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Proposing an integrated indicator to measure product repairability

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ABSTRACT

Repairing is one of the most relevant strategies within the Circular Economy (CE) concept since it contributes to waste prevention and extends product and components' lifespan. Thus, reparability becomes an essential issue from the early product design phases, where materials, geometries, and joints are defined. Despite some repairability indicators that can be found in the literature and are applied worldwide, there is a lack of connection between repairability and the early decision-making process for improving it from the design of components of subsystems of a product. To contribute in that research direction, this article presents the Product Repairability Index (PRI), which considers the intrinsic repairability of the product components, their assembly/disassembly complexity, repairing instructions, availability of spare parts, and the self-diagnosis aids provided by the product. The PRI also considers components' relative functional importance to identify those with higher repairability requirements concerning their functional importance in the whole product assembly. The proposed indicator has been applied to a coffee machine as a case study, following a step-to-step methodology and calculation criteria to generate a quantitative value and detect the possible aspects to redesign to make a product more repairable.

1. Introduction

The Circular Economy (CE) paradigm covers several actions and strategies to reduce the environmental impacts of resources that a product or service uses to fulfill its functions. This concept also fosters the expansion of lifespan and the design of durable products. Thus, waste prevention can be obtained by designing more durable products based on reuse, repair, remanufacturing, and refurbishment (Maitre-Ekern and Dalhammar, 2016). Therefore, durability is now a desirable attribute of products that can be defined as "*the ability to perform a function at the anticipated performance level over a given period, under the expected conditions of use and foreseeable actions. Performing the regular servicing, maintenance, and replacement activities as specified by the manufacturer will help to ensure that a product achieves its intended lifetime*" (Boulos et al., 2015). Supporting durability, the CE enables the conservation of products, components, and materials at their highest utility and value while distinguishing between technical and biological cycles (British Standard Institute, 2017). Thus, products, components, and materials can be reused, remanufactured, or recycled and fed back into the system, reducing further extraction of resources (Akrivos et al., 2019).

In that sense, several approaches like those developed by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2013) have proposed a series of circularity loops applicable through all the life stages of product development. The loops that make the resources stay closer to the user are the most sustainable since they do not involve additional resources to transform and handle materials. Repairing, aside from reuse, is classified into those loops. Consequently, repairing is one of the preferred actions to maintain the resources in circulation. Product design, on the other hand, is one of the most critical drivers for introducing CE in production systems (Golinska-Dawson and Pawlewski, 2015). The circular design approach is making new design strategies, rules, and considerations that need to be addressed during the identification of needs and conceptual design phases to ensure the circularity of products, components, and materials. In terms of modifications, after the conceptual stage, most product changes are irreversible (Curran et al., 2004; Weustink et al., 2000). During those early stages, the main features of products are defined; in some cases, manufacturers intentionally can even plan the obsolescence of products, reducing the lifespan to stimulate the repetitive replacement of products and more

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frequent consumption (Slade, 2006). Many products are not designed to be dismantled but are instead designed in a way that makes it very difficult to separate materials and components (Pickren, 2015).

Literature analysis showed that current research efforts are oriented mainly to material recyclability instead of material conservation to facilitate their reuse, repair, remanufacture, refurbishment, and repurpose. (Mesa et al., 2020). Repair is the starting point of other CE strategies like remanufacturing and refurbishing. Repairing is a strategy of product value retention which requires significantly fewer resources and, therefore, lower environmental and economic costs than other strategies like refurbishment and remanufacturing (Russell and Nasr, 2019). It is the ability to return a product to working conditions after failure in a reasonable amount of time and for a reasonable price (Flipsen et al., 2017). For example, products can be added to the economy through repair using second-life markets (Westblom, 2015). Ease-of-repair becomes vital in sustainable design since it enables a product's usefulness in the same life cycle, rather than going through a complex reverse logistic process and take-back systems (Huang, 2016). Sabbaghi et al. (Sabbaghi and Behdad, 2017a, 2017b) found that fostering repairability through sharing manuals or repairing information, among others, positively impacts future purchases of repairability products. Also, the cost spent on repairing the product could not be significant for the consumers. On the other hand, product warranty should be considered when making maintenance decisions (Yeh et al., 2007).

To assess the durability of products, methods, and metrics are required to assist designers and manufacturers in facilitating product lifespan extension (Mesa et al., 2020). Regarding repairability assessment, several indicators can be remarked from the existing literature to measure single aspects of the CE or general sustainability in products. For example, the ones included in Mesa et al. (Mesa et al., 2018), Parchomenko et al., (2019), Saidani et al., (2019), and (Ruiz-Pastor et al., 2022). Nevertheless, there is no standard metric or indicator to measure repairability at product and component levels. Design for repairability is usually difficult to measure or assess (Boulos et al., 2015). Several metrics foster holistically measuring the CE. For example, the Circularity Calculator (Ellen MacArthur Foundation - EMAF, 2015) or the tool developed by Moreno et al., (2016).

As repairability is one of the essential strategies under the CE umbrella, this work intends to develop a metric to evaluate the repairability of products thoroughly. Furthermore, there are indicators to assess other single aspects related to a CE in products, such as the one proposed by Mesa et al., (2018), which is developed to evaluate the assembly/disassembly of products. The indicator proposed considers all the necessary aspects of the products to achieve a comprehensive evaluation of their repairability in terms of overall product and component level, also considering the different parts and subassemblies and how they interact.

The following section shows a literature review of the existing repairability metrics. After that, the Product Repairability Indicator (PRI) is developed in Section 3. Section 4 englobes the application of the PRI metric to a coffee machine, which was selected as a case study. In Sections 5 and 6, the findings are discussed, as well as the possible future work and the challenges found during the development of the work. Finally, Section 7 shows the conclusions of the work.

