SUPPORTING THE IMPLEMENTATION OF THE RIGHT TO REPAIR:

TOOLS FOR REPAIRABILITY ANALYSIS AND VISUALISATION

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A Loles y Vicky, por vuestra dedicación, por transmitirme vuestros valores y por ser referentes para mí.

A mis abuelas, Lucre y Teresa, por haberlo dado todo por los vuestros y por enseñarme con el ejemplo.

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Compendium of publications

This doctoral thesis has been developed as a compendium of publications in indexed scientific journals (JCR). The following is a list of the journal articles included in this thesis:

ARTICLE I: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, M. D. (2024). Repair index of energy-related products: Application to capsule coffee machines. Sustainable Production and Consumption, 46, 146–160. https://doi.org/10.1016/j.spc.2024.02.011.

ARTICLE II: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, M. D. (2025). Supporting repairability analysis through graph-based visualisation. Journal of Cleaner Production *(under review since 2025 July)*.

ARTICLE III: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, M. D. (2025). Right to repair in practice: Environmental and economic performance of coffee machine repairs. Sustainable Production and Consumption, 57, 226-245. https://doi.org/10.1016/J.SPC.2025.05.011.

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Additional related contributions:

CONFERENCE IV: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, M. D. (2023). How does the design of a product influence the improvement of its end of life? Proceedings of the X Simposio Iberoamericano de Ingeniería de Residuos, 290–297. ISBN: 978-84-09-53123-3.

CONFERENCE V: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, M. D. (2024). Information for repair decision: consumer implications from environmental and economic perspectives. 1st International Conference on Socio-Environmental Footprints (ICSEF 2024), June.

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Summary

In recent years, the European regulatory framework for sustainable products has significantly evolved to promote the circular economy as a key strategy for achieving the Sustainable Development Goals set out in the 2030 Agenda. Within this framework, particular emphasis has been placed on repair strategies, recognising their crucial role in reducing raw material consumption, minimising e-waste generation and extending product lifespan. The recent adoption by the European Commission of the "Right to Repair" further strengthens this approach by establishing measures to enhance product repairability, improve access to spare parts and repair information and foster consumer empowerment in repair decisions. As a result, repairability has become a key pillar within circular economy policies, directly contributing to resource efficiency and more sustainable consumption and production patterns.

In this context, there arises a need to develop integrated tools that enable the analysis, evaluation, and visualisation of product repairability. This thesis addresses this need by proposing a methodological framework that combines, on the one hand, the application of the EN 45554 standard, and on the other, the representation and analysis of repairability through graph-based product modelling and visualisation. Finally, it includes the assessment of the environmental and economic impact of different end-of-life scenarios using Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methodologies.

To achieve the main objective, a five-stage methodological framework was implemented. First, a review of existing repairability assessment methods highlighted the lack of harmonised and their limited capacity to guide design improvements. Secondly, a Repairability Matrix based on the EN 45554 standard was developed, allowing the quantification of repairability at both component and product levels. It was adapted to the case study of capsule coffee machines, selected as a representative example of the small electrical and electronic equipment (sEEE) category. Its application to commercially available coffee machine models enabled the identification of key design factors and the proposal of a redesign that significantly enhanced their repairability. Third, a graph-based modelling approach was introduced, representing product architecture as a network to analyse component interdependencies, leading to the development and application of a novel graph-based Repair Index metric. Fourth, LCA and LCC were integrated with repairability data to assess the environmental and economic trade-offs between repair and replacement, confirming the benefits of repair for components with high failure probability and environmental impact. Finally, consumer and designer-oriented information tools were developed to visualise the results and support informed decision-making in line with the Right to Repair framework.

The thesis is structured into five chapters. Chapter 1 presents the introduction, research gap, objective, research questions and methodological approach. Chapter 2 includes the scientific publications that constitute the compendium of the thesis. Chapter 3 integrates and discusses the main results. Chapter 4 summarises the conclusions and

future development of the thesis. Chapter 5 presents a schematic summary of the thesis. Finally, Chapter 6 compiles the references used throughout the document.

Resumen

En los últimos años, el marco normativo europeo para los productos sostenibles ha evolucionado promoviendo la economía circular como una estrategia clave en la consecución de los Objetivos de Desarrollo Sostenible establecidos en la Agenda 2030. Destaca el papel fundamental de las estrategias de reparación en la reducción del consumo de materias primas, la minimización de residuos electrónicos y la extensión de la vida útil de los productos. La reciente adopción por parte de la Comisión Europea del "Derecho a reparar" refuerza este enfoque estableciendo medidas para mejorar la reparabilidad de productos, facilitar el acceso a piezas de recambio e información de reparación y empoderar al consumidor en la toma de decisiones. Como resultado, la reparabilidad se ha consolidado como un pilar fundamental de la economía circular, contribuyendo a la eficiencia de recursos y a patrones de consumo y producción sostenibles.

En este contexto, surge la necesidad de desarrollar herramientas integradas que permitan analizar, evaluar y visibilizar la reparabilidad de los productos. Esta tesis responde a esta necesidad mediante la propuesta de un marco metodológico que combina por un lado, la aplicación de la norma EN 45554, por otro, la representación y el análisis de la reparabilidad a través del modelado y representación de productos mediante grafos y, finalmente, el análisis del impacto ambiental y económico de diferentes escenarios de fin de vida aplicando las metodologías de Análisis de Ciclo de Vida (ACV) y Coste del Ciclo de Vida (CCV).

