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Repair index of energy-related products: Application to capsule coffee machines

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ABSTRACT

In recent years, the European regulatory framework related to sustainable products has evolved to promote the circular economy, with a special emphasis on repair strategies to reduce raw material consumption and e-waste generation. In this context, the present study aims to assess the repairability level of small electrical and electronic appliances, specifically focusing on capsule coffee machines, taking the EN 45554 standard (General methods for the assessment of the ability to repair, reuse, and upgrade energy-related products) as a reference. To achieve this objective, an interpretation of the standard is made with the aim of developing a repair matrix to facilitate the calculation of the repair index. The repair matrix is customised to the case study of capsule coffee machines. Following its application with four existing capsule coffee machines and having obtained their corresponding repair indexes, design requirements to improve the repairability of this product category are identified and applied in the design of a new capsule coffee machine with a higher (better) repair index. After this process, various improvement options for the repair matrix that enhance the accuracy of the EN 45554 requirements are discussed and applied, and finally compared with the Repairability assessment methodology (AsMeR).

1. Introduction

In recent years, the European regulatory framework related to sustainable products has evolved towards the promotion of more circular designs (European Commission, 2015, 2020a; European Parliament, 2009). Special emphasis has been placed on the incorporation of repair requirements as a strategy to extend the lifespan of products, with a major interest in Energy-related Products (ErP) (European Commission, 2022a).

The European Parliament and the Council (2009) impose eco-design requirements to enhance the energy efficiency of products. Nevertheless, since the approval of the Action Plans for the Circular Economy (European Commission, 2020a, 2015), requirements in terms of the durability, reusability, upgradability, and repairability of products should be established, promoting repairable products as a strategy to reduce resource consumption and waste generation. The European Commission approved the “right to repair” (European Commission, 2023; European Parliament, 2022, 2020), which encourages the reuse and repair of products, supporting systematic and cost-effective repair schemes, providing guarantees for spare parts, or improving access to information on repair and maintenance. Furthermore, the package adopted by the European Commission (2022b) will require traders to provide information on a product's repairability score. Furthermore, a consumer research study testing different label formats to illustrate repair information (European Commission, 2020b) concluded that reporting repairability information is an effective means of guiding consumers to choose more reparable products (Spiliotopoulos et al., 2022a, 2022b).

During the last few years, in line with the aforementioned European regulatory framework, several initiatives have been launched with the aim of assessing the level of repairability of products: standards such as ONR 192102 (2014) and EN EN 45554 (2020); methods developed by research units such as iFixit (Flipsen et al., 2016, 2019; Suovanen, 2023), AsMeR (Bracquené et al., 2018), Repair Score System (RSS) (Cordella et al., 2019); or national regulations such as the French Indice de Réparabilité (FRI) (Ministère de la Transition écologique, 2021).

Regarding the applicability of these methods, iFixit has a specific version for smartphones (Flipsen et al., 2016); FRI for vacuum cleaners, washing machines, dishwashers, TVs, laptops, smartphones, and lawnmowers (Ministère de la Transition écologique, 2021); RSS for

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smartphones and slate tablets (Spiliotopoulos et al., 2022a, 2022b); while EN 45554 (2020) is a general method that needs to be adapted in order to be implemented. The remaining initiatives are general methods for any specific product category. And with regard to national regulations, other European Member States have announced plans to develop national score systems following the example of France — notably, Spain and Belgium (BEUC, 2022). The Spanish Ministry of Consumer Affairs conducted a public consultation on the future regulation of the repair index for electrical and electronic devices in 2021 (MC, 2021), although no progress has been published to date. In Belgium, in June 2023, a regulation proposed by the Federal Minister of Environment introduced a repair index mirroring the French system for similar product categories (Zakia Khattabi, 2023), with the aim of aligning Belgium's index precisely with that used in France.

Bearing this context in mind, the aim of this study is to develop a new method able to measure the repairability level of capsule coffee machines and identify the design aspects that make it possible to increase the level of repairability for this product category. To this end, the standard EN 45554 (2020) is considered as a reference, since it is a general method agreed at European level and adaptable to any product category. To fulfil this objective, this study aims to answer the following research questions (RQ): (RQ1) How adaptable to different product categories is the general method proposed by the EN 45554 (2020) standard?; (RQ2) Is EN 45554 (2020) useful for identifying specific design aspects that contribute to improving the repair index?; (RQ3) Is it possible to increase the accuracy of the method proposed by EN 45554 (2020) by incorporating more quantitative information? To answer these questions, this paper is structured as follows: Section 2 contains a comprehensive review of the literature on repairability assessments; Section 3 presents the method followed to obtain a general repair matrix as an interpretation of EN 45554 (2020); Section 4 presents the adaptation of this general matrix to the case study of capsule coffee machines and its application to four existing capsule coffee machines as well as to a new design of capsule coffee machine that includes the improvements of the design aspects identified as a key for improving the repair index; and finally, a discussion of the results is presented in Section 5 and the conclusions and suggestions for the direction of future research in Section 6.

2. Literature review

Repair, as stated by Cooper (2020), emerges as a pivotal strategy for sustainable consumption. It holds a significant position within the framework of a circular economy, which endeavours to harmonise human activities with the constraints of our planet (Velenturf and Purnell, 2021).

As already seen in the introduction, to enhance and expand repair activities, policymakers globally are proposing and implementing various initiatives. Moreover, the literature addresses repairability from different perspectives. Some studies focus on the technical aspects, examining the design and materials that facilitate or hinder repair (Cordella et al., 2021). Others delve into the socio-economic implications, exploring how repair activities can contribute to job creation and waste reduction (European Commission, 2016; Godfrey et al., 2022). From business approach, Dao et al. (2021) highlight the importance of businesses in improving product repairability, concluding that collaboration between stakeholders and customers are key for successful business innovation through product repairability. There is also a growing body of research on the psychological benefits of repair, such as the sense of accomplishment and empowerment it can provide to individuals (Eubanks et al., 2022; Sorrel, 2020). In this line, Munten and Vanhamme (2023) recently analysed the effectiveness of repairability communications in influencing consumer perceptions, concluding that companies should communicate about product repairability to signal product quality.

Recognizing its significance and aligned with the European regulatory framework, various studies have focused on analysing the environmental impact of different end-of-life scenarios in order to determine when repairability is the best option according to the product category. Bovea et al. (2020) analyses different end-of-life scenarios for small household electric and electronic equipment pointing the repair and reuse option generally proves environmentally better than replacement. Pamminger et al. (2021) analyses the environmental impacts of different circular end-of-use scenarios for smartphones, concluding that repairing and refurbishing show the highest potential for smartphones in terms of circularity. In this line, in the past decade, several studies have been focused on determining the appropriateness of EEE replacement, such as TVs, air conditioners and refrigerators (Tomohiro et al., 2013), washing machines (Ardente and Mathieux, 2014), vacuum cleaners (Pérez-Belis et al., 2017), Boldoczki et al. (2020) and Kouloumpis et al. (2023) for ICT devices, Jerome et al. (2023) for motors or Rizan et al. (2022) for surgical scissors.

With this approach, there has been an increase in the development of standards and methods to analyse the repairability of products and several studies have focused on their applicability to different product categories. In order to obtain an overview of this research, a literature review was conducted using the Scopus and GoogleScholar databases as search engines and employing the strings "reparability", "circular economy", "repair", "method", "iFixit", "AsMeR", "EN 45554", "RSS", "FRI", "eDIM", and "coffee machine" within the title, keywords, or abstract of the article, and covering the period from 2015 (the year when the first European Circular Economy Action Plan (European Commission, 2015) was approved, which advanced repairability as a strategy for extending the lifetime of products) to the present. Of the articles found, the abstract of each one was inspected to identify those aimed at analysing, comparing, or applying any repair method/strategy. The results are reported in Table 1, which provides details for each article concerning the aim of the study, the repairability method applied, and the product category studied.

With regard to the aim of the studies, Table 1 shows that 36 % focused on the comparison of methods, 65 % on the calculation of the repair index, 23 % on the development of guidelines to improve product families, 12 % on the development of proposals of redesign to improve the repairability of products and 8 % on the proposal of guidelines to improve the repairability methods.

Concerning the repairability index used in each study, Table 1 reports that 35 % of them applied iFixit; 31 % respectively applied AsMer, RSS, and FRI; 15 % EN 45554; and 8 % ONR 192102. Regarding the method to calculate the disassembly time, only 48 % of the studies calculated this aspect, with eDIM being the method most commonly employed. The most commonly evaluated product category was smartphones (19 %), followed by vacuum cleaners (12 %), among others. Chronologically, the different versions of iFixit were applied to mobile phones (Flipsen et al., 2016, 2019), to torches (Flipsen et al., 2016), and to vacuum cleaners (Bracquené et al., 2019). ONR 192102 was applied to vacuum cleaners (Bracquené et al., 2018), while AsMeR was applied to vacuum cleaners (Bracquené et al., 2018), washing machines (Bracquené et al., 2021), and drip coffee machines (Blanco-Espeleta et al., 2021). RSS was applied to washing machines (Bracquené et al., 2021), to gas cooktops (Boix Rodríguez and Favi, 2022), and to mobile phones and slate tablets (Spiliotopoulos et al., 2022a, 2022b). FRI was also applied to mobile phones (Barros and Dimla, 2023). For mobile phones, their repairability has even been evaluated through the use of artificial intelligence (Liao et al., 2023), using the iFixit score as a reference.

Following the review of the literature, significant differences between ASMER, iFixit, RSS, and FRI were observed in the parameters of Information, Design, and Service. In the Information parameter, RSS led with 30 %, followed by ASMER (29 %), FRI (20 %), and iFixit (10 %). In terms of Design, iFixit showed a clear preference with 80 %, followed by RSS (55 %), FRI (40 %), and ASMER (38 %). In the Service parameter, FRI and ASMER shared the lead with 34 %, followed by RSS (15 %) and

Table 1
Literature review.