2. Literature review

This section summarizes the main approaches related to measuring product repairability. A revision of existing literature was performed using a systematic search procedure in the SCOPUS and WEB OF SCIENCE databases. A search query for SCOPUS was employed *"TITLE-ABS-KEY (product AND (repair OR reparability OR repairing) AND (metric OR indicator)) AND (LIMIT-TO (SUBJAREA, AND, "ENGI") OR LIMIT-TO (SUBJAREA, AND, "ENVI") OR LIMIT-TO (SUBJAREA, AND, "COMP") OR LIMIT-TO (SUBJAREA, AND, "BUSI") OR LIMIT-TO (SUBJAREA, AND, "MULT"))",* which provided 276 entries. Regarding Web of Science, the search query was *"product AND (repair OR reparability OR repairing OR repare) AND (metric OR indicator)"* resulting in 295 entries. Both searches were updated on September 2nd' 2022. After performing a duplicate elimination and excluding entries based on title, abstract, and keywords, 43 references were selected in the first group of selected works. In this first group, a detailed revision of documents provided a final selection of 24 research works that were revised to generate a high-related and summarized literature review analysis. The analysis of previous research is divided into two categories: conventional and circular repairability metrics. Each category is described in detail as follows.

2.1. *Existing repairability metrics*

Approaches concerning product repairability and its metrics can be reported since the late 90s when repairability was most related to reliability engineering and maintenance performance. One of the most common approaches in the first research was measuring the time associated with disassembling systems and products. One of the first authors was Kroll and Hanft (Hanft and Kroll, 1996; Kroll and Hanft, 1998), which proposed a quantitative evaluation method of product disassembly, mainly oriented to recycling but with relevance for repairing as well. Later, Desai and Mital (2003) developed a metric for disassemblability based on the design for disassembly approaches. In 2003, the iFixit tool was launched and is still one of the most referenced metrics to evaluate repairability in electronic products (Anon, 2003). The iFixit website now includes a grading system for assessing the ease of disassembly and repair of a product through a scorecard for different electronic devices. Its current version contains a quantitative evaluation of smartphones, tablets, and laptops.

Lugtigheid et al. (Lugtigheid et al., 2005) proposed an indicator that integrates the ages of parts of the component and its current state to determine which repair strategy is more suitable. The indicator was also conceived to measure the impact of different repair strategies on component failure intensity. More recently, Pandey & Mourelatos (Pandey and Mourelatos, 2013) proposed a set of metrics denominated Minimal Set of Metrics (MSOM) to describe the performance of repairable systems based on classical reliability theory. The MSOM can also be used as an attribute in a design optimization process to obtain comparative performance scenarios. Other metrics include time to first failure, mean time between failures, minimum failure-free period with probability, planning horizon, effective age, repair time, and cost. In 2014, the label of excellence for durable, repair-friendly designed electrical and electronic appliances ONR 192102:2014 (ISO, 2014) was launched by the Austrian Standards Institute. That label includes 40 criteria for white goods and 53 criteria for brown goods, and it was oriented to promote extended lifespan products.

Flipsen et al., (2017) developed a repairability rubric for electronic products based on iFixit repairability scorecard and was oriented to non-experts. Cordella et al. (Cordella et al., 2018) developed a comprehensive framework for assessing the repairability and upgradability of energy-related products based on lifecycle assessment and qualitative-quantitative analysis. The method employed as input analysis of complexity, the familiarity of tools, and availability of information. As an outcome, the proposed approach identifies design features highly related to repair and upgradeability. Similarly, Bracquene et al., (2019) compared semi-quantitative repairability methods such as the iFixt repairability scorecard and the Standard (ISO, 2014). They also proposed repairability criteria to quantify the ease of repair for energy-related products, considering the economic impact from a consumer perspective.

Recently proposed metrics are aligned with the CE concept and consider the relevance of repair. Vanegas et al., (2018) developed a method to determine the ease of disassembly of products denominated ease of Disassembly Metric (EDIM) to support the CE, including the repair, reuse, and recycling of products. The metric was based on the Maynard operation sequence technique (MOST).

Another approach concerning energy-related products was presented by Bracquené et al., (2018), denominated BENELUX Repairability criteria for energy-related products. This approach consisted of an assessment method with criteria organized into three main topics: information, product design, and service. The topics are analyzed across five stages: product identification, failure diagnostic, disassembly & reassembly, spare part replacement, and restoring to working condition.

Alamerew and Brissaud (2019) proposed an evaluation tool for CE strategies (remanufacturing, recycling, repair, and reuse) at a strategic level based on conventional economic, environmental, and social indicators. This approach is oriented to compare the sustainability performance of products for different circularity scenarios. In 2020 the standard EN 45554:2020 (BS EN 45554:2020. General Methods for the Assessment Of the Ability to Repair, Reuse, Upgrade Energy-Related Products, 2020) was launched as a guide to measure the degree of repairability, reuse, and upgrade energy-related products. The standard defines a set of criteria which include disassembly depth, fasteners configuration, availability of tools, working environment, required skill levels, diagnostic support and interface, spare parts availability, information availability, return model, data transfer and deletion, password and factory reset for reuse considering both product and service related systems.

De Fazio et al. (de Fazio et al., 2021) proposed a method to assess the ease of disassembly and repair of household products denominated the Disassembly Map, a novel product architecture mapping method to facilitate design for disassembly. Such a tool is handy when designing for serviceability and repairability based on a representation of all steps required to dismantle a product completely. In the same year, Spiliotopoulos et al., (2021), sponsored by the Joint Research Centre (JRC) and the European Commission, performed a study to analyze and develop a scoring system for repairing and upgrading products. The study proposed different ways and methods to score product repairability and a list of failure rates and resulting priority parts for vacuum cleaners as a case study.

Nowadays, the iFixit tool aligns with the concept of CE and now provides very accurate measurements of the repairability degree considering CE strategies and a more lifecycle approach than its first version. More recently, Pollard et al. (Pollard et al., 2022) remark on the degree of repairability of a product as an environmental, social, and economic indicator. Environmental impact is measured based on resource savings; the social aspect relates to the consumer awareness of circular employment in repair shops and the degree of accessibility to repair services, spare parts, or repair instructions. Moreover, the market share of repair and reuse services compared to sales of new products is an economic indicator. More recently, the French Repairability Index was launched by the French Government (French Government, 2021). The index also includes a label that must be displayed when selling products in France. As a forecast, this repairability measurement is expected to be integrated into a Durability Index that includes Reliability and Upgradability.