Para alcanzar el objetivo principal, se implementó una metodología dividida en 5 etapas. En primer lugar, se revisaron los métodos existentes de evaluación de reparabilidad, evidenciando la falta de enfoques armonizados y su limitada capacidad para visibilizar y orientar mejoras de diseño. En segundo lugar, se desarrolló una Matriz de reparabilidad basada en la norma EN 45554, que permite cuantificar la reparabilidad a nivel de componente y producto, y se adaptó al caso de estudio de cafeteras de cápsulas como ejemplo representativo de la categoría de pequeños aparatos eléctricos y electrónicos (pAEE). Su aplicación a modelos de cafeteras de mercado permitió identificar factores clave de diseño y proponer un rediseño que mejoró significativamente su reparabilidad. En tercer lugar, mediante un enfoque de modelado del producto basado en grafos, se representó la arquitectura de los productos como una red, se analizaron las interdependencias entre los componentes y se desarrolló y aplicó un nueva métrica de cálculo del índice de reparabilidad. En cuarto lugar, se integraron los resultados de reparabilidad con los análisis de ACV y CCV para evaluar los compromisos ambientales y económicos entre reparación y sustitución, confirmando los beneficios de la reparación en componentes con alta probabilidad de fallo y elevado impacto ambiental. Finalmente, con el objetivo de aumentar la accesibilidad a esta información y facilitar su comunicación, se desarrollaron herramientas de información orientadas tanto a consumidores como a diseñadores, visualizando los resultados y apoyando la toma de decisiones informadas de acuerdo con el marco del "Derecho a Reparar".

La tesis se estructura en cinco capítulos. El Capítulo 1 presenta la introducción, los objetivos, las preguntas de investigación y la metodología. El Capítulo 2 recoge los artículos científicos que componen el compendio de la tesis. El Capítulo 3 integra y discute los principales resultados. El Capítulo 4 resume las conclusiones alcanzadas. El Capítulo 5 resume esquemáticamente toda la Tesis. Finalmente, el Capítulo 6 recopila las referencias empleadas a lo largo del trabajo.

Resum

En els darrers anys, el marc normatiu europeu per als productes sostenibles ha evolucionat promovent l'economia circular com una estratègia clau en l'assoliment dels Objectius de Desenvolupament Sostenible establits en l'Agenda 2030. Destaca el paper fonamental de les estratègies de reparació en la reducció del consum de matèries primeres, la minimització de residus electrònics i la prolongació de la vida útil dels productes. La recent adopció per part de la Comissió Europea del "Dret a reparar" reforça aquest enfocament establint mesures per a millorar la reparabilitat dels productes, facilitar l'accés a recanvis i informació de reparació, i empoderar el consumidor en la presa de decisions. Com a resultat, la reparabilitat s'ha consolidat com un pilar fonamental de l'economia circular, contribuint a l'eficiència dels recursos i a patrons de consum i producció sostenibles.

En aquest context, sorgix la necessitat de desenvolupar eines integrades que permeten analitzar i visualitzar la reparabilitat. Esta tesi respon a esta necessitat mitjançant la proposta d'un marc metodològic que combina d'una banda, l'aplicació de la norma EN 45554, per un altre, la representació i l'anàlisi de la reparabilitat a través del modelatge i representació de productes mitjançant grafs i, finalment, l'anàlisi de l'impacte ambiental i econòmic de diferents escenaris de fi de vida aplicant les metodologies d'Anàlisis de Cicle de Vida (ACV) i Cost del Cicle de Vida (CCV).

Per a assolir l'objectiu principal, es va implementar una metodologia dividida en cinc etapes. En primer lloc, es van revisar els mètodes existents d'avaluació de reparabilitat, posant de manifest la falta d'enfocaments harmonitzats, plenament quantitatius i la seua limitada capacitat per a orientar millores de disseny. En segon lloc, es va desenrotllar una Matriu de reparabilitat basada en la norma EN 45554, que permet quantificar la reparabilitat a nivell de component i producte, i es va adaptar al cas d'estudi de cafeteres de càpsules com a exemple representatiu de la categoria de xicotets aparells elèctrics i electrònics (pAEE). La seua aplicació a models de cafeteres de mercat va permetre identificar factors clau de disseny i proposar un redissenye que va millorar significativament el seu reparabilitat. En tercer lloc, es va introduir un enfocament de modelatge basat en grafs que representa l'arquitectura del producte com una xarxa per a analitzar les interdependències dels components, desenvolupant-se i aplicant-se una nova mètrica de càlcul de l'índex de reparabilitat. En quart lloc, es van integrar els resultats de reparabilitat amb les anàlisis de ACV i CCV per a avaluar els compromisos ambientals i econòmics entre reparació i substitució, confirmant els beneficis de la reparació en components amb alta probabilitat de fallada i elevat impacte ambiental. Finalment, es van desenvolupar eines d'informació orientades tant a consumidors com a dissenyadors, visualitzant els resultats i donant suport a la presa de decisions informades d'acord amb el marc del "Dret a Reparar".

La tesi s'estructura en cinc capítols. El Capítol 1 presenta la introducció, els objectius, les preguntes d'investigació i la metodologia. El Capítol 2 recull els articles científics que componen el compendi de la tesi. El Capítol 3 integra i discuteix els principals resultats. El Capítol 4 resumeix les conclusions assolides. El Capítol 5 resumeix de manera

esquemàtica tota la Tesi. Finalment, el Capítol 6 recopila les referències emprades al llarg del treball.