	Goal					Method: Repair index						Method: Disassembly time		Case study											
Reference	Comparison of methods	Calculation of repair index	Guidelines to improve the product family	Redesign proposal to improve repairability	Guidelines to improve the methods	ONR 192102	EN 45554	iFixit	AsMeR	RSS	FRI	eDiM	The Disassembly Map	Smartphones	Torches	Vacuum cleaners	Washing machines	Drip coffee machine	Capsule coffee machines	Tertiary coffee makers	Gas cooktops	Electric ovens	TV	Kettle	Mechanical products
(Barros and Dimla, 2023)	●	●			●			●			●			●											
(Boix Rodríguez et al., 2023)		●			●					○		●										●			
(Pozo Arcos, 2023a)	●							○		○															
(Pozo Arcos, 2023b)	●							○			○														
(Suovanen, 2023)								○																	
(Wandji Wouapi et al., 2023)	●							○	○	○	○														●
(Liao et al., 2023)		●												●											
(Erdmann et al., 2023)		●			●							●													●
(Sandez et al., 2023)		●										●	●											●	
(Schischke et al., 2022)	●						○				●			●											
(Matarin et al., 2022)			●				●													●					
(Boix Rodríguez and Favi, 2022)		●	●	●						●											●				
(Dangal et al., 2022)	●				●	●	○		○	○	○	○													
(BEUC, 2022)					●						○														
(Dominik and Merz, 2022)		●	●								●					●									
(Bracquené et al., 2021)	●	●							●	●		●					●								
(Blanco-Espeleta et al., 2021)	●	●					○		●	○	○	●						●							
(De Fazio et al., 2021)		●											●			●									
(Flipsen et al., 2019)		●						●						●											
(Bracquene et al., 2019)	●	●			●	●		●	●							●									
(Vanegas et al., 2018)		●										●											●		
(Flipsen et al., 2016)		●						●						●	●										

Method takes into account (●), method is not applied for any calculation (○) (De Fazio et al., 2021; Dominik and Merz, 2022; Erdmann et al., 2023; Matarin et al., 2022; Pozo Arcos, 2023a, 2023b; Sandez et al., 2023; Schischke et al., 2022; Vanegas et al., 2018; Wandji Wouapi et al., 2023).

iFixit (10 %). These results suggest that each method has its own focus and priorities in evaluating repairability, which can influence the interpretation and application of their results. Careful consideration of these factors is required when selecting and utilising these methods for repairability evaluation.

Emphasising the importance of comparing repairability methods, Bracquené et al. (2019, 2021) compared AsMeR, iFixit, and ONR 192102 for vacuum cleaners, and RSS and AsMeR for washing machines, respectively; Barros and Dimla (2023) compared iFixit and FRI for smartphones. Dangal et al. (2022) compared the methods EN 45554, FRI, iFixit, RSS, AsMeR, and ONR 192102 according to their objectivity (whether the scoring levels in each criterion were clearly defined with a quantifiable and operator-independent testing method) and their completeness (whether each criterion included features and design principles that drove its repairability), and concluded that, in general, all of them are acceptably objective and complete; although FRI and iFixit were found to be the most objective and RSS the most complete.

Despite the general acceptance of these repairability methods, some studies identify their limitations. According to Boix Rodríguez et al. (2023), the evaluation of certain criteria, as well as components, is subject to subjectivity or interpretation, and the majority of the methods do not provide help with identifying measures that promote product repairability during the design process (Boix Rodríguez and Favi, 2022). In this respect, the findings of Barros and Dimla (2023) suggest that the highest repair scores, which indicate easier repairability, are not always achieved in products that include product architectures that follow design guidelines for disassembly. Finally, the literature review also suggests that it is necessary to converge towards a single method that becomes mandatory and allows the incorporation of the specificities of different product categories to obtain more accurate scores (BEUC, 2022).

3. Method

This section describes the methodological approach adopted to conduct this research regarding the interpretation of EN 45554 (2020) in a matrix format. This standard provides a non-product-specific method and parameters to assess the ability to repair products. It is not intended to be applied directly; therefore, its application requires its interpretation and adaptation to the product category under study. In this section, the content of the standard is interpreted and structured in the form of a matrix, the Repair Matrix (RM), which facilitates the calculation of the Repair Index (RI) for any product category.

EN 45554 (2020) provides a general method for measuring the ability to repair, reuse, and upgrade ErP that encompasses criteria related to the product itself and the support provided when the product is placed on the market. It was developed with the aim of achieving long product lifetimes. Therefore, this section proposes a universal RM to obtain an RI, by introducing a comprehensive method as a preliminary step preceding its tailoring to a specific product category, which is put forward to enhance its comprehensibility and adaptability to different product categories. In this endeavour, the subsequent elements of the standard have been systematically parameterised and organised within a matrix framework, as visually represented in Fig. 1. The practical

Group	#	p_j	Wp_j	Sc		i_1 Wpp_1	…	i_n Wpp_n	S_j
Product design	#1	Disassembly sequence depth	Wp_1	Disassembly depth for the part i (Di) Disassembly reference depth for the part i ((Dref)		$S_{1,1}$	…	$S_{1,n}$	S_1
	#2	Fasterner type	Wp_2	Reusable	A	$S_{2,1}$	…	$S_{2,n}$	S_2
				Removable	B				
				Not removable and and not reusable	C				
	#3	Tools needed	Wp_3	Toolless	A	$S_{3,1}$	…	$S_{3,n}$	S_3
				Common general purpose	B				
				Professional product group specific tools	C				
				Propietary tools	D				
				Not viable with any existing tool	E				
	#4	Working environment	Wp_4	Home / no requirements	A	$S_{4,1}$	…	$S_{4,n}$	S_4
				Specialised workshop	B				
				Production environment	C				
	#5	Skill level	Wp_5	Apprentice	A	$S_{5,1}$	…	$S_{5,n}$	S_5
				Generalist	B				
				Professional	C				
				Manufacturer	D				
				Not viable with any skill	E				
Manufacturer support	#6	Diagnostic support and interfaces	Wp_6	Visually intuitive interface	A	$S_{6,1}$	…	$S_{6,n}$	S_6
				Coded interface with public reference table	B				
				Publicly available hardware / software interface	C				
				Proprietary interface	D				
				Not viable with any type of interface	E				
Spare Parts	#7	Spare parts availability	Wp_7	Publicly available	A	$S_{7,1}$	…	$S_{7,n}$	S_7
				Available to independent suppliers	B				
				Available to suppliers	C				
				Available for manufacturer	D				
				Spare part not available	E				
	#8	Spare parts interface	Wp_8	Standard part with standard interface	A	$S_{8,1}$	…	$S_{8,n}$	S_8
				Exclusive part with standard interface	B				
				Exclusive part with non-standard interface	C				
	#9	Spare parts availability duration	Wp_9	Long-term availability	A	$S_{9,1}$	…	$S_{9,n}$	S_9
				Mid-term availability	B				
				Short-term availability	C				
				No information on duration of availability	D				
Information	#10	Information type	Wp_{10}	Comprehensive information available	A		S_{10}		S_{10}
				Basic information available	B				
				No information available	C				
	#11	Information availability	Wp_{11}	Publicly available	A		S_{11}		S_{11}
				Available to independent suppliers	B				
				available to suppliers	C				
				Available for manufacturer	D				
	#12	Return options	Wp_{12}	Exhaustive return options	A		S_{12}		S_{12}
				Basic return options	B				
				No return option	C				
	#13	Data management	Wp_{13}	Integrated data not stored	A		S_{13}		S_{13}
				Under request	B				
				Not available	C				
	#14	Restart type	Wp_{14}	Integrated restart	A		$S_{14,}$		S_{14}
				External restart	B				
				Service restart	C				
				No restart	D				
					S_i	S_1	…	S_n	RI
					RI_i	RI_1	…	RI_n	

Fig. 1. Repair Matrix (RM).

implementation of the standard requires the following elements to be determined meticulously:

- Parameters (p_j) are the aspects considered when assessing the compliance of ErP in relation to repair. There are 14 parameters ($j = 1, \dots, 14$) which must be evaluated. To ensure the analysis is comprehensive, these parameters are categorised into nine distinct groups: product design, parameters related to product design and ease of disassembly; working environment, a parameter related to the working environment used in the repair process; skill level, a parameter that refers to the knowledge required for a successful repair; manufacturer support, a parameter related to the diagnostic support provided by the manufacturer; spare parts, parameters related to the availability of spare parts and their design; information, parameters related to the information supplied to the user and its availability; return options, a parameter related to the return models for the product; data management, a parameter related to the management of information stored by the product; and restart type, a parameter related to the factory reset of the product.
- The weighting factor of each parameter (Wp_j) represents the relative importance or degree of influence of a parameter in relation to the other parameters under consideration.
- Priority parts (pp_i) are defined as target components that are functionally relevant and associated with typical failures for a specific product category (Spiliotopoulos et al., 2022a, 2022b). These parts are identified and given priority in terms of maintenance and updates, as their failure can have a significant impact on the overall operation of the system. A product has i ($i = 1, \dots, n$) priority parts.
- The weighting factor of each priority part (Wpp_i) represents the relative importance or degree of influence of each priority part in relation to the other parts under consideration.
- Scale (Sc) represents the rate of each parameter with different levels (between three and five). The levels of each parameter are named using a letter scale (A, B, C, and/or D and/or E).
- Score (S) represents the score that a given product/priority part of the product obtains for each parameter. The following scores can be distinguished:
  - o Partial score of a parameter ($S_{j,i}$) is the score assigned to a specific parameter (j) within a priority part (i). It represents the level of compliance of the priority part for that parameter. For parameter #1 the Eq. (1) must be applied, the parameters #2 to #9 follow the Eq. (2). Moreover, parameters #10 to #14 are analysed for the whole product, and their scores follow the Eq. (3).