2.2. Relevant repairability metrics

At this point, it is possible to identify the most comprehensive approaches to measure repairability. Since there are many works related to product repair, but only cover specific tasks related to the overall process (i.e., disassembly & reassembly). Six metrics were selected from the literature based on their comprehensiveness, robustness, and demonstrated effectiveness after their product implementation. Table 1 summarizes the six metrics, detailing their primary focus, criteria, and scoring system.

From the six repairability metrics shown in Table 1, the following aspects can be remarked as preliminary findings to study the gaps to cover with the indicator developed in this research.

Table 1
Summary of existing metrics related to product repairability measurement.

Metric or Indicator	Focused on	Criteria and Scoring System
French Repairability Index (French Government, 2021)	Electronic products (smartphones, laptops, televisions, washing machines, lawnmowers)	Five criteria: Documentation, Disassembly (accessibility, tool, fasteners), availability of spare parts, Price of spare parts, Criterion specific to the category of equipment concerned 0-20 points range and normalized to 0-10
EN 45554:2020 (European Committee for Standardization 2020)	Energy-related products	11 Rating criteria: Disassembly depth, Fasteners, Tools, Working Environment, Skill level, Diagnostic support and interface, Availability of spare parts, Types and Availability of information, Return models, Data transfer and deletion, password and factory reset for reuse Classes A-F, aggregation: numeric values for each class
JRC Analysis (Spiliotopoulos et al., 2021)	Generic products	Six parameters: Disassembly depth, Fasteners (type), Tools (type), Spare parts (target group), Software updates (duration), Repair information 1-5 score per Criterion and weighted importance
BENELUX Repairability criteria (Bracquené et al., 2018)	Energy-related products	Three main criteria types (Information provision, Product Design, Service) across five repair steps that include product identification, failure diagnostic, disassembly & reassembly, spare part replacement, and restoring to working condition Normalized to 0–100%
iFixit/Flipsen (Flipsen et al., 2017)	Electronic portable products	26 criteria that include: Repair manual available, no special tools needed, spare parts available, no substantial efforts needed, easy access to critical components, cost of repair/ spare parts/tools, standardized spare parts, risk of injuries, no excessive amounts of adhesives, ease of identification of the problem, no comprising other components, time to repair, modularity of parts/ components, identification of components, availability of tools, no special training needed, number of tools,

(*continued on next page*)

Table 1 (*continued*)

Metric or Indicator	Focused on	Criteria and Scoring System
		upgradeability, self-explanatory repair processes, recyclable components, others. Normalized to 0-10
ONR 192102:2014 (ISO, 2014)	White goods, brown goods	40 criteria for white goods and 53 criteria for brown goods. Criteria are focused on repairability to ensure long-lasting, durable products. 17 and 21 criteria for white and brown goods are marked as mandatory, respectively. Three Quality levels Good (5–6 points), very good (7–8), and excellent (9–10)

- Most metrics are developed for a specific product type (electronics or household appliances). Thus, extending a generic calculation for any product is complex. In some cases, metrics require specific analysis of the type of product in order to generate a calculation basis for its repairability.
- All metrics focus on determining a global rating or product score without considering specific subassemblies or components. The possibility of performing a partial reparation, considering the single elements of the product and their interaction, is crucial to achieving a good saving of resources.
- Although few metrics consider functionality in product functioning, in most metrics, subassemblies or components are not classified according to their relevance or importance in mechanical functionality and criticality within the whole product.
- Metrics are commonly oriented to measure but do not provide useful information to generate improvements in other redesign processes. Thus, the designer or manufacturer has not a clear path of improvement regarding the repairability weaknesses of the product.
- Evaluating repairability during the product development process would make preventing failure easier, with the consequent saving of resources. This way, the repairability calculations are done when the product is already on the market. Most of the metrics are product-user-level.

3. Developing the Product Repairability Indicator

The Product Repairability Indicator (PRI) comprises two main parameters related to parts within the product structure: The Relative Functional Importance (RFI), associated with the relevance of a component in terms of the number of physical and functional connections within the whole product assembly. The Overall Repairability (Ro) condenses the ability to be repaired based on physical attributes and external market conditions.

3.1. Relative functional importance

RFI is the relative degree of importance for a component concerning the whole product assembly. It is calculated regarding the number of components in contact and the number of functions associated with that component. Eqs. (1) and (2) show the calculation of RFI.

$$FI = \frac{N_i * F_i}{C_T} \quad \text{Eq. 1}$$

$$RFI = \frac{FI}{\sum_{i=1}^{n} FI} \quad \text{Eq. 2}$$

Where FI is the absolute functional importance of component i, N_i the number of components in contact with component i; F_i the number of functions associated with component i; and C_T is the total number of comprising components of the product. RFI is calculated as the ratio between FI for a component i and the total sum of FI. Therefore, the total sum of RFI must be equal to 1.0.

It is important to clarify that RFI is employed in this manuscript as a measure of repair criticality based on the number of functions and mechanical connections associated with each component. This scoring system was selected because a failure in a product part in contact with more components has a higher possibility of affecting the overall functioning of the product, and this fact strongly affects the repairability capacity in terms of the number of components to substitute or the weight of the product affected by the reparation or failure, among others. Thus, it will be more important to repair a component with a higher RFI since it represents a major interaction of components (in assembly and functional relationships). In this manuscript, the authors did not consider partial failures or working conditions with damaged components, which can be a potential scenario for many products with failures in non-critical components.

3.2. Overall repairability

The calculation of Ro depends on five main parameters (P1 to P5) related to the product structure, disassembly/reassembly complexity, and extended producer responsibility. Each one of the parameters is described in detail as follows:

Intrinsic repairability (P1): Defined as the degree of dismantling a product can offer based on its number of separable and reversible joints and tool accessibility. This parameter measures the degree of repairability included by the designer/manufacturer since the design phase in terms of the number and type of joints in the product and the accessibility to such joints.