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List of abbreviations and symbols

ABS	Acrylonitrile Butadiene Styrene
AsMeR	Assessment Matrix for ease of Repair
EC	European Commission
EcI	Economic Impact
EEE	Electrical and Electronic Equipment
EF	Environmental Footprint
EI	Environmental Impact
EoL	End-of-Life
EPS	Expanded Polystyrene
EU	European Union
EUR	Euro
FRI	French Reparability Index
GBP	Great British Pound
HDPE	High-density Polyethylene
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low-density Polyethylene
ORDS	Open Repair Data Standard
PA	Polyamide (Nylon)
PCB	Printed Circuits Board
PE	Polyethylene
PET	Polyethylene Terephthalate
POM	Polyoxymethylene
PP	Polypropylene
PPS	Polyphenylene Sulphide
PS	Polystyrene
PVC	Polyvinyl Chloride
RI	Repair Index
RI_i	Repair Index of a priority part
RM	Repair Matrix
RSS	Repair Score System
SAN	Styrene Acrylonitrile
Sc	Scale
SD	Standard deviation
SDG	Sustainable Development Goal
sEEE	Small Electric and Electronic Equipment
SMMA	Styrene Methyl Methacrylate

D	Distribution stage
D_{EI}	Environmental impact of the distribution stage for EEE.
EcI_{Repair}	Economic impact of repair scenarios
$EcI_{Replacement}$	Economic impact of replacement scenarios.
EI_{Repair}	Environmental impact of repair scenarios
$EI_{Replacement}$	Environmental impact of replacement scenarios
EoI_{EI}	Environmental impact of the end-of-life treatment of initial EEE
EoI_j	Environmental impact of the end-of-life treatment of the priority part j
J	Priority part
L	Lifespan
L_p	Lifespan of the product category
L_j	Lifespan of the priority part j
LE	Lifespan Extension
LE_j	Lifespan extension of the priority part j
M	Raw material
M_{EI}	Environmental impact of the raw material stage for EEE
S	Score
Si	Score of a priority part
S_j	Score of a parameter
$S_{j,i}$	Partial score of a parameter
P	Production stage
P_{EI}	Environmental impact of the production stage for EEE
pp_i	Priority parts
p_j	Parameters
R_j	Environmental impact of the repair of the priority part j
Re_j	Economic impact of the repair of the priority part j
RP	Retail price
U	Use stage
U_{EcL}	Annual economic impact of the use stage for EEE
U_{EI}	Annual environmental impact of the use stage for EEE
Wppi	Weighting factor of each priority part
Wp_j	Weighting factor of each parameter

1 INTRODUCTION

1.1 RESEARCH CONTEXT AND BACKGROUND

In recent years, the European regulatory framework for sustainable products has significantly evolved to promote the circular economy as a key strategy for achieving the Sustainable Development Goals set out in the 2030 Agenda (United Nations, 2015). The recent publication of the "Right to Repair" directive (European Parliament, 2024a) and Regulation (EU) 2024/1781 (European Union, 2024) represents a significant step forward in promoting sustainable consumption. These developments support both the Circular Economy Action Plan (European Commission, 2020a) and the European Green Deal (European Commission, 2019a).

As products play a central role in this ecological transition, Regulation (EU) 2024/1781 encourages production and consumption patterns that align with the EU's overarching sustainability objectives, particularly in relation to climate, environment, energy, resource use and biodiversity (European Union, 2024). Moreover, the regulation introduces ecodesign requirements aimed at enhancing product reparability and durability while reducing environmental impact, thereby fostering greater reuse and repair of products. Beyond overarching ecodesign principles, the regulation grants the European Commission the authority to establish category-specific requirements, recognising that each product group entails distinct environmental impacts and technical design challenges. This targeted approach ensures that provisions related to repairability, durability and information disclosure are appropriately tailored to the functional characteristics and actual usage patterns of each category.

According to the European Commission (2023c), the premature disposal of reparable goods contributes to increased waste generation and greenhouse gas emissions, as well as higher demand for valuable resources in the production of new products. Additionally, it is estimated that consumers waste approximately €12 billion annually by choosing replacement over repair (European Commission, 2023c). As a result, repairability has become a key pillar within circular economy policies, directly contributing to resource efficiency and more sustainable consumption and production patterns. This calls for a comprehensive examination of the main factors shaping its effective integration into product systems, from legislation and design strategies to user awareness.

The European Commission will require traders to provide information on a product's repairability score, starting with smartphones and tablets (European Commission, 2023d), a measure that will gradually be extended to additional product categories. In response to these regulatory developments, various initiatives have been developed to assess product repairability. These include standards such as ONR 192102 (2014) and EN 45554 (2020); methodologies proposed by iFixit (Flipsen et al., 2019, 2016; Suovanen, 2023), AsMeR (Bracquené et al., 2018), the Repair Score System (RSS) (Cordella et al., 2019; Spiliotopoulos et al., 2022); as well as national initiatives such as the French Durability Index (Ministère de la Transition écologique, 2020; The French Agency for Ecological Transition, 2021). These methods focus primarily on design-related parameters such as ease of disassembly, tools required and joint types.

Based on these design-related parameters, understanding product architecture and disassembly processes is increasingly recognised as essential to achieving sustainability and circular economy goals. Designers and engineers must consider component connectivity, accessibility and disassembly sequencing to enable maintenance and recovery. Recent studies confirm their value: Agrawal et al. (2016) used graph and matrix-based approaches to model disposition routes in reverse logistics; Alrufaifi et al. (2024) applied centrality metrics to evaluate how wear and failures modify disassembly graphs; Formentini and Ramanujan (2023) developed the Design for Circular Disassembly (DfCD) methodology to map disassembly processes. Complementary visual tools such as the Disassembly Map (De Fazio et al., 2021) and the Peony Diagram (Huang et al., 2025) further enhance the visualisation of component hierarchies and disassembly constraints.

Beyond the assessment of repairability as a design attribute, increasing attention has also been paid to the environmental and economic implications of repairability. Although these aspects have begun to be explored in scientific literature, much of the research has focused on developing repairability indices, often overlooking more comprehensive environmental and economic analyses that compare end-of-life scenarios across different products within the same category or identify patterns within these categories.