$$S_{1,i} = 1 - \left(\frac{D_i - 1}{Dref_i - 1}\right) \text{ with } S_{1,i} = 0 \text{ for } D_i > Dref_i \tag{1}$$

$$S_{j,i} = Sc \cdot Wp_j \cdot Wpp_i \text{ for } 9 \geq j > 1 \tag{2}$$

$$S_{j,i} = Sc \cdot Wp_j \text{ for } j \geq 10 \tag{3}$$

- o Score of the parameter (S_j) is the final score of the product for a specific parameter (j), which is obtained by adding all the partial scores of the parameters (Sj,i) for all the priority parts (i), following Eq. (4).

$$S_j = \sum\nolimits_{i=1}^{n} S_{j,i} \text{ with } S_j = S_{j,i} \text{ for } j \geq 10 \tag{4}$$

- o Score of the priority part (S_i) is the final score of the product for a specific priority part (i), which is obtained by adding all the partial scores of the parameters (Sj,i) for the priority part (i), following Eq. (5).

$$S_i = \sum\nolimits_{j=1}^{n} S_{j,i} \tag{5}$$

- Repair index (RI) represents the level of repairability of the product and is obtained from the sum of the scores of all the parameters (S_j) or the sum of the score of all priority parts (S_j), according to Eq. (6). Furthermore, the Priority Part Repair Index (RI_i) is obtained as the weighted sum of the partial score of a parameter ($S_{j,i}$) with their weighting factor (Wp_j) according to Eq. (7).

$$RI = \sum\nolimits_{j=1}^{n} S_j \textbf{ or } RI = \sum\nolimits_{i=1}^{n} S_i \tag{6}$$

$$RI_i = \sum\nolimits_{j=1}^{9} \left(S_{j,i} \cdot Wp_j\right) + \sum\nolimits_{j=10}^{14} S_{j,i} \tag{7}$$

According to the description of the elements of the RM, parameters (p_j) and their weighting factors (Wp_j), priority parts (pp_i) and their weighting factors (Wpp_i), and the scale (Sc) must be defined for each specific product category; while scores ($I_{j,i}$, S_i and S_j) should be defined for any product in that product category. Also, the repair indexes (RI and RI_i) should be calculated at product level.

In order to apply the RM reported in Fig. 1 to any product category, the parameters (p_j) and their weighting factors (Wp_j), priority parts (pp_i) and their weighting factors (Wpp_i), and the scale (Sc) need to be adapted to the product category under study. To do so, it is necessary to carry out a preliminary stage involving an information search. This is a key stage when implementing the method, as it requires obtaining current and accurate information regarding the product failures, priority components, availability of spare parts and other relevant factors. This procedure in line with other methods, which are customised for the product category under study. This is the case, for example, of the FRI, which has versions for vacuum cleaners, washing machines, computers, smartphones, televisions, pressure washers, and lawnmowers (Ministère de la Transition écologique, 2021); or the RSS, which has versions for smartphones and slate tablets (Spiliotopoulos et al., 2022a, 2022b).

4. Results

This section shows the adaptation and the application of the RM proposed in Section 3 and Fig. 2, to the case study of the product category "capsule coffee machines", following the steps described in Fig. 2. First, the RM matrix was adapted to the product category by defining the parameters and the priority parts, their corresponding weighting factors, and the scales. Then, the adapted RM was applied to different existing capsule coffee machines, which enabled the identification of aspects that would enhance the RI of this product category. By applying these aspects, a new design of capsule coffee machines was proposed and evaluated, achieving a higher RI than one of the previously analysed capsule coffee machines.

4.1. Adaptation of RM to capsule coffee machines

This section adapts the RM shown in Fig. 1 for the calculation of the RI to the case study of capsule coffee machines. This product category was selected due to its widespread presence in Spanish households. In Spain, according to the MAPA (2022), coffee in capsules represents 22.0 % of the total coffee purchased by households. In addition, there has been an increase in the presence of coffee in households, with a rise of 11.5 % in per capita consumption compared to 2019.

To apply the RM to the product category capsule coffee machines and calculate the RI, it is essential to quantify the elements p_j, Wp_i, pp_i, Wpp_i and Sc. Table 2 shows alternative sources of information that can be applied, the one applied in this case study being marked (●) in the last column.

4.1.1. Parameters and their weighting factors (p_j and Wp_j)

The first step in the process of adapting the RM to capsule coffee machines was the definition of the weighting factors of the fourteen

Table 2
Source of information to adapt RM.

Elements of the RM to be defined		Alternative source of information	Source selected for the product category capsule coffee machine
Parameters and the weighting factor of each parameter	p_j Wp_j	Repair centres	●
		Reuse organisations	
		Consumer organisations	
Priority parts and the weighting factor of each priority part	pp_i Wpp_i	Regulation	
		Manufacturers of the product	
		Repair centres	●
		Reuse organisations	
		Consumer organisations	
		Repair database	●
Scale	Sc	Literature	●
		Consumer organisations	

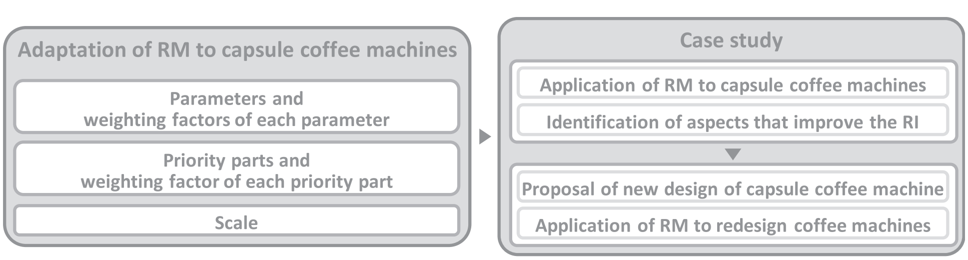

Fig. 2. Results.

parameters. To gather this data, telephone interviews with Spanish repair centres were conducted, as reported in Table 2. A total of 24 telephone calls were made and ten successful completed responses were obtained (response rate of 41 %). Only repair technicians with experience in repairing capsule coffee machines were interviewed. During each phone call, each of the 14 parameters reported in Fig. 1 was explained to the repair technician, then he/she was asked to rank them based on their own experience. The results reported in Table 3 show the average level of importance assigned to each parameter evaluated (Wp_j) and its corresponding standard deviation. It can be observed that the parameter with the highest average weighting is "Skill level" (16.3 %), followed by "Information type" (14.9 %), and "Information availability" (14.9 %). In contrast, parameters such as "Spare parts interface", "Return options", "Data management", and "Restart type" obtained an importance level of zero, since they are not taken into account during the repair process of capsule coffee machines.

4.1.2. Priority parts and their weighting factor (pp_i and Wpp_i)

The second step in the process of adapting the RM to capsule coffee machines was the definition of the list of priority parts and their weighting factors. To accomplish this step, the information was extracted from repair centres and repair databases, as indicated in Table 2:

- Open Repair Alliance (2022) offer data for five repair databases: Anstifung, with 306 coffee machines; Fixit Clinic, with nine coffee machines; Repair Café International, with 2678 coffee machines; Repair Café Wales, with 38 coffee machines; and The Restart Project, with 494 coffee machines. These databases enable the identification, for each appliance brought for repair, of aspects such as the failure cause, the part causing the failure, or the final state of the repair. Out of the 3525 coffee machines analysed in the Open Repair Alliance databases (2022), it was discovered that 72 % of them were effectively repaired. Concerning individual components, a greater percentage of successful repairs was observed for all components, apart from the boiler, circuit board, and capsule reader. In terms of user diagnosis, water leaks were the most common indication, followed by problems related to insufficient heating, lack of maintenance, and excessive scaling.
- The iFixit website (iFixit, 2013) offers repair information in the form of guides, troubleshooting solutions, and support questions. Of the total 289 coffee machines included in this website, 57 of them correspond to capsule coffee machines. Information for each one was classified, and the most common repaired components were identified.
- Interviews with repair centres, as described in Section 4.1, were also conducted to identify the components that are more prone to require repair. The interviewees were asked to rank the components based on the number of repairs they perform.

Table 3
Average weighting factor of the parameters.

Parameter (j)		Weighting factor (Wp_j)	
		Average	Standard deviation (SD)
#1	Disassembly sequence depth	11.2 %	3.5
#2	Fastener type	5.5 %	2.5
#3	Tools needed	4.0 %	1.5
#4	Working environment	2.9 %	1.6
#5	Skill level	16.3 %	1.3
#6	Diagnostic support and interfaces	9.4 %	3.2
#7	Spare parts availability	10.5 %	3.1
#8	Spare parts interface	0.0 %	0.0
#9	Spare parts availability duration	10.5 %	3.1
#10	Information type	14.9 %	2.9
#11	Information availability	14.9 %	2.9
#12	Return options	0.0 %	0.0
#13	Data management	0.0 %	0.0
#14	Restart type	0.0 %	0.0
		100 %	

The results obtained from each source were grouped and are graphically represented on the left of Fig. 3. The percentages show the absolute value of the component failure rate, presenting the values obtained from the three sources of information. The list of priority parts (pp_i) is on the right. To select them and their weighting factors (Wpp_i), a cut-off rule needs to be defined (Bracquené et al., 2021). In this case study, the cut-off is the minimum percentage of likely failures, 70 % of total failures, shown on the right of Fig. 3.

It is observed in Fig. 3 that the water pump, hoses, and coffee conditioning are the parts that undergo the most repairs. All three data sources agree that the first symptom of failure is water leakage, which is usually caused by a lack of maintenance. In the case of the water pump and hoses, periodic descaling is essential; while for the coffee conditioning, the cleaning of the capsule housing is necessary.