Assembly/reassembly complexity (P2): Involves the difficulty of performing disassembly and reassembly tasks. It is based on five subparameters: handling, alignment requirements, tools required, joint interfaces, and the use or not of fixing devices. If a disassembly and reassembly process is simple, intuitive, and easy for the user, it would be easier to enable a repair process. Table 2 shows the detailed levels and

Table 2
Subparameters for Assembly/reassembly complexity.

Sub parameters	Level	Value
P2.1 Handling	One hand Two hands > Two hands	2 1 0.5
P2.2Alignment (joints)	No alignment ½ (90°) ¾ (270°) 4/4 (360°) Two rotations	2 1.75 1.5 1.0 0.5
P2.3 Tool	No tool Conventional Specialized	2.0 1.0 0.5
P2.4 Interface	Easy Normal Difficult	2.0 1.0 0.5
P2.5 Fixing devices	Not required Conventional Specialized	2.0 1.0 0.5

values for each one of the subparameters mentioned above.

Producer repairability instructions (P3): This parameter is associated with the number and degree of repair tasks the user can perform following the product manual or handbook. When a product has instructions and troubleshooting guidelines, the designer/manufacturer enables the repair process.

Spare parts availability (P4): Spare parts are a critical issue during repair tasks, especially when the product requires parts replacement. This parameter largely depends on the manufacturer's interest in providing parts for users when the product suffers a partial failure. However, it also depends on the market dynamics and commercialization strategies (i.e., local brands do not have the same market cover as a multinational brand, so it would be easier to get spare parts from big companies). P4 is calculated as the average value between two subparameters, P4.1, related to the commercial availability of spare parts, and P4.2, related to warranty periods offered by the original manufacturer. Table 3 shows the levels, descriptions, and scores for P4.1 and P4.2.

Self-diagnosis (P5): Is defined as the ability of a product to show when a partial or total failure has occurred. Most recurrent failures can be documented in a troubleshooting guideline or the user's manual. In simple products, lights, sounds, or messages can be implemented. In complex systems, robust self-diagnosis is achieved through sensors and data acquisition. Here the use of industry 4.0 tools facilitates the diagnosis in real-time for rapid decision-making processes.

The five parameters are defined on a numerical scale from 0 to 2, where 2 implies the maximum value for each parameter. Table 4 summarizes the levels, descriptions, and scores for each parameter. Once the C1 to C5 parameters are calculated, their sum is interpreted as Ro defined as the degree of repairability for a component. Eq. (3) describes the calculation for Ro, which vary from 0 to 10, where 10 indicates the maximum possible score.

$$R_o = P1 + P2 + P3 + P4 + P5 \quad \text{Eq. 3}$$

3.3. Product Repairability Indicator

The PRI for a component *i* is obtained from the multiplication of Ro and RFI (See Eq. (4)). On the other hand, the product PRI (PRI_T) is the total sum of PRI values for all comprising components of the product (Eq. (5)). Therefore, it is possible to calculate the PRI for both, component and product depending on the scope of the analysis or case study. Fig. 1 shows the proposed algorithm to calculate the PRI_T. It is essential to clarify that the product needs to be disassembled to guarantee a minimum repairability score. Thus, the PRI is not applicable for products based on integral architecture (not separable components). Fig. 1 has a verification question to provide an inappropriate response when the product cannot be separated into their components.

$$PRI = R_o * RFI \quad \text{Eq. 4}$$

$$PRI_T = \sum_{i=1}^{n} PRI \quad \text{Eq. 5}$$

Table 3
Subparameters for Assembly/reassembly complexity.

Level	*P4.1 Commercial availability of spare parts*	Score
Excellent	Full spare stock available on the manufacturer's website or at local dealers	2.0
Good	Partial spare stock available on the manufacturer's website or at local dealers	1.5
Fair	Partial spare parts available as second-hand parts on websites and local dealers	1.0
Poor	Spare parts not available	0.0
	P4.2 Warranty periods offered by the manufacturer	
Excellent	Warranty above 76% of the useful life of the product	2.0
Good	Warranty between 26% and 75% of the avg useful life of the product	1.5
Fair	Warranty during 25% or less of the avg useful life of the product	1.0
Poor	No warranty	0.0

Table 4
Summary of calculation parameters for the PRI, including levels, description, and score.

Parameter	Levels	Description	Score
P1	Excellent	100% separable joints and full accessibility	2
	Good	75–99% separable joints and accessibility	1.75
	Fair	50–75% separable joints	1.5
	Poor	Less than 49% of separable joints	1.0
	Null	0% Separable joints	0.0
P2	Excellent	Avg value of criteria (1.75–2.0)	According to avg calculation
	Good	Avg value of criteria (1.5–1.74)	
	Fair	Avg value of criteria (1.0–1.49)	
	Poor	Avg value of criteria ≤0.99	
P3	Excellent	Complete guidelines for repairing and diagnosing failures in all components. Includes maintenance tasks (preventive and corrective)	2.0
	Good	Partial guideline for repairing and diagnosing failures in some components. Includes some maintenance tasks	1.5
	Fair	Partial guidelines for repair failures in some components	1.0
	Poor	It does not include repair or maintenance tasks	0.0
P4	Excellent	Avg value of criteria (1.75–2.0)	According to avg calculation
	Good	Avg value of criteria (1.5–1.74)	
	Fair	Avg value of criteria (1.0–1.49)	
	Poor	Avg value of criteria ≤0.99	
P5	Excellent	The product includes failure warnings (sound or visual) and a definition of all failure modes in the owner's manual	2.0
	Good	The product includes some failure warnings (sound or visual) and definition of some typical failure modes in the owner's manual	1.5
	Fair	The product does not include failure warnings. Some failure modes are described in the owner's manual	1.0
	Poor	The product does not include failure warnings or failure modes in the owner's manual	0.0

4. Case study

A 0.6L coffee maker is selected as a case study to validate and demonstrate the application and usefulness of the PRI metric. To implement the case study, it was required to disassemble the coffee maker and make an inventory of components, functionalities, the number of components in contact, type of joints and disassembly tasks, commercial availability of spare parts, and repairability instructions from the original manufacturer. Fig. 2 shows the full assembly of the coffee maker, while Fig. 3 shows the detailed summary of components after the product disassembly. The calculation of *Ro* and *FRI* for the case