In addition to these regulatory and methodological frameworks, grassroots and community-driven initiatives have also emerged, reinforcing a growing societal commitment to repair and empowering consumers to play an active role in the shift towards more sustainable consumption, The Open Repair Alliance (2024) is an international network dedicated to supporting organisations involved in community repair while also striving to optimise the collection and publication of data on the repair of Electrical and Electronic Equipment (EEE). Currently, it comprises databases from non-profit organisations that champion collective repair initiatives and collect data related to repairs using a collaborative standard format known as the Open Repair Data Standard (ORDS). This enables relevant information on out-of-warranty repairs to be documented and shared with both commercial repairers and users, promoting demand for more repairable products, enhancing informational support and facilitating access to repair services. Regarding consumers, their role has become increasingly central to the transition towards more sustainable consumption models. Empowering consumers with clear, transparent and comparable repairability information is essential to enable informed decisions and foster more responsible purchasing and repair behaviours. Understanding the environmental and economic implications of repairing versus replacing a faulty product is crucial. Notably, 77% of consumers are willing to repair rather than replace (European Commission, 2020c). In this regard, the recent Regulation (EU) 2024/1781 (European Union, 2024) emphasises that, to allow consumers to effectively assess and compare products, the format, content and display of repairability scores should include easy-to-understand language or pictograms. Furthermore, according to Directive (EU) 2024/825 (European Parliament, 2024b), manufacturers should provide additional relevant information on repair, including, but not limited to, the estimated cost of spare parts. In this sense, 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., 2022).

In order to effectively advance repairability policies and practices, it is crucial to identify product categories where intervention can generate the greatest impact. This includes products that are widely used, frequently discarded due to minor faults and currently underrepresented in repairability research. One such example is the case of capsule coffee machines, which fall under the small electrical and electronic equipment (sEEE) category and are present in the majority of European households. According to Baldé et al. (2024) small EEE constitutes the largest category of e-waste in terms of mass, accounting for 20 billion kg in 2022, or almost one-third of the world's total e-waste. In particular, capsule coffee machines show a clear growth trend in the European market, with annual sales increasing from 3.01 million units in 2010 to a projected 11.04 million in 2025 and the installed stock rising from 12.55 to 62.06 million units over the same period (Spiliotopoulos et al., 2025). Coffee machines are among the most frequently repaired small household appliances. This category has also been highlighted by R2R Europe (2024) due to the frequent disposal of machines caused by minor faults, the lack of explicit requirements for repairable design and the limited availability of spare parts and replaceable components. Despite their popularity, their actual average lifetime remains limited to 5-7 years, significantly below the consumer-expected 8.7 years. A recent Joint Research Centre (JRC) study (Spiliotopoulos et al., 2025) ranks coffee machines among the top product groups most in need of a reparability scoring system, based on failure rates, market penetration and repair feasibility. Additionally, European Commission (2016) estimates that repair could extend their lifespan by up to four years, making them one of the most repair-benefiting products after vacuum cleaners.

Given the evolving regulatory landscape, the growing societal interest in repair and the lack of in-depth environmental and economic analysis for certain product categories such as capsule coffee machines, this research aims to contribute to filling this gap by integrating design, environmental and economic perspectives. By focusing on a widely used yet under-researched product group, this work seeks to generate a methodological contribution that enables the repairability assessment and visualisation of small electrical appliances, addressing a regulatory and scientific gap for this product category. Ultimately, this thesis aims to support the transition towards more sustainable and repair-friendly product systems through evidence-based analysis that combines standard-based matrices, graph-theoretical modelling, and life cycle tools to inform product design, regulatory action and consumer awareness.

1.2 RESEARCH GAPS

Despite these advances, several research gaps (RG) still remain. In general, there is a need to develop comprehensive tools capable of analysing and visualising product repairability, integrating product repair, environmental impacts, economic costs and consumer-oriented information. To provide a more comprehensive perspective, Table 1.1 summarises the specific research gaps identified and associates them with the stakeholders primarily affected, being these researchers, policy makers, designers and consumers.

TABLE 1.1 IDENTIFIED RESEARCH GAPS CLASSIFIED BY STAKEHOLDERS

RESEARCHERS		
RG1. Although existing repairability frameworks are in use, they could be further developed into implementation-oriented formats suitable for a broader range of product categories.	RG1.1	Although the EN 45554 (2020) standard provides a general framework for evaluating the ability to repair energy-related products, it lacks detailed procedures for practical implementation and requires further methodological development to enhance its applicability to specific product categories.
	RG1.2	Despite their widespread market presence, short lifespan and significant repair potential, capsule coffee machines have received limited attention in repairability research. Existing literature has primarily focused on large appliances and Information and Communication Technology (ICT) products, leaving a lack of empirical studies addressing the specific repairability challenges and design improvement opportunities for this increasingly relevant product category. Notably, the European Commission ranks coffee machines among the product groups most urgently in need of a repairability scoring system, reinforcing their designation as a policy priority within European regulatory frameworks.
POLICY MAKERS		
RG2. Although existing repairability frameworks have been implemented, policy makers still lack coherent and reliable indicators to support effective regulation.	RG2.1	Although repairability frameworks have been applied in specific product categories. There is a clear need for the development of a methodology adaptable to multiple product categories and transferable across countries with similar regulatory contexts. That would ensure international comparability, providing policy makers with coherent and reliable indicators to guide regulation.
	RG2.1	Current approaches rarely incorporate the economic and policy dimensions of repairability. Key aspects such as repair costs, spare part prices and the broader economic impacts on consumers and service providers are often overlooked, limiting the capacity of policy makers to design effective and balanced regulations.

PRODUCT DESIGNERS		
RG3. Existing repairability assessment methods are not sufficiently oriented towards guiding design decisions.	RG3.1	Existing quantitative methods for evaluating repairability do not support visual analysis or facilitate decision-making based on product architecture, while those that enable visual representation lack a systematic integration of quantitative repair-related information. Furthermore, although graph-based modelling has been applied to product design and disassembly studies, it has not yet been specifically adapted to the context of repairability, neither to support visualisation nor to generate specific repairability metrics.
	RG3.2	Few studies in the literature incorporate environmental and economic performance indicators into their evaluations. LCA and LCC approaches, although widely used in sustainability assessment, are rarely integrated with repairability metrics to support decision-making for both designers and consumers when choosing between repair and replacement options.
CONSUMERS		
RG4. Repairability information remains insufficiently accessible and visual to effectively support consumer decision-making.	RG4.1	The problem is twofold: the availability of information and its ease of understanding. There is no information available to consumers about the environmental and economic impact, and it must also be easily understandable in order to effectively support informed choices and promote more sustainable consumption behaviours.