4.1.3. Scale (Sc)

The third step in the process of adapting the RM to capsule coffee machines was to assign a value to the levels of the scale for each parameter (A, B, C, and/or D and/or E, according to Fig. 1). The literature review was selected as the information source, as shown in Table 2. The application of the RSS system (Cordella et al., 2019) to smartphones and slate tablets (Spiliotopoulos et al., 2022a) use a scale ranging from 1 to 5, while FRI (Ministère de la Transition écologique, 2021) use a scale from 0 to 10. A range from 0 to 10 was selected in order to facilitate the assignment of a rating to the different levels of each scale (A, B, C, and/or D and/or E), regardless of the number of levels, and then the RI calculation. Therefore, parameters having a scale with three levels were assigned a score of 0, 5, 10 for each level; with four levels: 0, 3.3, 6.6, 10; and with five levels: 0, 2.5, 5, 7.5, 10.

The information obtained in Section 4.1.1 (p_j and Wp_j-average), Section 4.1.2 (pp_i and Wpp_i) and Section 4.1.3 (Sc) for the case study of capsule coffee machines was included in the general proposed matrix reported in Fig. 1 (see Fig. 4).

The RM in Fig. 4 has been filled out with ten columns, each corresponding to each of the priority parts identified for the selected product category (capsule coffee machines), along with their respective weighting factors. Additionally, each parameter has been linked to its weighting factor and its scale.

4.2. Case study

This section contains a comprehensive practical application of the method to four representative capsule coffee machines, including the results and their implications. This practical examination demonstrates the utility and effectiveness of the proposed evaluation method and provides findings on the repairability of these specific appliances.

4.2.1. Application of RM to capsule coffee machines to market appliances

In this section, the RM outlined in Fig. 4 was applied to four representative capsule coffee machines models currently available on the market (Fig. 5) to calculate their RI and obtain the necessary information for the next stages of the methodology. These models differ from each other in terms of the coffee loading system (aluminium - C1, plastic - C2, pads - C3, and a combination of plastic and aluminium - C4) and their market price, which ranges from €30 to €115. These four capsule coffee machines were manually disassembled by an experienced researcher, and the process was carried out in a laboratory adapted for the task, using professional tools, and with the appropriate materials to document the entire process.

The RM (Fig. 4) was applied to C1, C2, C3, and C4 coffee machines and the results are available in the Supplementary Material file (Tables S1, S2, S3, and S4, respectively). Table 4 shows the RI and RI_i for each appliance.

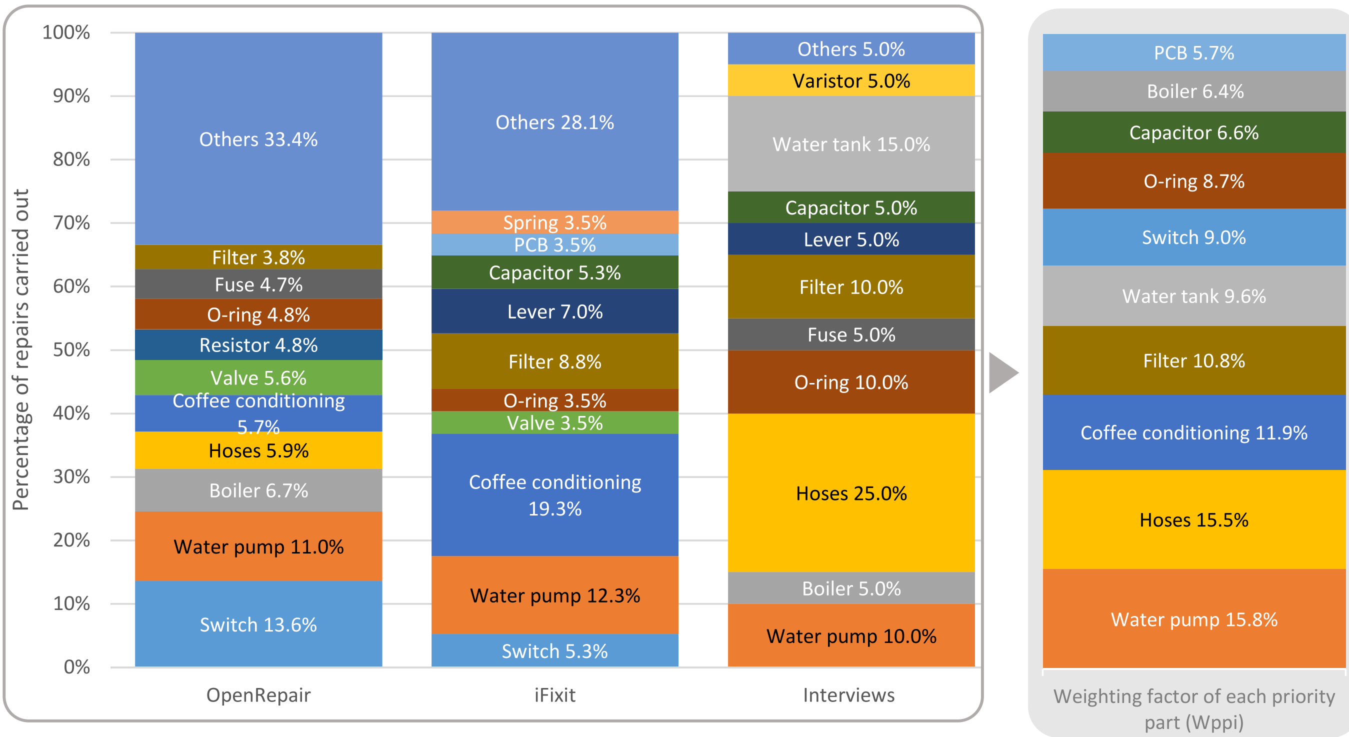

Fig. 3. Percentage of repairs carried out recorded by OpenRepair database, iFixit, and repair centre interviews. Weighting factor of each priority part (Wpp_i).

With regard to the RI of each capsule coffee machine, it is observed that C3 is the best rated, although there are no significant differences between them.

Concerning the parameters/group of parameters evaluated, parameter #5, Skill Level, is that with the highest score; followed by Product design #1–#3; Spare parts #7–#9; and Information #10, #11. In contrast, there are four parameters which score zero: Manufacturer support #6, Return options #12, Data management #13, and Restart type #14 — since their corresponding weighting factors are zero, as presented in Table 3. Common to all coffee machines is the lack of provision of diagnostic support, which would facilitate the identification of the problem related to the priority part. There is no opportunity for broader repair, reuse, and/or upgrade scenarios due to the lack of a design allowing for a diagnostic interface. The lack of information on priority parts, component compatibility, step-by-step disassembly instructions, necessary tool identification, fault tables, or a spare parts list is also common. A significant portion of the score obtained in the analysed capsule coffee machines comes from the Skill level, as it is the parameter with the highest overall weighting factor.

Regarding the priority parts, the water tank is identified as the priority part with the highest score for all capsule coffee machines (Table 4), while the capacitor has the lowest average score. The water tank is designed to be easily removable in all cases due to the frequent need to refill it with water. The frequency of removal depends on factors such as the amount of water used per capsule, the number of capsules consumed per day, and the capacity of the tank. Therefore, the design of the water tank incorporates elements that facilitate the extraction and placement process. This design feature results in low disassembly and assembly times, contributing to a higher repair index compared to the other priority parts.

4.2.2. *Identification of aspects that improve the RI*

After applying the RM to the four capsule coffee machines, the subsequent phase involves examining the aspects that have the potential to enhance the RI. This analysis encompasses the identification and analysis of the aspects that could improve the score from several parameters, including the depth of the disassembly sequence, the type of fasteners employed, the required skill level, and the availability of spare parts. Furthermore, the interface of the spare parts, the duration for which they remain accessible, and the quality and accessibility of the information essential for conducting repair tasks are taken into consideration. Aspects that could improve the repair index include:

- Product design #1–#3, the required effort to access and/or replace priority parts is evaluated through the disassembly intensity. According to EN 45554 (2020), this is the number of steps required to remove a product part without damaging it. In this case, only C3 obtains disassembly intensity values below the average for all prioritised parts, as Fig. 6 shows. Proper organisation of parts increases the ease of disassembly and consequently reduces the disassembly depth of each part.

- Fastener type #2. The reversibility and reusability of fastenings are closely interrelated with the evaluation of necessary tools, as well as the ease of repair, reuse, and upgrade. As shown in Table 5, in 55 % of the cases, the priority parts are reusable. An optimised and modular internal organisation of priority parts is closely related to the disassembly intensity of the part. In Fig. 7, the internal architecture of each of the analysed coffee machines is shown. The C1 capsule coffee machine has a horizontal distribution of its components. Everything is connected and dependent on the upper body of the conditioning system, with some parts covered by lids. In the C2 and C3 capsule coffee machines, the internal organisation follows a vertical structure. In both, all important components of the device are coupled from bottom to top behind the front outer casing. Accessing their interior involves fewer steps than in the case of C1. In C2 and C3, the protection and casing system is simplified. They differ in the location of the printed circuit board, which is more accessible in C3. The internal architecture of C4 is very similar to that of C2 and C3, but in this case the components follow a diagonal distribution around an elongated boiler. The arrangement of components in C4 facilitates the identification of the priority parts, but its complex