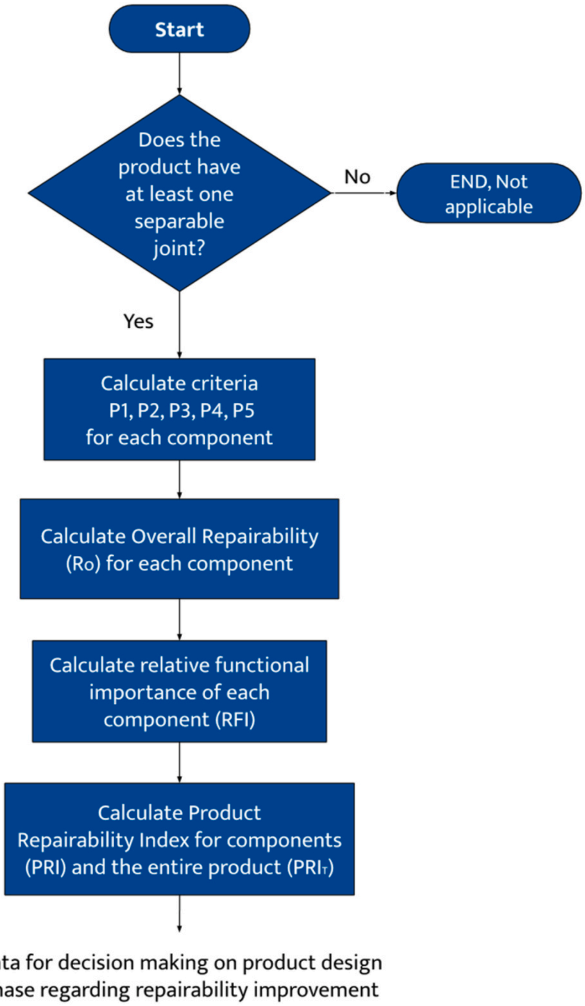

Fig. 1. Algorithm for implementing the PRI for a product.

Fig. 2. Case study: coffee maker 0.6L.

study are described as follows.

4.1. Calculation of RFI

A complete product disassembly is required to generate an inventory of components that must include an identification number, name, functions, number of functions, and number of components in contact. Fig. 3 shows the list of comprising components for the coffee maker, and Table 5 summarizes the inventory of components, including Fi and Ni. Calculation of FI and RFI is provided as well. RFI is calculated following the procedure described in section 4.

4.2. Calculation of ro

Calculation of parameters P1 to P5 were calculated based on levels and descriptions mentioned in Section 4. Table 6 summarizes the calculation of sub-parameters and parameters P1 to P5. The Value of Ro was obtained for each component from the sum of all P1 to P1 parameters.

4.3. Calculation of PRI and PRI_T

Once the Ro and RFI were calculated, the PRI was obtained for each component and the coffee maker. Table 7 shows the calculations for Ro, RFI, and PRI. As a holistic result, the PRI_T for the coffee maker reached a score of 5.21/10 (52.1% of repairability).

5. Findings and discussion

This section includes the most relevant findings once the PRI was applied to the case study. Findings are explained in terms of four main aspects: Relative Functional Importance, Overall Repairability, PRI_T, and limitations of the proposed metric.

Relative functional importance provided helpful information about which components are more critical based on their functional and assembly interactions within the product. In the case of the coffee maker, three components represent 53% of RFI: lower body - C9 (20%), Upper body – C14 (20%), electronic components I – C7 (6%), and ON/OFF Switch – C21 (7%). The rest of the components obtained individual values below 5%. Thus, repairability criticality is focused on fewer components. The highest values of functional importance for the lower body and upper body (40%) are mainly due to the number of assembly relationships (Ni = 11) in the assembly and the number of functions (Fi = 2); therefore, those components represent the highest RFI values in the product. In terms of R_o, the most repairable components in the coffee maker were the Bottom Cover – C1 (8.35), Dosing Tube – C13 (8.30), Bottom Base – C6 (7.00), and LED light – C26 (7.00), Electronic components – C7 (6.30), Upper Cover – C14 (6.25), and Lateral Cover – C15 (6.25). These results were due to the valuation of parameters P1 and P2. All components previously mentioned obtained minimum values of 1.75 for P1 and 1.35 for P2. In the case of P2, ten components did not score, resulting in a lower value of R_o.

A plot of Ro vs. RFI is presented in Fig. 4 as a complementary output of the proposed indicator to identify which components have higher repairability and their associated functional importance. Analyzing Fig. 4, it is possible to classify components with high importance but lower repairability as an improvement opportunity from design (for example, C9 and C12).

Analyzing values of PRI for individual components, the highest valuation was obtained by Lower Body -C9 (0.86), Upper Body – C12 (0.86), Electronic components – C7 (0.50), Bottom Cover – C1 (0.42) and ON/OFF Switch – C21 (0.39). These components represent 58% of the PRI_T for the coffee maker (3.03/5.21). In the case of C9, and C12, the functional importance weighted the high value of PRI. In the case of C1, the R_o had a more significant influence on the PRI value. Components C7 and C21 owe their PRI score to the fact that they had intermediate values of RFI and R_o. These results demonstrate that, in some cases, the most important components (in terms of assembly and functional relevance) are not the most repairable.

The calculation of PRI_T shows a medium score for the coffee maker, obtaining 5.21 out of 10.00. Thus, the product offers an intermediate

Fig. 3. Component Inventory of the coffee-maker.

Table 5
Inventory, functional description, and calculation of RFI for the coffee maker.