1.3 RESEARCH QUESTIONS

In order to address the identified research gaps, five research questions (RQ) have been formulated to guide the investigation. Table 1.2 presents these research questions together with the expected outcomes associated with each.

TABLE 1.2 RESEARCH QUESTIONS AND EXPECTED OUTCOMES OF THE THESIS.

RESEARCH QUESTION 1	Expected outcome 1
What are the limitations and advantages of current methods for evaluating the repairability of EEE?	A characterisation of existing methods, identifying their main strengths and weaknesses, as well as the methodological aspects that require further development to improve repairability assessment.
RESEARCH QUESTION 2	**Expected outcome 2**
How can EN 45554 be adapted to build a reliable assessment framework for evaluating the repairability of small electrical and electronic equipment?	A repairability assessment method based on EN 45554, adapted to the characteristics of small electrical and electronic equipment, enabling a quantifiable and reproducible assessment of product repairability.
RESEARCH QUESTION 3	**Expected outcome 3**
In what way can a graph-based model represent and quantify the repairability of products?	A graph-based modelling approach that represents product architecture and disassembly sequences, facilitating the visualisation of the product's structure while allowing the quantification of repairability through network metrics and a dedicated graph-based Repair Index metric.
RESEARCH QUESTION 4	**Expected outcome 4**
What environmental and economic benefits arise from prioritising component repair over replacement in small electrical and electronic equipment?	Quantification of the environmental and economic impacts associated with product repair versus replacement, providing comparative results based on LCA and LCC.
RESEARCH QUESTION 5	**Expected outcome 5**
How does the joint presentation of repairability, environmental impact and repair cost indicators influence a consumer's decision to buy or repair products?	Development of visual representations that combine repairability, environmental, and economic indicators to support consumer decision-making, adapted to formats commonly used in product communication, such as environmental labelling.

1.4 OBJECTIVE OF THE THESIS

This thesis aims to contribute to the implementation of the Right to Repair through the development of tools for repairability assessment and visualisation. To this end, six main objectives (O) have been defined and are further broken down into specific objectives, as presented in Table 1.3.

TABLE 1.3 GENERAL AND SPECIFIC OBJECTIVES OF THE THESIS.

General objective	Code	Specific objective
OBJECTIVE 1 (RQ1)		
To identify and critically analyse existing methods for evaluating the repairability of electrical and electronic equipment.	O1.1	To provide a systematic review of repairability assessment methods proposed in the scientific literature.
	O1.2	To map and evaluate repairability assessment methods and requirements adopted in policy and regulatory frameworks.
	O1.3	To identify gaps, inconsistencies and standardisation issues across existing repairability assessment methodologies.
	O1.4	To characterise the product categories covered by academic and policy-based repairability methods.
OBJECTIVE 2 (RQ2)		
To design and validate an assessment framework, based on EN 45554 criteria.	O2.1	To establish a method based on EN 45554 to enable the quantification of repairability parameters.
	O2.2	To demonstrate the applicability of the method through a case study.
	O2.2.1	To adapt the parameters of the method to capsule coffee machines.
	O2.2.2	To assess the repairability of a sample of capsule coffee machines.
	O2.3	To refine and improve the proposed method based on empirical insights from the case study.
OBJECTIVE 3 (RQ3)		
To propose and implement a repairability assessment approach based on graph theory, capable of assessing and visualising product repairability.	O3.1	To review and analyse existing graph-based tools and metrics from repairability assessment perspective.
	O3.2	To adapt existing metrics in order to enhance their applicability to repairability analysis.
	O3.3	To develop a new graph-based metric for the evaluation of product repairability.
	O3.4	To explore the applicability of graph-based metrics, including the newly developed one, through a capsule coffee machine case study.
OBJECTIVE 4 (RQ4)		
To evaluate the environmental and economic benefits of prioritising repair over replacement adaptable to different categories of small electrical and electronic equipment (sEEE).	O4.1	To stablish a methodology for assessing the environmental and economic impacts of specific categories of electrical and electronic equipment through LCA and LCC, integrating repair-related information and metrics.
	O4.1.1	To identify priority parts and failure frequencies.
	O4.1.2	To define repair scenarios.
	O4.2	To apply and test the methodology in a case study (capsule coffee machines), generating evidence on the environmental and economic implications of repair.
OBJECTIVE 5 (RQ5)		
To design tools for analysing and visualising repairability that effectively inform the consumer and support informed decision-making.	O5.1	To identify relevant information related to repair index, environmental impact and economic performance.
	O5.2	To explore the integration of environmental and economic impacts into the European energy label.
	O5.3	To develop visual formats that present repairability information in a clear, accessible and actionable way for empower consumers and designers.

OBJECTIVE 6

To maximise the impact of the research by disseminating results to both academic and practical contexts.	O6.1	To share the research outcomes with the scientific community through research articles, conferences and other academic publications.
	O6.2	To disseminate the developed findings and tools to relevant stakeholders, facilitating their application in repairability, circular economy and product design practices.

1.5 METHODOLOGY

The methodological procedure adopted in this thesis to address the research questions and achieve the defined objectives is structured into five main stages (S). These stages, together with their corresponding sub-stages, are summarised in Table 1.4 and are described in detail in the subsequent chapter of the thesis.