		p_j	Wp_j		Sc \ Wpp_i	Water pump	Hoses	Coffee conditioning	Filter	Water tank	Switch	O-ring	Capacitor	Boiler	PCB	S_j
						15.8%	15.5%	11.9%	10.8%	9.6%	9.0%	8.7%	6.6%	6.4%	5.7%	
Product design	#1	Disassembly sequence depth	11.2%	Disassembly depth for the part i (Di) / Disassembly reference depth for the part i ((Dref)		$S_{1,1}$	$S_{1,2}$	$S_{1,3}$	$S_{1,4}$	$S_{1,5}$	$S_{1,6}$	$S_{1,7}$	$S_{1,8}$	$S_{1,9}$	$S_{1,10}$	S_1
	#2	Fastener type	5.5%	Reusable	10	$S_{2,1}$	$S_{2,2}$	$S_{2,3}$	$S_{2,4}$	$S_{2,5}$	$S_{2,6}$	$S_{2,7}$	$S_{2,8}$	$S_{2,9}$	$S_{2,10}$	S_2
				Removable	5											
				Not removable and and not reusable	0											
	#3	Tools needed	4.0%	Toolless	10	$S_{3,1}$	$S_{3,2}$	$S_{3,3}$	$S_{3,4}$	$S_{3,5}$	$S_{3,6}$	$S_{3,7}$	$S_{3,8}$	$S_{3,9}$	$S_{3,10}$	S_3
				Common general purpose	7.5											
				Professional product group specific tools	5											
				Propietary tools	2.5											
				Not viable with any existing tool	0											
	#4	Working environment	2.9%	Home / no requirements	10	$S_{4,1}$	$S_{4,2}$	$S_{4,3}$	$S_{4,4}$	$S_{4,5}$	$S_{4,6}$	$S_{4,7}$	$S_{4,8}$	$S_{4,9}$	$S_{4,10}$	S_4
				Specialised workshop	5											
				Production environment	0											
	#5	Skill level	16.3%	Apprentice	10	$S_{5,1}$	$S_{5,12}$	$S_{5,13}$	$S_{5,4}$	$S_{5,5}$	$S_{5,6}$	$S_{5,7}$	$S_{5,8}$	$S_{5,9}$	$S_{5,10}$	S_5
				Generalist	7.5											
				Professional	5											
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support	#6	Diagnostic support and interfaces	9.4%	Visually intuitive interface	10	$S_{6,1}$	$S_{6,2}$	$S_{6,3}$	$S_{6,4}$	$S_{6,5}$	$S_{6,6}$	$S_{6,7}$	$S_{6,8}$	$S_{6,9}$	$S_{6,10}$	S_6
				Coded interface with public reference table	7.5											
				Publicly available hardware / software interface	5											
				Proprietary interface	2.5											
				Not viable with any type of interface	0											
Spare Parts	#7	Spare parts availability	10.5%	Publicly available	10	$S_{7,1}$	$S_{7,2}$	$S_{7,3}$	$S_{7,4}$	$S_{7,5}$	$S_{7,6}$	$S_{7,7}$	$S_{7,8}$	$S_{7,9}$	$S_{7,10}$	S_7
				Available to independent suppliers	7.5											
				Available to suppliers	5											
				Available for manufacturer	2.5											
				Spare part not available	0											
	#8	Spare parts interface	0.0%	Standard part with standard interface	10	$S_{8,1}$	$S_{8,2}$	$S_{8,3}$	$S_{8,4}$	$S_{8,5}$	$S_{8,6}$	$S_{8,7}$	$S_{8,8}$	$S_{8,9}$	$S_{8,10}$	S_8
				Exclusive part with standard interface	5											
				Exclusive part with non-standard interface	0											
	#9	Spare parts availability duration	10.5%	Long-term availability	10	$S_{9,1}$	$S_{9,2}$	$S_{9,3}$	$S_{9,4}$	$S_{9,5}$	$S_{9,6}$	$S_{9,7}$	$S_{9,8}$	$S_{9,9}$	$S_{9,10}$	S_9
				Mid-term availability	6.6											
				Short-term availability	3.3											
				No information on duration of availability	0											
Information	#10	Information type	14.9%	Comprehensive information available	10					$S_{10,T}$						S_{10}
				Basic information available	5											
				No information available	0											
	#11	Information availability	14.9%	Publicly available	10					$S_{11,T}$						S_{11}
				Available to independent suppliers	6.6											
				Available to suppliers	3.3											
				Available for manufacturer	0											
	#12	Return options	0.0%	Exhaustive return options	10					$S_{12,T}$						S_{12}
				Basic return options	5											
				No return option	0											
	#13	Data management	0.0%	Integrated data not stored	10					$S_{13,T}$						S_{13}
				Under request	5											
				Not available	0											
	#14	Restart type	0.0%	Integrated restart	10					$S_{14,T}$						S_{14}
				External restart	6.6											
				Service restart	3.3											
				No restart	0											
					S_i	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	**RI**
					RI_i	RI_1	RI_2	RI_3	RI_4	RI_5	RI_6	RI_7	RI_8	RI_9	RI_{10}	

Fig. 4. RM adapted to capsule coffee machines.

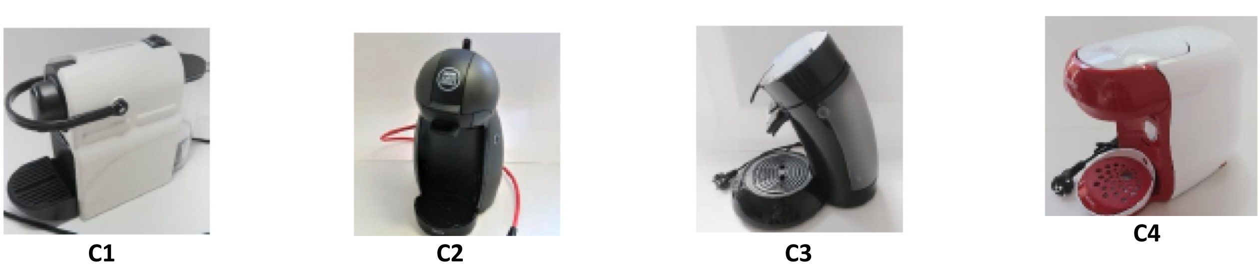

Fig. 5. Selected market capsule coffee machines.

architecture involves longer disassembly times. Only in C3 does replacing the priority parts not involve replacing any other parts.

- Tools needed #3. According to EN 45554 (2020) standard, the necessary tools to disassembly a product are determined during the product design process and are characteristic of it. For the four capsule coffee machines analysed, the necessary tools are basic tools included in Annex A of the standard (Table A.3).
- Skill level #5. In the repair process, the level of skill includes the ability to identify and locate the defect, access the parts, and successfully repair or replace them. This involves the safe handling of tools, management of possible risks, and understanding of the functioning of the coffee machine. Having knowledge about the function of each component and being familiar with different types of connections were essential in performing the disassembly process in all four capsule coffee machines. In all four models, the only disassembly that could be conducted without prior knowledge is the removal of the water tank, owing to its features, as explained in Section 4.2.1. For the remaining components, most repair tasks would only be feasible for professionals who are well versed in the product category.
- Manufacturer support #6. None of the manufacturer's manuals and websites provide the necessary information to facilitate the identification of any problems or defects related to a priority part.

Table 4
Repair Index (RI) and by Priority Part Repair Index (RI_i).

	Repair Index (RI)										Priority Part Repair Index (RI_i)									
	Parameter/group of parameters										Priority parts									
	Product design #1–#3	Working environment #4	Skill level #5	Manufacturer support #6	Spare parts #7–#9	Information #10 #11	Return options #12	Data management #13	Restart type #14	RI	Water pump	Hoses	Coffee conditioning	Filter	Water tank	Switch	O-ring	Capacitor	Boiler	PCB
C1	0.74	0.29	0.80	0.00	0.82	0.49	0.00	0.00	0.00	**3.13**	2.86	3.13	2.86	3.13	4.40	3.21	3.13	2.72	3.13	2.72
C2	0.89	0.29	0.89	0.00	0.85	0.49	0.00	0.00	0.00	**3.41**	3.40	3.13	3.80	2.39	5.52	3.25	3.64	2.72	3.19	2.72
C3	1.23	0.29	1.12	0.00	0.82	0.49	0.00	0.00	0.00	**3.95**	3.94	3.93	3.83	4.34	5.25	2.61	4.14	3.37	3.75	4.05
C4	0.74	0.29	1.02	0.00	0.85	0.49	0.00	0.00	0.00	**3.39**	2.91	3.66	3.12	3.26	5.52	3.08	2.86	3.04	2.86	3.45

Providing accessible and user-friendly information for the correct diagnosis of the fault would aid the user and facilitate the repair task.

- Spare parts #7–#9, concerning the availability of spare parts, most of the priority parts are available to independent repair providers, which makes self-repair by the user impossible. Moreover, spare parts interface, the possibility of repairing, reusing, or upgrading a part is influenced by its interface. The presence of a standard interface will ultimately determine the success of a repair, regardless of whether the component itself is standard or not. Nevertheless, having a standard priority part would facilitate its subsequent use and make it more accessible for a user to purchase. In addition, there is the question of the spare parts availability duration. According to the European Directive 2019/771 (2019), manufacturers must provide spare parts and components for ten years from the date when the product is discontinued. Therefore, the more extra years manufacturers guarantee, the greater the favourable impact on repair.
- Information #10–#11. All four of the analysed coffee machines have a common issue: the lack of exhaustive public information regarding the priority parts. Additionally, they do not provide step-by-step disassembly instructions, identification of the necessary tools, fault tables, or spare parts lists.

4.2.3. Proposal of a new design of capsule coffee machine that improves the RI (C5)

Based on the results obtained, areas for improvement have been identified, and specific actions have been proposed to increase the repairability of the analysed product category. This involves making improvements in product design, simplifying the disassembly sequence, using more accessible fasteners, expanding the availability of spare parts and enhancing the technical documentation available to repairers, for instance. The proposed actions include strategic organisation of components, modular design, increased use of quick-fit fasteners, and ease of identification through intuitive internal architecture and component labelling. Additionally, providing user-friendly diagnostic information such as printed information labels and QR codes is suggested. To improve spare part availability, implementing component positioning systems with adaptable features to other components is recommended. Regarding information, the aim is to provide comprehensive and publicly available information about priority parts. All these actions are aimed at improving the RI of the capsule coffee machines.

Taking into consideration the improvement proposals obtained in Section 4.2.2, the design process shown in Fig. 8 has been followed to develop a new capsule coffee machine (C5). Starting from the initial stages of conceptual design, fundamental goals and requirements are established to guide the next step of generating ideas and sketching alternatives. After evaluating and selecting the option that best meets the objectives and constraints, the design evolves in the preliminary design phase. In this stage, functional and ergonomic studies are conducted to ensure the viability and functionality of the appliance. As the design progresses towards the detailed design of the capsule coffee machine, all components, their connections, materials used, and manufacturing processes are defined in detail. The design is supported by mechanical and manufacturing studies to ensure the technical feasibility of the product. Additionally, associated commercial elements are determined. Finally, a complete 3D model is created, allowing for visualisation and analysis of the design. From this model, the disassembly sequence is defined.