Comp.	Name	Functions	Fi	Components in contact	Ni	FI	RFI
C1	Bottom Cover	To support other components	1	C6, C2,C3, C4, C5, C9	6	0.23	0.06
C2	Hot Plate	To transfer heat to the coffee pot	1	C9, C3, C4, C5	4	0.15	0.04
C3	Silicon Ring	To isolate	1	C2, C4	2	0.08	0.02
C4	Ring	To isolate	1	C2, C3	2	0.08	0.02
C5	Hot Plate fasteners	To fasten the hot plate	1	C2	1	0.04	0.01
C6	Bottom base	To support coffee pot	1	C9	1	0.04	0.01
C7	Electronic components I	To control heat/water/coffee flow	3	C2, C9	3	0.23	0.06
C8	Power cord & Plug	To receive/transport electricity	1	C9	1	0.04	0.01
C9	Lower Body	To contain other components/support the upper body	2	C1, C2, C3, C4, C6, C7, C8, C12, C19, C20, C22	11	0.85	0.20
C10	Electronic comp. Support	To fasten electronic circuit	1	C11, C12	2	0.08	0.02
C11	Electronic components II	To control coffee maker functions	1	C10, C12	2	0.08	0.02
C12	Upper Body	To support coffee pot and filter	2	C10, C11, C19, C20, C13, C18, C14, C15, C21, C25, C26	11	0.85	0.20
C13	Dosing Tube	To steer coffee to the cup	1	C12	1	0.04	0.01
C14	Upper Cover	To protect internal components	1	C12	1	0.04	0.01
C15	Lateral Cover	To protect internal components/facilitate coffee pouring	2	C12	1	0.08	0.02
C16	Filter Basket	To support filter and filter frame	1	C18, C17	2	0.08	0.02
C17	Filter	To filter coffee	1	C16, C18	2	0.08	0.02
C18	Filter Frame	To support filter	2	C16, C17, C12	3	0.23	0.06
C19	Water tubes	To transport water	1	C9, C12, C13, C20	4	0.15	0.04
C20	Water tube connectors	To connect water tubes	1	C13, C19	2	0.08	0.02
C21	ON/OFF Switch	To turn on/off the coffee maker	2	C25, C12, C11, C26	4	0.31	0.07
C22	Coffee Pot	To contain coffee	1	C23, C24, C9	3	0.12	0.03
C23	Coffee Pot Handle	To facilitate the handling of the coffee pot	1	C22, C24	2	0.08	0.02
C24	Coffee Lid	To protect the liquid inside the pot	1	C22, C23	2	0.08	0.02
C25	Selection Knob	To select hot water/coffee mode	1	C21, C11, C26	3	0.12	0.03
C26	LED light	To indicate that the coffee maker is on	1	C21, C12, C25	3	0.12	0.03
	TOTAL					4.19	

performance considering functional importance and repairability. Comparing the PRI whit previous metrics such as the iFixit, the French Repairability Index, and the EN 4555:2020, the following benefits and differentiated elements can be remarked.

- The PRI provides helpful information for the whole product and each component individually. Thus, the decision-making related to redesign tasks is more specific and robust for designers and manufacturers. The indicator can be applied in the product development stage, helping to prevent potential reparations in the future. It applies to several typologies of products.
- Clear identification of the most important components in the whole product regarding repairability provides comprehensive input for the redesign. The analysis of RFI and Overall Repairability obtained from the case study is a roadmap for improving weak components in terms of repairability. With the PRI indicator is possible to assess the possible partial reparations since it considers the relevance of the parts and subassemblies in the overall picture of the product.
- Metrics like iFixit and EN 45554:2020 are comprised of more detailed criteria, and data can be summarized in more detail. Thus, vast data is required from the product to ensure a proper assessment, but that data also enable a better understanding of a repairability diagnostic. The PRI requires less information from the product but can be enriched by combining criteria from other metrics. Doing extra analysis to obtain data is unnecessary to implement the PRI. The PRI works only with the product information available at the development stage, which is less complex and comprehensive.

From the information obtained in the case study, it is possible to generate redesign interventions to improve the product architecture and therefore the repairability and product lifecycle management of components (Mesa et al., 2019). However, it is important to clarify that

Table 6
Calculation of PRI based on the five parameters (P1–P5).

Comp	Name	Parameters												Ro
		P1	P21	P22	P23	P24	P25	P2	P3	P41	P42	P4	P5	
C1	Bottom Cover	2.00	1.00	1.75	1.00	2.00	1.00	1.35	2.00	2.00	1.00	1.50	1.50	**8.35**
C2	Hot Plate	2.00	1.00	1.75	1.00	2.00	1.00	1.35	0.00	2.00	1.00	1.50	0.00	**4.85**
C3	Silicon Ring	2.00	1.00	2.00	2.00	2.00	2.00	1.80	0.00	2.00	1.00	1.50	0.00	**5.30**
C4	Ring	2.00	1.00	2.00	2.00	2.00	2.00	1.80	0.00	2.00	1.00	1.50	0.00	**5.30**
C5	Hot Plate fasteners	1.75	1.00	1.75	1.00	2.00	1.00	1.35	0.00	2.00	1.00	1.50	0.00	**4.60**
C6	Bottom base	2.00	2.00	2.00	2.00	2.00	2.00	2.00	0.00	2.00	1.00	1.50	1.50	**7.00**
C7	Electronic components I	1.50	1.00	1.75	1.00	2.00	1.00	1.30	2.00	2.00	1.00	1.50	0.00	**6.30**
C8	Power cord & Plug	0.00	NA	NA	NA	NA	NA	NA	2.00	2.00	1.00	1.50	1.50	**5.00**
C9	Lower Body	0.00	NA	NA	NA	NA	NA	NA	1.50	2.00	1.00	1.50	1.50	**4.50**
C10	Electronic comp. Support	1.75	1.00	0.50	1.00	1.00	1.00	0.90	2.00	2.00	1.00	1.50	0.00	**6.15**
C11	Electronic components II	0.00	NA	NA	NA	NA	NA	NA	0.00	2.00	1.00	1.50	0.00	**1.50**
C12	Upper Body	0.00	NA	NA	NA	NA	NA	NA	1.50	2.00	1.00	1.50	1.50	**4.50**
C13	Dosing Tube	2.00	2.00	2.00	2.00	1.00	2.00	1.80	1.50	2.00	1.00	1.50	1.50	**8.30**
C14	Upper Cover	1.75	1.00	2.00	2.00	0.50	2.00	1.50	0.00	2.00	1.00	1.50	1.50	**6.25**
C15	Lateral Cover	1.75	1.00	2.00	2.00	0.50	2.00	1.50	0.00	2.00	1.00	1.50	1.50	**6.25**
C16	Filter Basket	0.00	NA	NA	NA	NA	NA	NA	0.00	2.00	1.00	1.50	1.50	**3.00**
C17	Filter	0.00	NA	NA	NA	NA	NA	NA	1.50	2.00	1.00	1.50	1.50	**4.50**
C18	Filter Frame	0.00	NA	NA	NA	NA	NA	NA	1.50	2.00	1.00	1.50	1.50	**4.50**
C19	Water tubes	2.00	2.00	2.00	2.00	2.00	2.00	2.00	0.00	2.00	1.00	1.50	0.00	**5.50**
C20	Water tube connectors	2.00	1.00	2.00	2.00	2.00	2.00	1.80	0.00	2.00	1.00	1.50	0.00	**5.30**
C21	ON/OFF Switch	2.00	2.00	2.00	2.00	2.00	2.00	2.00	0.00	2.00	1.00	1.50	0.00	**5.50**
C22	Coffee Pot	0.00	NA	NA	NA	NA	NA	NA	NA	2.00	1.00	1.50	1.50	**3.00**
C23	Coffee Pot Handle	0.00	NA	NA	NA	NA	NA	NA	NA	2.00	1.00	1.50	1.50	**3.00**
C24	Coffee Lid	0.00	NA	NA	NA	NA	NA	NA	NA	2.00	1.00	1.50	1.50	**3.00**
C25	Selection Knob	1.75	1.00	2.00	2.00	1.00	1.00	1.40	0.00	2.00	1.00	1.50	0.00	**4.65**
C26	LED light	2.00	2.00	2.00	2.00	2.00	2.00	2.00	0.00	2.00	1.00	1.50	1.50	**7.00**