Stage 1 consists of a critical review of existing repairability evaluation methods, which provides the foundation for Stage 2, where an assessment framework based on EN 45554 is designed and validated. Building on this, Stage 3 explores the assessment and visualisation of repairability through graph-based modelling, while Stage 4 evaluates the environmental and economic impacts of repair and replacement scenarios using life cycle assessment (LCA) and life cycle cost (LCC) analysis. Finally, Stage 5 integrates the outcomes of the previous stages to design and validate consumer information tools, ensuring the practical applicability and societal impact of the research. Together, these stages provide a comprehensive and coherent methodological pathway to address the thesis objectives.

TABLE 1.4 STAGES OF THE THESIS.

STAGE 1		
Critical review of existing repairability evaluation methods.	S1.1	Comprehensive literature review of repair evaluation and the current state of the art of repairability methods.
STAGE 2		
Design and validation of an assessment framework based on EN 45554.	S2.1	Adaptation of parameters and assignment of weighting factors.
	S2.2	Definition of priority parts and assignment of weighting factors.
	S2.3	Adaptation of categories and scales for parameter scoring.
	S2.4	Application of the method to existing capsule coffee machine models.
	S2.5	Identification of design aspects influencing the method.
	S2.6	Development of a redesigned capsule coffee machine incorporating repairability improvements.
	S2.7	Application of the method to the redesigned product.
STAGE 3		
Assessment and visualisation of repairability through graph-based modelling.	S3.1	Node modelling and visualisation.
	S3.2	Edge modelling and visualisation.
	S3.3	Graph visual structuring using layout algorithms.
	S3.4	Application of analytical tools for repairability assessment.
	S3.5	Review and interpretation of existing graph-based metrics.
	S3.6	Development of a graph-based repairability metric.
	S3.7	Application of the graph-based model to a case study of capsule coffee machine.
	S3.8	Development of graph-based visualisation tools to support designers in analysing product repairability.
STAGE 4		
Life cycle assessment (LCA) and life cycle cost (LCC) analysis of repair and replacement scenarios of capsule coffee machines.	S4.1	Data collection on repair for priority parts: failure rate, failure age and success repair rate.
	S4.2	Scenario definition: category product lifespan, Life Extension and Priority part lifespan.
	S4.3	Goal, system boundaries and functional unit.
	S4.4	Life Cycle Inventory.
	S4.5	Life Cycle Impact Assessment: Environmental impact assessment and economic impact assessment of repair and replacement scenarios.

STAGE 5

Design and validation of consumer information tools.	S5.1	Identification of relevant information for consumer decision-making (repair index, environmental impact and economic performance).
	S5.2	Exploration of integration possibilities within the European energy label framework.
	S5.3	Development of visual formats for presenting repairability, environmental and economic information.

1.6 STRUCTURE OF THE THESIS

The thesis is organised into five chapters covering the introduction, the compendium of publications, the presentation and discussion of results, the general conclusions and the references. The structure of the thesis is presented in Table 1.5, which summarises the relationship between the methodological stages, the research objectives, the research questions, and the publications included in the compendium of publications. It also highlights the connection between the methodological stages and the dissemination outputs generated throughout the research process.

TABLE 1.5 STRUCTURE OF THE THESIS.

RESEARCH QUESTION 1	OBJECTIVE 1 AND 6	STAGE 1	PUBLICATIONS
What are the limitations and advantages of current methods for evaluating the repairability of electrical and electronic equipment?	O1. To identify and critically analyse existing methods for evaluating the repairability of electrical and electronic equipment. O6. To maximise the impact of the research by disseminating results to both academic and practical contexts.	Critical review of existing repairability evaluation methods.	All articles *Conference I*
RESEARCH QUESTION 2	**OBJECTIVE 2 AND 6**	**STAGE 2**	**PUBLICATIONS**
How can EN 45554 be adapted to build a reliable assessment framework for evaluating the repairability of small electrical and electronic equipment?	O2. To design and validate an assessment framework, based on EN 45554 criteria. O6. To maximise the impact of the research by disseminating results to both academic and practical contexts.	Design and validation of an assessment framework based on EN 45554.	Article I *Conference IV*
RESEARCH QUESTION 3	**OBJECTIVE 3 AND 6**	**STAGE 3**	**PUBLICATIONS**
In what way can a graph-based model represent and quantify the repairability of products?	O3. To propose and implement a repairability assessment approach based on graph theory, capable of assessing and visualising product repairability. O6. To maximise the impact of the research by disseminating results to both academic and practical contexts.	Assessment and visualisation of repairability through graph-based modelling.	Article I Article II *Conference III*

RESEARCH QUESTION 4	OBJECTIVE 4 AND 6	STAGE 4	PUBLICATIONS
What environmental and economic benefits arise from prioritising component repair over replacement in small electrical and electronic equipment?	O4. To evaluate the environmental and economic benefits of prioritising repair over replacement adaptable to different categories of small electrical and electronic equipment (sEEE). O6. To maximise the impact of the research by disseminating results to both academic and practical contexts.	Life cycle assessment (LCA) and life cycle cost (LCC) analysis of repair and replacement of Capsule coffee machines.	Article I Article III *Conference V*

RESEARCH QUESTION 5	OBJECTIVE 5 AND 6	STAGE 5	PUBLICATIONS
How does the joint presentation of repairability, environmental impact, and repair cost indicators influence a consumer's decision to buy or repair products?	O5. To design tools for analysing and visualising repairability that effectively inform the consumer and support informed decision-making. O6. To maximise the impact of the research by disseminating results to both academic and practical contexts.	Design and validation of consumer information tools.	Article I Article II Article III *Conference II* *Conference V*

ARTICLE I: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, M. D. (2024). Repair index of energy-related products: Application to capsule coffee machines. Sustainable Production and Consumption, 46, 146–160. https://doi.org/10.1016/j.spc.2024.02.011.