As for the product design #1–#3, the application of the RM highlights the significance of the internal architecture of products, particularly capsule coffee machines. The organisation of priority parts is key when it comes to facilitating repair tasks, increasing product lifespan and preventing premature waste. Given that one of the objectives is the optimisation of product architecture —more specifically, making a well-structured and ordered product with a minimum number of components (Favi and Germani, 2012) — the new design features a modular structure with horizontal architecture and an intuitive arrangement of

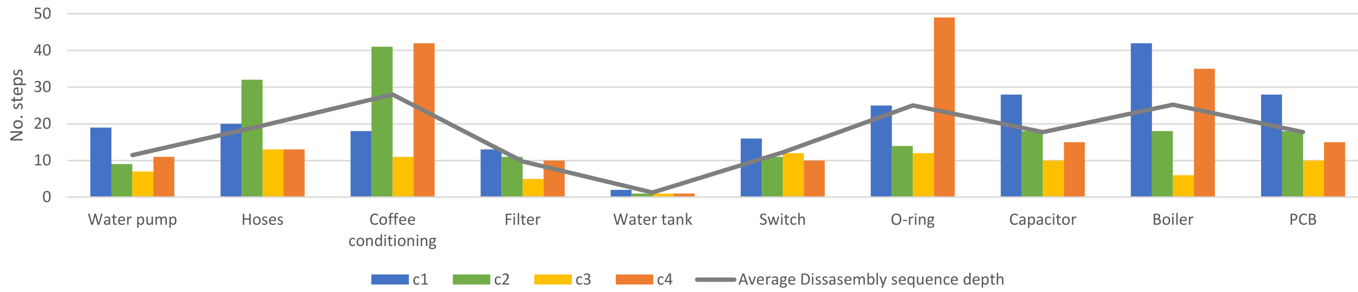

Fig. 6. Disassembly sequence depth

Table 5
Fastener type and Skill ability in the case study capsule coffee machines.

		Water pump	Hoses	Coffee conditioning	Filter	Water tank	Switch	O-ring	Capacitor	Boiler	PCB
Fastener type	Reusable	C2	C1, C2, C3	C2, C3	C1, C3	C1, C2, C4	C1, C2	C1, C2, C3	C1, C2	C1	C1, C2, C3
	Removable	C1, C3, C4	C4	C1, C4	C4	C3	C4	C4	C3, C4	C2, C3, C4	C4
	Not removable				C2		C3				
	Not reusable										
Skill ability	Apprentice					C1, C2, C3, C4					
	Generalist	C3	C3, C4	C2	C3, C4			C3			C3, C4
	Professional	C1, C2, C4	C1, C2	C3, C4	C1, C2		C1, C2, C3, C4	C1, C2, C4	C3, C4	C1, C2, C3, C4	
	Manufacturer			C1					C1, C2		C1, C2
	Not viable										

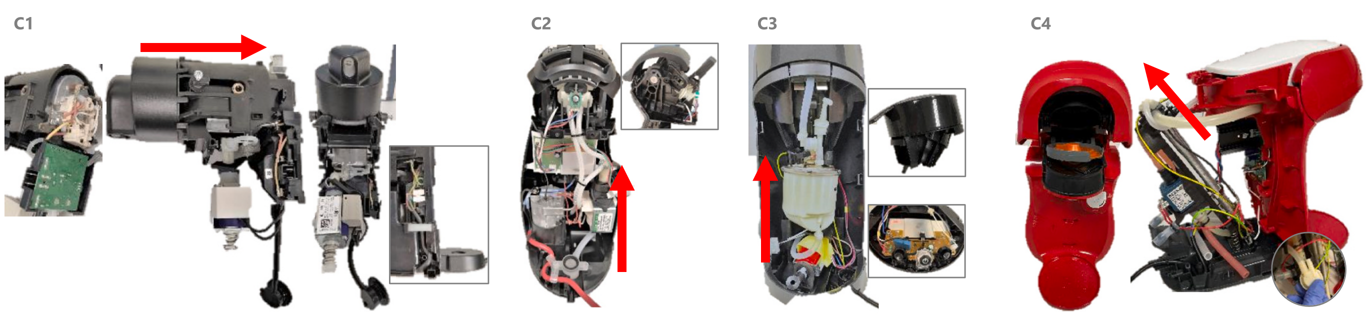

Fig. 7. Internal architecture

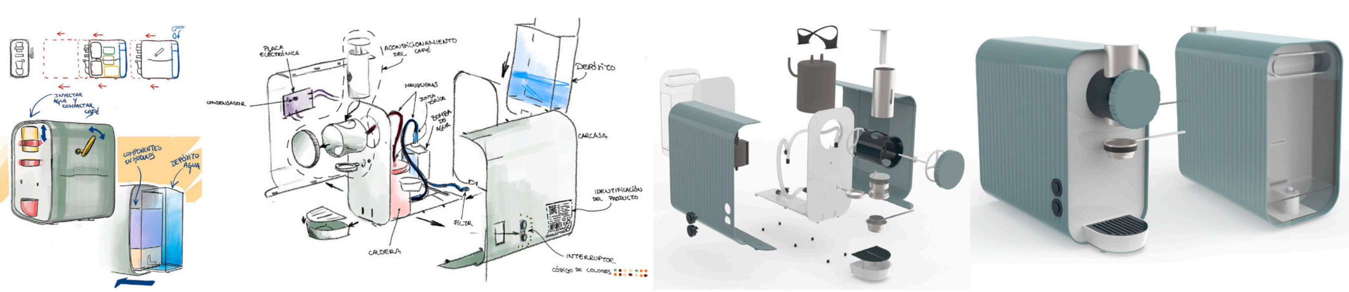

Fig. 8. Design process of capsule coffee machine (C5) improving its RI.

components. Thanks to this design, the internal organisation of the capsule coffee machine allows access to most priority components by simply removing the correct casing. The water pump is assembled behind the back casing, the boiler behind the front casing, and the circuit board behind the left casing. The boiler and pump are attached to the system using adaptable elements that can accommodate different shapes and geometries of future replacement components, thus minimising the use of third-party parts and fasteners.

The joint design has been enhanced. It was noted that the use of snap fits results in less disassembly time and greater ease of component replacement or upgrading. Therefore, the entire assembly of the capsule coffee machine has been made using snap fits, eliminating the need for third-party elements, simplifying assembly and disassembly.

With regard to manufacturer support #6, the main body of the coffee machine includes a printed information label on one side, complete with user manuals and repair guides. Fault diagnosis is improved with the use of colour-coded switches incorporated into the two switches.

Regarding spare parts #7–#9, the new design incorporates standardised priority components. Additionally, it features positioning systems inside the product that can adapt to different interfaces of priority components. In accordance with the European Directive 2019/771 (2019), it is guaranteed to have available spare parts for at least ten years after the cessation of production.

In addition, as for information #10–#11, user manuals and disassembly/assembly guides, as well as diagnostic tables and common failure information, are provided. The information can be found in printed form accompanying the product and/or on the manufacturer's websites.

4.2.4. Application of RM to the new capsule coffee machine (C5): obtaining RI and comparison with that obtained in commercial appliances

The RM (Fig. 4) was applied to the new design for a capsule coffee machine (C5) described in Fig. 8. The RI obtained for C5 was 8.83, as shown in Fig. 9 (in light blue) and Table S5 in the Supplementary Material file. The pictograms and the scale from A to D (A $\geq$ 7.5; 7.5 > B $\geq$ 5.0; 5.0 > C $\geq$ 2.5; >2.5) used in Fig. 9 were obtained from European Commission (2018).

The following describes the reasons for the significant improvement of the RI compared to that of the previous capsule coffee machines analysed (C1, C2, C3, and C4):

- Regarding the parameters/groups of parameters:
  - Product design (#1–#3): C5 achieved a score of 1.26, which is significantly higher compared to C1 (0.74), C2 (0.89), C3 (1.23), and C4 (0.74). This indicates that C5 has made substantial improvements in the product design, surpassing the other cases in this specific aspect.
  - Working environment (#4): C5 obtained a consistent score of 0.29, similar to C1, C2, C3, and C4. No significant differences were observed in this aspect between the cases, suggesting that the work environment remained relatively similar across all scenarios.
  - Skill level required (#5): C5 achieved a score of 1.26, surpassing the scores of C1 (0.80), C2 (0.89), C3 (1.12), and C4 (1.02). This indicates that C5 improved the required skill level, making repairs more feasible compared to the other cases.
  - Manufacturer support (#6): C5 received a score of 0.94, while C1, C2, C3, and C4 scored 0.00 in this aspect. This highlights that C5 implemented a higher level of manufacturer support, which likely facilitated repair processes more effectively than the other cases.
  - Spare parts (#7–#9): C5 achieved a score of 2.11, significantly surpassing C1 (0.82), C2 (0.85), C3 (0.82), and C4 (0.85). This indicates that C5 made substantial improvements in the availability of spare parts, enhancing the overall repairability of the product compared to the other cases.
  - Information (#10, #11): C5 attained the highest score of 2.97, compared to C1 (0.49), C2 (0.49), C3 (0.49) and C4 (0.49). This indicates that C5 successfully provided a greater quantity and quality of information, making it easier for users to perform repairs compared to the other cases.
- Regarding the priority parts, the water pump, hoses, coffee conditioning, and filter exhibit an RI_i of 8.47, suggesting a reasonable repairability in these components. The water tank stands out, with a RRUi of 10.00, indicating a high reparability. The switch has an RI_i of 8.90, while the O-ring presents an RI_i of 8.61. Components such as the capacitor, boiler, and printed circuit board have an RI_i of 9.16, 9.16 and 9.18, respectively. These results indicate a good repairability in these specific components. Overall, these data demonstrate