NA: Not applicable

Table 7
Calculation of PRI and PRI_T for the coffee maker.

Component	Name	Ro	RFI	PRI
C1	Bottom Cover	8.35	0.06	**0.42**
C2	Hot Plate	4.85	0.04	**0.15**
C3	Silicon Ring	5.30	0.02	**0.11**
C4	Ring	5.30	0.02	**0.11**
C5	Hot Plate fasteners	4.60	0.01	**0.05**
C6	Bottom base	7.00	0.01	**0.07**
C7	Electronic components I	6.30	0.06	**0.50**
C8	Power cord & Plug	5.00	0.01	**0.05**
C9	Lower Body	4.50	0.20	**0.86**
C10	Electronic comp. Support	6.15	0.02	**0.12**
C11	Electronic components II	1.50	0.02	**0.03**
C12	Upper Body	4.50	0.20	**0.86**
C13	Dosing Tube	8.30	0.01	**0.08**
C14	Upper Cover	6.25	0.01	**0.06**
C15	Lateral Cover	6.25	0.02	**0.13**
C16	Filter Basket	3.00	0.02	**0.06**
C17	Filter	4.50	0.02	**0.09**
C18	Filter Frame	4.50	0.06	**0.23**
C19	Water tubes	5.50	0.04	**0.17**
C20	Water tube connectors	5.30	0.02	**0.11**
C21	ON/OFF Switch	5.50	0.07	**0.39**
C22	Coffee Pot	3.00	0.03	**0.09**
C23	Coffee Pot Handle	3.00	0.02	**0.06**
C24	Coffee Lid	3.00	0.02	**0.06**
C25	Selection Knob	4.65	0.03	**0.14**
C26	LED light	7.00	0.03	**0.21**
TOTAL **(PRI_T)**				**5.21**

decisions in the design phase depend on the identified improvement opportunities and technical and financial resources availability. In any case, the development of the product is the more suitable stage for design changes and improvements, both in mechanical/functional and economic terms. For the case study, a list of potential interventions is proposed in Table 8.

Redesign interventions proposed also depends on the company's resources and strategic plan. Thus, improvement of repairability is not recommended without analyzing each product's environmental and economic implications. It is necessary to measure the potential environmental and economic savings from repair as an input of the decision-making process in redesign scenarios. On the one hand, the environmental impact of repair must be correctly measured to ensure that the benefit in terms of emissions and resource consumption is low enough to warrant repair. On the other hand, regarding product costs, it is probable that repair tasks could represent higher costs for the company, and product prices will not compensate for the repair costs. Therefore, a recirculation model with differentiated prices could be required. In addition, repairability has limits as CE strategy; in the case of energy-related products, the efficiency of some components (engines, compressors, pumps) tends to decrease over time. Thus, some major replacements are required to ensure appropriate efficiency of products (e.g. rotative elements such as engines, motors, compressors, pumps, among others). In that case, the repair is recommended for other components with a more constant performance response as long as environmental and economic benefits represent for the company.

It is important to clarify that repairability can be defined only in product attributes, but consumer behavior needs to be addressed to have a robust and positive response. It has been demonstrated that product replacement is not only based on rational decision-making but also emotional, functional, social, epistemic, and conditional values can influence the consumer decision to either retain an owned product or replace it with a new one (van den Berge et al., 2021). Thus, consumers must be self-aware to ensure that repairability potential is fully implemented and that the consumer is taking responsibility for his role to generate a more circular product lifecycle.

6. Challenges and future work

There are some aspects to highlight after the work is carried out, which represent current challenges in the repairing field or could be possible future works. Data is a game changer in product repairability, especially in light of industry 4.0, since the data analysis provides reliability-related information to generate more robust diagnosability and avoid premature failures. And the impact of repairs during the remaining life of products and systems (Lazarova-Molnar and Mohamed,