ARTICLE II: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, M. D. (2025). Supporting repairability analysis through graph-based visualisation. Journal of Cleaner Production (*under review since 2025 July*).

ARTICLE III: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, M. D. (2025). Right to repair in practice: Environmental and economic performance of coffee machine repairs. Sustainable Production and Consumption, 57, 226-245. https://doi.org/10.1016/J.SPC.2025.05.011.

This is further supported by additional publications indexed in SJR-ranked journals:

CONFERENCE I: Blanco-Espeleta, E., Bovea, D. M., & Pérez-Belis, V. (2023). Design of a capsule coffee machine integrating principles of reparability. Proceedings from the International Congress on Project Management and Engineering, 588–597. https://doi.org/10.61547/3387.

CONFERENCE II: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, D. M. (2024). Product repair databases. Adaptation of data collection format for repairability assessment. Proceedings from the International Congress on Project Management and Engineering, 743–752. https://doi.org/10.61547/2403011

CONFERENCE III: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, D. M. (2025). Exploring the relationship between product representation through graphs and repairability. Proceedings from the International Congress on Project Management and Engineering (*forthcoming*).

Additional related contributions:

CONFERENCE IV: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, M. D. (2023). How does the design of a product influence the improvement of its end of life? Proceedings of the X Simposio Iberoamericano de Ingeniería de Residuos, 290–297. ISBN: 978-84-09-53123-3.

CONFERENCE V: Blanco-Espeleta, E., Pérez-Belis, V., & Bovea, M. D. (2024). Information for repair decision: consumer implications from environmental and economic perspectives. 1st International Conference on Socio-Environmental Footprints (ICSEF 2024), June.

2 COMPENDIUM OF PUBLICATIONS

Article I

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

Eduardo Blanco-Espeleta, Victoria Pérez-Belis, María D. Bovea,
Sustainable Production and Consumption,
Volume 46,
Pages 146-160,
Year 2024,
ISSN 2352-5509,
https://doi.org/10.1016/j.spc.2024.02.011.

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).

KEYWORDS

Repairability, Circular Economy, ErP, Design for Repair, DfR; Repair Matrix, EN 45554

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., 2022).

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 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 smartphones and slate tablets (Spiliotopoulos et al., 2022); 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 repairability index for electrical and electronic devices in 2021 (MCA, 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 repairability 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 I.1 shows that 36% focused on the comparison of methods, 65% on the calculation of the repairability 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 I.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., 2017; 2019), to torches (Flipsen et al., 2016), and to vacuum cleaners (Bracquene 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., 2021a). RSS was applied to washing machines (Bracquené et al., 2021), to gas cooktops (Rodríguez and Favi, 2022), and to mobile phones and slate tablets (Spiliotopoulos et al., 2022). 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.

TABLE I.1 LITERATURE REVIEW.

	Goal					Method								Case study											
						Repair index						Disassembly time													
Reference	Comparison of methods	Calculation of repairability 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)	●	●			●			●			●			●											
(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)			●				●													●					
(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 (O).

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 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, 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 Figure I.1. The practical 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, ..., 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., 2022). 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, ... , 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:
  - 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.

$$S_{1,i} = 1 - \left(\frac{D_i - 1}{Dref_i - 1}\right) \; with \; S_{1,i} = 0 \; for \; D_i > Dref_i \quad \text{[Eq. 1]}$$

$$S_{j,i} = Sc \cdot Wp_j \cdot Wpp_i \;\; for \; 9 \geq j > 1 \quad \text{[Eq. 2]}$$

$$S_{j,i} = Sc \cdot Wp_j \;\; for \; j \geq 10 \quad \text{[Eq. 3]}$$

  - 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 ($S_{j,i}$) for all the priority parts (i), following Eq. 4.

$$S_j = \sum_{i=1}^{n} S_{j,i} \;\; with \; S_j = S_{j,i} \; for \; j \geq 10 \quad \text{[Eq. 4]}$$

  - 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 ($S_{j,i}$) for the priority part (i), following Eq. 5.

$$S_i = \sum_{j=1}^{n} S_{j,i} \quad \text{[Eq. 5]}$$

- 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.

$$RI = \sum_{j=1}^{n} S_j \ \textbf{or} \ RI = \sum_{i=1}^{n} S_i \qquad \text{[Eq. 6]}$$

$$RI_i = \sum_{j=1}^{9} \left(S_{j,i} \cdot Wp_j\right) + \sum_{j=10}^{14} S_{j,i} \qquad \text{[Eq. 7]}$$

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.

		p_j	Wp_j		Sc	i_1	...	i_n	S_j
					Wpp_i	Wpp_1	....	Wpp_n	
Product design	#1	Disassembly sequence depth	Wp_1	Disassembly depth for the part i (Di)		$S_{1,1}$	...	$S_{1,n}$	S_1
				Disassembly reference depth for the part i ((Dref)					
	#2	Fastener 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	

FIGURE I.1 REPAIR MATRIX (RM).

In order to apply the RM reported in Figure I.1 to any product category, the parameters (p_j) and their weighting factors (Wp_i), 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., 2022).

4 RESULTS

This section shows the adaptation and the application of the RM proposed in Section 3 and Figure I.2, to the case study of the product category "capsule coffee machines", following the steps described in Figure I.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.

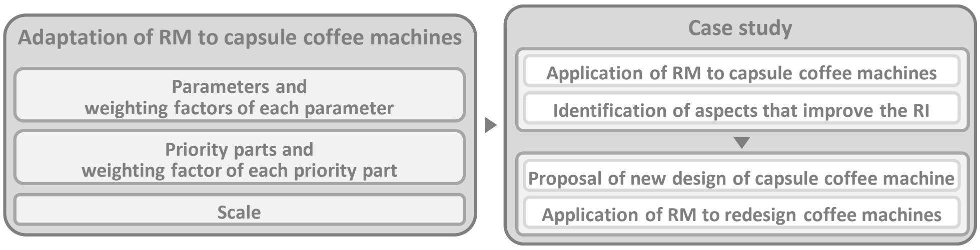

FIGURE I.2 RESULTS.