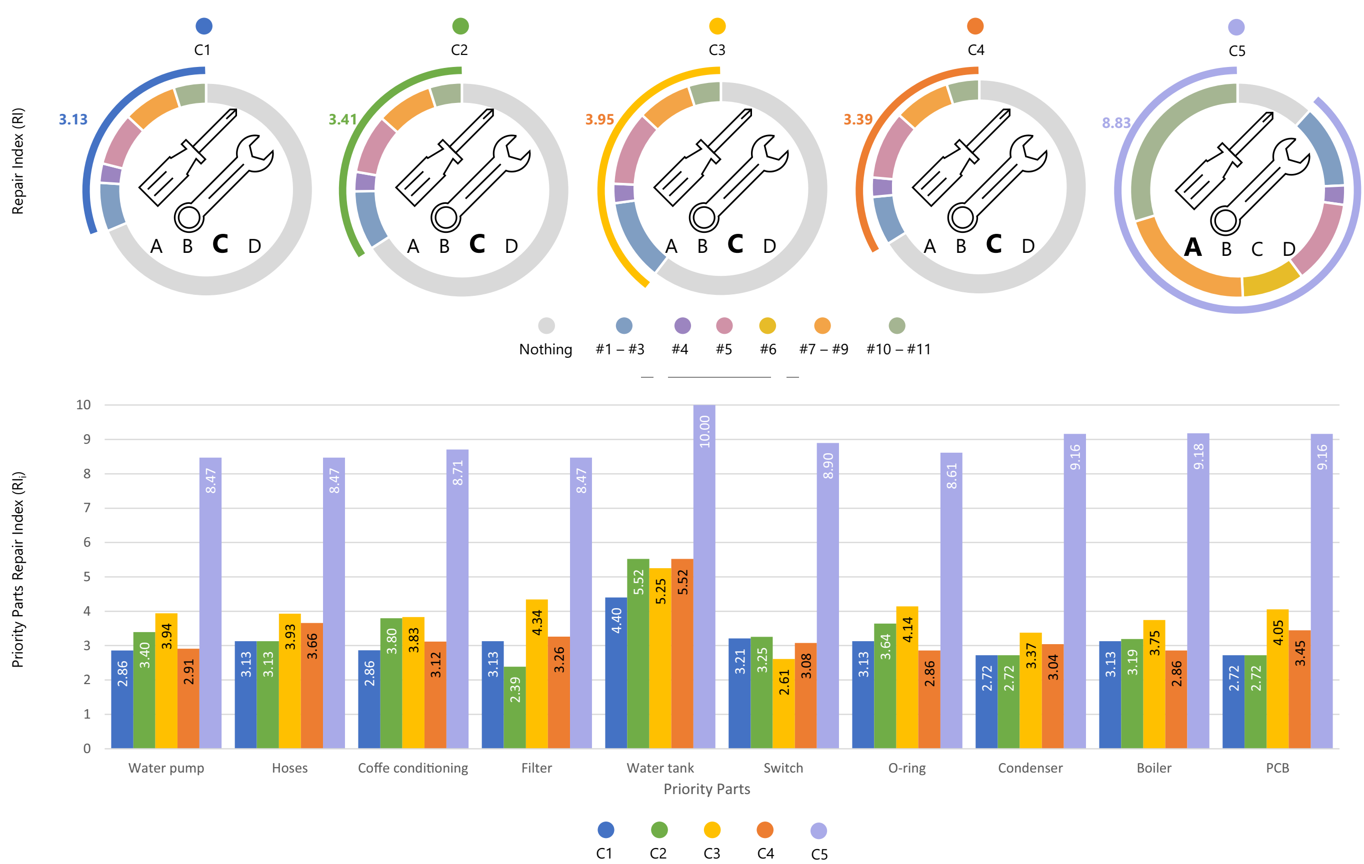

Fig. 9. Repair Index (RI) and Priority Part Repair Index (RI_i).

that the majority of the prioritised components analysed display a positive level of reparability, which is encouraging for the effective maintenance and repair of capsule coffee machine C5.

5. Discussion

5.1. Improvement of the accuracy of the Repair Index

Of the 14 parameters included in the standard, two shortcomings have been identified that could be addressed to obtain a more accurate and faithful result. One of the identified issues is related to the lack of price evaluation of spare parts. In compliance with Directive 2009/125/EC (European Parliament, 2009), companies are obligated to guarantee the availability of spare parts for a period of ten years, thereby upholding the essential “right to repair”. However, the price of spare parts will significantly impact the user's ultimate decision. To evaluate this aspect, methods such as FRI (Ministère de la Transition écologique, 2021) and AsMeR (Bracquené et al., 2018), incorporate specific parameters. To enhance the RM, a remedial measure is suggested in the form of a matrix based on AsMeR, shown in Table 6. The present proposal fulfils the recommendation by BEUC (2022), which suggests incorporating criteria related to the price of spare parts.

Another of the identified issues is the lack of precision achieved when applying parameter #1, Disassembly sequence depth. This arises from the fact that the number of steps does not accurately determine the duration of the process, as it depends on the type of joint employed in each step. For instance, in the case study, the disassembly depth of the PCB in C1 encompasses 28 steps, in contrast to C2 which involves 18 steps. However, following the application of the eDIM methodology, the time required for the target component in C1 amounts to 516.1 s, whereas for C2 it stands at 521 s. In essence, although capsule coffee machine C2 reduces disassembly depth by 35.7 %, it increases eDIM time by 0.1 %. Consequently, more accurate scores will be obtained. As a remedial action to improve the disassembly depth, taking into account Eq. (1), the following matrix based on eDIM is proposed, presented in Table 7.

In order to assess the impact of incorporating the improvements regarding the cost of the spare parts and disassembly depth, as illustrated in Tables 6 and 7, these parameters were incorporated into the RM, creating the reformulated Repair Matrix (rRM), as shown in Fig. 10. The new parameter #1, Disassembly Time, has been calculated using the quantitative eDIM tool (Peeters et al., 2018). The eDIM method evaluates the ability or ease with which components or assemblies can be removed from products to facilitate repair, refurbishment, and reusability, or to improve recycling. It is a quantitative method aimed at calculating the disassembly and reassembly time, resulting in the sum (total time in seconds) of both processes. The new parameter #10, Spare parts cost, has been calculated using the information available on the official manufacturers' websites (see Table S6 in the Supplementary Material). When incorporating a new parameter, it was necessary to recalculate the weighting factor of each parameter (Wp_j). Therefore, Wp_{10} is obtained from the average extracted from the group of spare parts parameters (Wp_7, Wp_8 Wp_9), and the remainder ($Wp_{1–9,11–15}$) have been readjusted accordingly.

Table 6
Score matrix to assess Spare parts cost.

Parameter (j)	Levels (j_{levels})	Scale (Sc)
Spare parts cost	Average price of the priority part i is less than or equal to 5 % of the product price	A
	Average price of the priority part i is between 5 % and 10 % of the product price (10 % included)	B
	Average price of the priority part i is between 10 % and 20 % of the product price (20 % included)	C
	Not available	D

Table 7
Score matrix to assess Disassembly Time.

Parameter (j)	Levels (j_{levels})	Score	
Disassembly Time (S_{time})	Disassembly Time for the priority part i (D_i)	$S_{time,i} = 1 - ((D_i - 1)/(Dref_i - 1))$ with $S_{time,i} = 0$ for $Di > Dref_i$	[Eq. 8]

The rRM has been applied to the capsule coffee machines C1, C2, C3, C4, and C5 of the case study in order to obtain the new reformulated Repair Index (rRI) for each one. The rRM are reported in Tables S7, S8, S9, S10, and S11 of the Supplementary Material, while the comparison between RI and rRI are reported in Table 8. The results show that, for each coffee machine, the rRI has slightly decreased compared to the RI, although the order is maintained (from highest to lowest RI or rRI).

5.2. Sensitivity analysis

In order to evaluate the robustness of the method, a sensitivity analysis was carried out to study the influence of the weighting factors for the priority parts (Wp_j), since they were obtained from an interview, as described in Table 3. The results in Sections 4 and 5.1 have been obtained using the average value of the Wp_j. So, in this section the influence of the use of the average $Wp_j \pm SD$ on the results of the RI and rRI for the five capsule coffee machines (C1, C2, C3, C4, and C5) is analysed. The results are reported in Table 9, where it can be observed that the preference order for both RI and rRI remains the same, despite minimal variations in the repair scores. The complete calculation of the sensitivity analysis is reported in Table S13 of the Supplementary Material.

5.3. Comparison of results with other reference methods

As seen in Section 2, there is no single and internationally accepted method to measure the level of repairability of products. According to Table 1, AsMer is the general method (applicable to any product category) most applied in the literature, since there is not a specific version of iFixit developed for capsule coffee machines.

Table 10 reports the repair index obtained after applying AsMeR (scale 1 to 100) to the capsule coffee machines of the case study (C1, C2, C3, C4, and C5), the AsMeR calculation are reported in Tables S14, S15, S16, S17, and S18 of the Supplementary Material. As can be observed, AsMeR method exhibits higher values compared to RI and rRI (Table 9). This difference may be due to the fact that AsMeR evaluates the product as a whole (global approach), while RM and rRM evaluate the product by its priority parts, one by one. That is, AsMeR is a less accurate method than RM and rRM. However, despite this methodological aspect and differences in the repair scores, the order of preference according to the repair index remains almost the same, except for C1 and C4.

6. Conclusion

This paper provides a matrix (RM) that simplifies and facilitates the application of the UNE 45554 (2020) standard to calculate the repairability of any product category (RI). In addition, this matrix has been reformulated (rRM) to increase the accuracy of the repair index calculated (rRI) by improving the methodological procedure of two of their parameters.