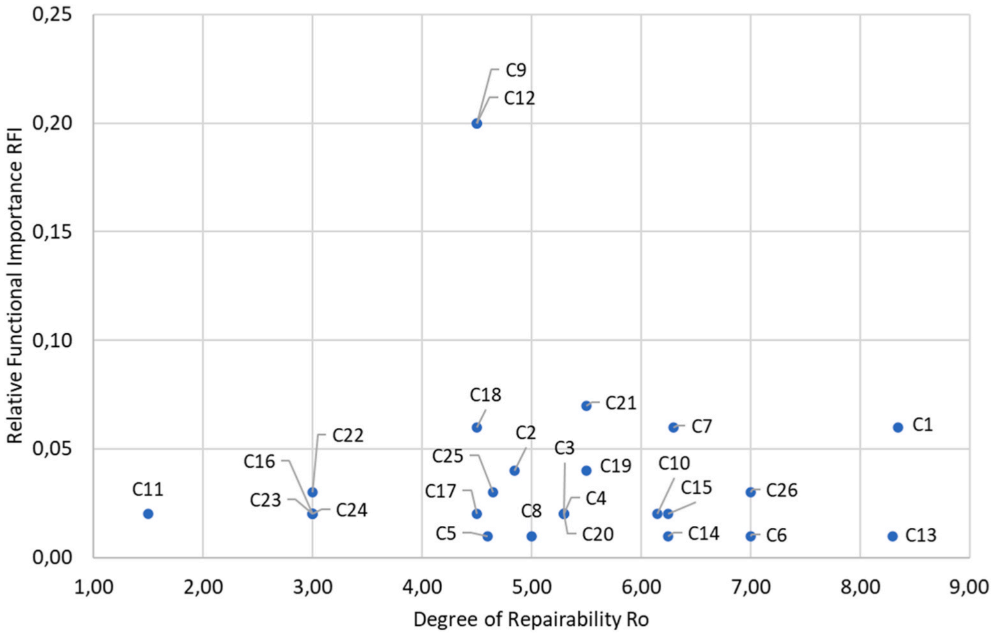

Fig. 4. Graphical summary of the relationship between Degree of Repairability (Ro) and Relative Functional Importance (RFI).

Table 8
Redesign interventions for the coffee maker.

Aspect/ Parameter	Potential intervention
RFI	To modify product architecture to reduce the concentration of assembly/functional relationships in components C9, and C14. Provide a modular architecture to facilitate rapid disassembly and assembly of parts in case of replacement
P1, P2	To ensure 100% separable joints and full accessibility. The current design has disassemblability issues (low score) in components C8, C9, C11, C12, C16, C17, C18
P3	Include a complete guideline to repair no-standardized components. Generate a troubleshooting section in the user manual to facilitate the repair at home
P4	Manufacturing (Business): generate a business channel to offer spare parts. Create a second-hand market/refurbished parts market supported by the manufacturer.
P5	Include more frequent failure modes in the owner's manual. Generate a list of failure warnings through LED indicators (or display) or sound warnings.

2019). Repair data, such as failure mode occurrence, increasing failure modes occurrence over time, and low repair success rates, is now a piece of valued information that can enhance the lifecycle performance of products and components (Wagner et al., 2021).

As a positive issue, devices can be taken apart and easily repaired at home. Critical parts can be replaced at home (Easy to fix) (Boyer et al., 2017). However, to do this, it is necessary to provide the user with all the information needed about product reparation, and, usually, there is imperfect or incomplete information accompanying products regarding how to repair or dispose of the product (Dennis, 2006). The reparation information should be provided to the consumer entirely and understandably. Repair is an opportunity to communicate values to users and raise awareness through increased knowledge about the product, how they are made, how they should be maintained, and the actual impact of their disposal. It is necessary to work on motivation, encouraging product attachment, and self-awareness around consumption paths (Sonego et al., 2022). On the other hand, legislation for manufacturers needs to promote more incentives to design durable products and therefore promote consumer behavior paths (Lawlor and Rob, 2015).

Another issue to consider in future works is measuring a component or part that needs to be repaired affects the functions of the product. There is the possibility of partial product performance if the broken part is not crucial. This possible partial functioning is needed to be considered too. The end of the product's lifetime could depend on the importance of the broken component in the whole system. This way, it would be possible not to discard the product sooner than needed.

In terms of the applicability of the PRI, it can be a time-consuming task since it requires specific information about all components within the product. However, such specificity allows identifying weak points in the design that can be improved to ensure a higher repairability. As future work, it is expected to automate and generate a user interface (web or app) to facilitate the PRI calculation in a more user-friendly interface.

Regarding the usefulness of PRI for future policies and legislation, it is remarkable that products can be characterized in terms of repairability, and weak components or subassemblies can be typified to establish a minimum value of repairability to promote more sustainable practices for designers and manufacturers.

7. Conclusions

The PRI aims to provide a holistic approach to measuring the repairability potential of consumer products based on their intrinsic assembly structure, the degree of repairability included in the design process, and external factors such as the availability of spare parts. The main novelty of the proposed approach is presented as the analysis of the relative importance of components in the whole product assembly and the repairability associated with easiness of disassembly, availability of spare parts, repair information in the owner's manual, and diagnosability. The PRI also provides detailed information for both component and product levels, facilitating the identification of the most critical components and potential redesign interventions to ensure an extended and more circular helpful life of products and components. With the development of the PRI indicator, it is intended to make a step forward in introducing sustainability in product design engineering by enhancing product repairability. In this way, helping designers to improve their products in terms of repairability will be possible.

Additionally, metrics like the PRI proposed in this work provide specific information about which components or subassemblies are involved in low repairability scores and represent more improvement opportunities. From a policy and legislative perspective, the PRI can contribute to identifying different types of products (laptops, fridges, washers, smartphones, among others), which are the typical components involved with low repairability within the overall repairability score. Thus, it is possible to establish a minimum repairability score for different products based on the information obtained from the PRI, specifically in typical low repairability components. The development of the PRI indicator is a step forward in terms of resource-saving in the product development sector, assessing repairability comprehensively and more accessible from the product design stage.

Author contributions

Conceptualization: JAM; Data curation LRP & JAM; Formal analysis: LRP; Investigation; Methodology JAM; Project administration JAM; Resources JAM; Software LRP; Supervision JAM; Validation LRP & JAM; Visualization JAM; Writing - original draft LRP & JAM; Writing - review & editing: JAM & LRP. Both authors contributed equally to the preparation and writing of this article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jaime A. Mesa reports administrative support and writing assistance were provided by Universidad del Norte, Barranquilla, COL.

Data availability

No data was used for the research described in the article.

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