenario is dominated by a different primary cause of component disposal, which is captured by the respective KPIs. In contrast, all other parameters, including the total number of disposed components, are held constant. The conventional Scrap Ratio (SR) is calculated in accordance with [7], which defines scrap quantity as the produced quantity that does not meet quality requirements and cannot be reworked. The scenarios are synthetic and intended to demonstrate conceptual differentiation rather than empirical validation.

To perform the calculations, information on material inflows and outflows, as well as general component characteristics, must be specified. The inflow parameters consist of the number of components released from cores into the system and the number of virgin components produced. The outflow parameters comprise the number of reprocessed components and the quantities assigned to each of the four disposed component categories. In addition, two further parameters are required to compute the relevant KPIs: the number of distinct components and the number of distinct components that are compatible with one or more products. The KPIs can then be calculated as described in section 3. An overview of the four scenarios used for demonstration is summarized in Table 1.

	Sc. 1	**Sc. 2**	**Sc. 3**	**Sc. 4**
Core	850	850	850	850
Virgin	150	150	150	150
Reprocessed	700	700	700	700
Discarded	225	25	25	25
Outdated	25	225	25	25
Irrecoverable	25	25	225	25
Misprocessed	25	25	25	225
Distinct	50	50	50	50
Compatible	45	25	45	45
CCR	90%	**50%**	90%	90%
CQI	97.06%	97.06%	**73.53%**	97.06%
QR	97.5%	97.5%	97.5%	**77.5%**
CER	**75.68%**	96.55%	96.55%	96.55%
RCR	82.35%	82.35%	82.35%	82.35%
SR	42.86%	42.86%	42.86%	42.86%

Table 1. Four exemplary scenarios demonstrating the need for a more detailed classification and measurement

In the first scenario, a high number of discarded components is the primary driver of total disposal. This indicates that components were deliberately removed from the system, which is reflected in a reduced CER. In the second scenario, the large number of outdated components, combined with the lower number of components that are compatible with one or more products, are the dominant influencing factors. The resulting low CCR reveals that a substantial share of functionally intact components is no longer usable due to design-related incompatibilities. In the third scenario, irrecoverable components constitute the main reason for disposal. The CQI captures this situation by indicating systemic quality issues in the incoming cores, where components fail to meet the required condition. The fourth scenario represents a production setting with a high number of misprocessed components, indicating unintentional material loss or process-induced damage, which is reflected in a low QR.

Across all scenarios, the RCR and SR remain constant, as they capture only the total quantity of disposed components without distinguishing their underlying causes. This highlights the necessity of a differentiated categorization of disposal metrics to enable a more comprehensive and meaningful assessment of circularity performance.

5. Discussion and Outlook

This paper presents a structured terminology that enables a precise categorization of the different reasons for the non-use of components within remanufacturing systems, by differentiating disposed components into the four categories: outdated, irrecoverable, misprocessed, and discarded. All relevant disposal mechanisms in contemporary and cross-generational remanufacturing environments are systematically captured. This differentiation addresses a long-standing gap in existing performance measurement approaches, which commonly rely on aggregated scrap indicators that obscure the underlying causes of component removal.

The proposed terminology is complemented by four dedicated key performance indicators, namely the Circularity Effectiveness Ratio, the Compatible Component Ratio, the Core Quality Index, and the Quality Ratio. Together, these indicators provide a more granular and transparent view of performance losses along the remanufacturing process. The validation scenarios demonstrate that systems with identical conventional scrap ratios can exhibit fundamentally different operational challenges. The KPIs, therefore, offer a practical diagnostic tool that enables targeted interventions, ranging from improving core acquisition strategies to stabilizing disassembly processes or adjusting product architectures for enhanced generational compatibility.

The results also underline the strategic value of distinguishing between avoidable and unavoidable disposal categories. Irrecoverable and outdated components represent structural constraints rooted in core quality and product design, while misprocessed and discarded components reflect operational issues or decision-making within the factory. This distinction provides an enhanced basis for prioritizing improvement measures, aligning resources, and guiding continuous improvement initiatives.

Future research should explore the integration of the proposed terminology and KPIs into digital production systems, such as Manufacturing Execution Systems or digital twins for remanufacturing. This would enable real-time monitoring, automated anomaly detection, and data-driven decision support. Furthermore, the terminology may serve as a foundation for evaluating design for remanufacturing strategies, product architectures oriented towards compatibility, and economic optimization models. Ultimately, empirical validation across various product categories and industrial sectors would further enhance the generalizability and applicability of the framework.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG - German Research Foundation) - SFB 1574 - 471687386

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