Regarding Research Question 1 (RQ1: How adaptable to different product categories is the general method proposed by the EN 45554 (2020) standard?), this study has demonstrated that thanks to the proposed RM, EN 45554 (2020) is easily adaptable to the product category of capsule coffee machines. For this to happen, with any product category, the elements of the RM and rRM— weighting factor of each parameter (Wp_j), priority parts (pp_i), weighting factor of each priority part, and scale (Sc) — need to be identified using the information

		p_j	Wp_j		Sc \ Wpp_i	Water pump	Hoses	Coffe conditioning	Filter	Water tank	Switch	O-ring	Capacitor	Boiler	PCB	S_j
						15.8%	15.5%	11.9%	10.8%	9.6%	9.0%	8.7%	6.6%	6.4%	5.7%	
Product design	#1	Disassembly time	10.5%	Disassembly Time for the part i (Di) / Disassembly Time for the part i (Dref)		$S_{1,1}$	$S_{1,2}$	$S_{1,3}$	$S_{1,4}$	$S_{1,5}$	$S_{1,6}$	$S_{1,7}$	$S_{1,8}$	$S_{1,9}$	$S_{1,10}$	S_1
	#2	Fastener type	5.1%	Reusable	10	$S_{2,1}$	$S_{2,2}$	$S_{2,3}$	$S_{2,4}$	$S_{2,5}$	$S_{2,6}$	$S_{2,7}$	$S_{2,8}$	$S_{2,9}$	$S_{2,10}$	S_2
				Removable	5											
				Not removable and and not reusable	0											
	#3	Tools needed	3.7%	Toolless	10	$S_{3,1}$	$S_{3,2}$	$S_{3,3}$	$S_{3,4}$	$S_{3,5}$	$S_{3,6}$	$S_{3,7}$	$S_{3,8}$	$S_{3,9}$	$S_{3,10}$	S_3
				Common general purpose	7.5											
				Professional product group specific tools	5											
				Propietary tools	2.5											
				Not viable with any existing tool	0											
	#4	Working environment	2.7%	Home / no requirements	10	$S_{4,1}$	$S_{4,2}$	$S_{4,3}$	$S_{4,4}$	$S_{4,5}$	$S_{4,6}$	$S_{4,7}$	$S_{4,8}$	$S_{4,9}$	$S_{4,10}$	S_4
				Specialised workshop	5											
				Production environment	0											
	#5	Skill level	15.2%	Apprentice	10	$S_{5,1}$	$S_{5,12}$	$S_{5,13}$	$S_{5,4}$	$S_{5,5}$	$S_{5,6}$	$S_{5,7}$	$S_{5,8}$	$S_{5,9}$	$S_{5,10}$	S_5
				Generalist	7.5											
				Professional	5											
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support	#6	Diagnostic support and interfaces	8.8%	Visually intuitive interface	10	$S_{6,1}$	$S_{6,2}$	$S_{6,3}$	$S_{6,4}$	$S_{6,5}$	$S_{6,6}$	$S_{6,7}$	$S_{6,8}$	$S_{6,9}$	$S_{6,10}$	S_6
				Coded interface with public reference table	7.5											
				Publicly available hardware / software interface	5											
				Proprietary interface	2.5											
				Not viable with any type of interface	0											
Spare Parts	#7	Spare parts availability	9.8%	Publicly available	10	$S_{7,1}$	$S_{7,2}$	$S_{7,3}$	$S_{7,4}$	$S_{7,5}$	$S_{7,6}$	$S_{7,7}$	$S_{7,8}$	$S_{7,9}$	$S_{7,10}$	S_7
				Available to independent suppliers	7.5											
				Available to suppliers	5											
				Available for manufacturer	2.5											
				Spare part not available	0											
	#8	Spare parts interface	0.0%	Standard part with standard interface	10	$S_{8,1}$	$S_{8,2}$	$S_{8,3}$	$S_{8,4}$	$S_{8,5}$	$S_{8,6}$	$S_{8,7}$	$S_{8,8}$	$S_{8,9}$	$S_{8,10}$	S_8
				Exclusive part with standard interface	5											
				Exclusive part with non-standard interface	0											
	#9	Spare parts availability duration	9.8%	Long-term availability	10	$S_{9,1}$	$S_{9,2}$	$S_{9,3}$	$S_{9,4}$	$S_{9,5}$	$S_{9,6}$	$S_{9,7}$	$S_{9,8}$	$S_{9,9}$	$S_{9,10}$	S_9
				Mid-term availability	6.6											
				Short-term availability	3.3											
				No information on duration of availability	0											
	#10	Spare parts cost	6.5%	Average consumer price of part i is less than or equal to 5% of catalogue price	10	$S_{10,1}$	$S_{10,2}$	$S_{10,3}$	$S_{10,4}$	$S_{10,5}$	$S_{10,6}$	$S_{10,7}$	$S_{10,8}$	$S_{10,9}$	$S_{10,10}$	S_{10}
				Average consumer price of pat i is between 5% and 10% of catalogue price (10% included)	6.6											
				Average consumer price of part i is between 10% and 20% of catalogue price of the product (20% included)	3.3											
				Not available	0											
Information	#11	Information type	13.9%	Comprehensive information available	10					S_{11}						S_{11}
				Basic information available	5											
				No information available	0											
	#12	Information availability	13.9%	Publicly available	10					S_{12}						S_{12}
				Available to independent suppliers	6.6											
				Available to suppliers	3.3											
				Available for manufacturer	0											
	#13	Return options	0.0%	Exhaustive return options	10					S_{13}						S_{13}
				Basic return options	5											
				No return option	0											
	#14	Data management	0.0%	Integrated data not stored	10					S_{14}						S_{14}
				Under request	5											
				Not available	0											
	#15	Restart type	0.0%	Integrated restart	10					S_{15}						S_{15}
				External restart	6.6											
				Service restart	3.3											
				No restart	0											
			100%													
					S_i	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	rRI
					RI_i	rRI_1	rRI_2	rRI_3	rRI_4	rRI_5	rRI_6	rRI_7	rRI_8	rRI_9	rRI_{10}	

Fig. 10. Reformulated Repair Matrix (rRM) for capsule coffee machines.

Table 8
RI and rRI for the case study.

Repair Index	C1	C2	C3	C4	C5	Order (High RI > Low RI)
RI (Fig. 4)	3.13	3.41	3.95	3.39	8.83	C5 > C3 > C2 > C4 > C1
rRI (Fig. 10)	2.94	3.10	3.77	3.32	9.16	C5 > C3 > C4 > C2 > C1

sources suggested in Table 2. The proposed RM and rRM help achieve a universal methodology for calculating the repair index of products, since it is adaptable to any product category. Furthermore, it aligns with the suggestion of investigating the incorporation of a repair score for products not yet covered by specific eco-design requirements, offering consumers comparable repairability information for such products.

Regarding Research Question 2 (RQ2: Is EN 45554 (2020) useful for identifying specific design aspects that contribute to improving the repair index?), this study has demonstrated that the standard is useful because incorporates parameters that encompass the entire repair process, organised into nine groups. In total, there are 14 parameters that objectively evaluate the reusability, reparability, and upgradability of

Table 9
Sensitivity analysis.

Repair Index	Wp_j (Table 3)	C1	C2	C3	C4	C5	Order (High RI > Low RI)
RI (Fig. 4)	Average	3.13	3.41	3.95	3.39	8.83	C5 > C3 > C2 > C4 > C1
	Average + SD	3.24	3.51	4.00	3.40	8.86	C5 > C3 > C2 > C4 > C1
	Average − SD	2.60	2.94	3.72	3.33	8.97	C5 > C3 > C2 > C4 > C1
rRI (Fig. 10)	Average	2.94	3.10	3.77	3.32	9.16	C5 > C3 > C4 > C2 > C1
	Average + SD	3.02	3.17	3.81	3.32	9.21	C5 > C3 > C4 > C2 > C1
	Average − SD	2.49	2.76	3.60	3.29	8.89	C5 > C3 > C4 > C2 > C1

Table 10
Repair index according to AsMeR.

Repair Index	C1	C2	C3	C4	C5	Order (High RI > Low RI)
AsMeR	46	48	50	44	89	C5 > C3 > C2 > C1 > C4

the product. The blocks are Product design, Working environment, Skill level, Manufacturer support, Spare parts, Information, Return options, Data management, and Restart type. From the RM and rRM, the Score of the parameter (S_j) is obtained, which is the final assessment or rating of the product for a specific parameter. Therefore, it is possible to compare the S_j scores and identify which group of parameters obtains the lowest scores (S_j); these will be the design opportunities to improve the RI and rRI.

Regarding Research Question 3 (RQ3: Is it possible to increase the accuracy of the method by incorporating more quantitative information?), this study has demonstrated that the adjustment of parameters #1 and #10 have allowed a new rRM and rRI to be obtained, as an evolution of the initial RM and RI. These methodological adjustments reflect an evolution in the focus of the evaluation to obtain a more accurate and comprehensive measurement of the repairability of products.

Regarding the case study (C1–C5), RI and rRI results have been compared with those obtained by applying AsMeR and by carrying out a sensitivity analysis on the parameter Wp_j. Despite the slight differences in the results, the preference order of the capsule coffee machines according their repair scores remains almost the same. Therefore, it is shown that the RM and rRM matrices provide a robust framework for assessing the repairability of products, with capsule coffee machines being the application case chosen in this study. These matrices provide in-depth insights of the repairability of each priority parts, and this information is indispensable for designers, enabling them to identify potential areas of improvement in product design. In the context, designers also can use these matrices to measure the repairability of their initial designs and of designs incorporating improvements that enhance their repair index. From a professional's perspective, these matrices can be useful to make informed decisions about which products are worth repairing, since high values of RI-rRI imply greater ease of repairability and, therefore, more cost-effective repairs.

This topic should be further investigated in the future in order to extend the research to other case studies in the product category of capsule coffee machines, as well as to other product categories, with the aim of providing a robust and conclusive methodology aligned with the European regulatory framework.

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

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