4.1 ADAPTATION OF RM TO CAPSULE COFFEE MACHINES

This section adapts the RM shown in Figure I.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 I.2 shows alternative sources of information that can be applied, the one applied in this case study being marked (●) in the last column.

TABLE I.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	p_j	Repair centres	●
factor of each parameter	Wp_j	Reuse organisations	
		Consumer organisations	
Priority parts and the weighting	pp_i	Regulation	
factor of each priority part	Wpp_i	Manufacturers of the product	
		Repair centres	●
		Reuse organisations	
		Consumer organisations	
		Repair database	●
Scale	Sc	Literature	●
		Consumer organisations	

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 parameters. To gather this data, telephone interviews with Spanish repair centres were conducted, as reported in Table I.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 Figure I.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 I.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.

TABLE I.3 AVERAGE WEIGHTING FACTOR OF THE PARAMETERS.

		Weighting factor (Wp_j)	
Parameter (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%	

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 I.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.

The results obtained from each source were grouped and are graphically represented on the left of Figure I.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 Figure I.3.

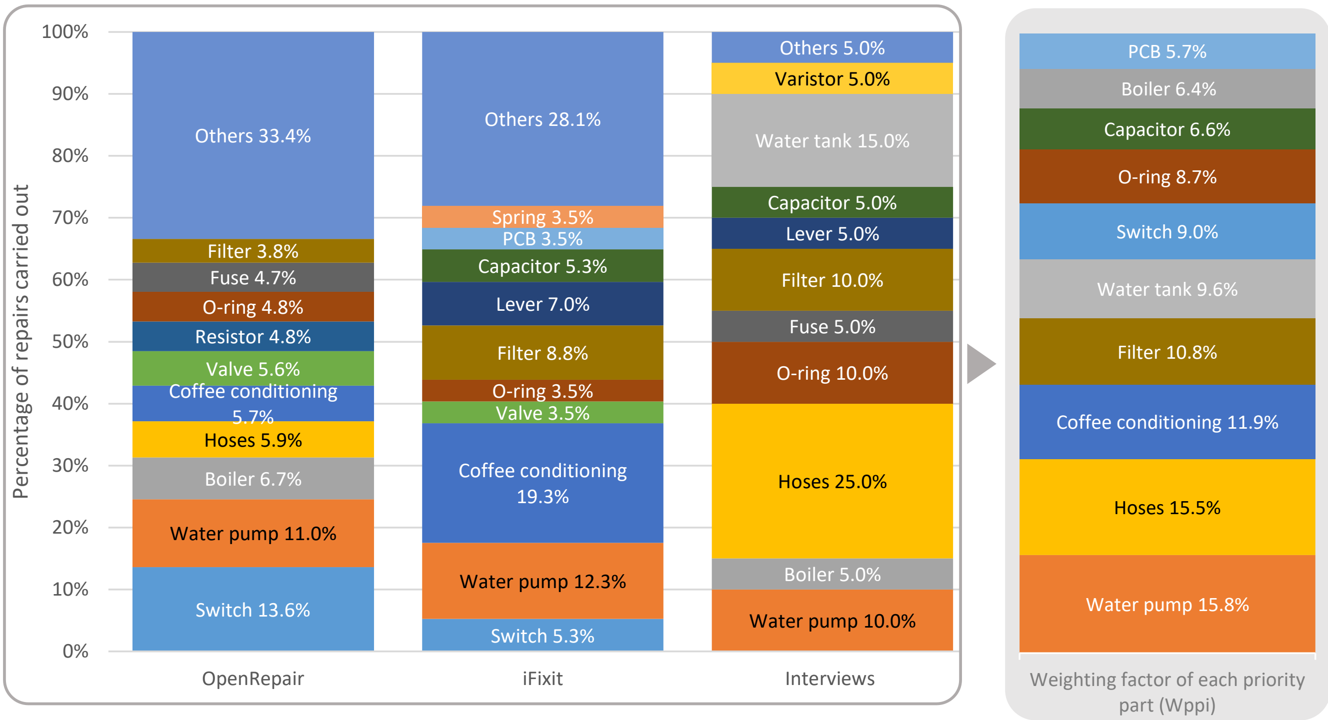

FIGURE I.3 PERCENTAGE OF REPAIRS CARRIED OUT RECORDED BY OPENREPAIR DATABASE, IFIXIT, AND REPAIR CENTRE INTERVIEWS. WEIGHTING FACTOR OF EACH PRIORITY PART (Wpp_i).

It is observed in Figure I.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 Figure I.1). The literature review was selected as the information source, as shown in Table I.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 Sections 4.1.1 (p_j and Wp_j-average), 4.1.2 (pp_i and Wpp_i) and 4.1.3 (Sc) for the case study of capsule coffee machines was included in the general proposed matrix reported in Figure I.1 (see Figure I.4).

		p_j	Wp_j		Sc \ Wpp_i	Water pump 15.8%	Hoses 15.5%	Coffee conditioning 11.9%	Filter 10.8%	Water tank 9.6%	Switch 9.0%	O-ring 8.7%	Capacitor 6.6%	Boiler 6.4%	PCB 5.7%	S_j
Product design	#1	Disassembly sequence depth	11.2%	Disassembly depth for the part i (Di)		$S_{1,1}$	$S_{1,2}$	$S_{1,3}$	$S_{1,4}$	$S_{1,5}$	$S_{1,6}$	$S_{1,7}$	$S_{1,8}$	$S_{1,9}$	$S_{1,10}$	S_1
				Disassembly reference depth for the part i ((Dref)												
	#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}	

FIGURE I.4 RM ADAPTED TO CAPSULE COFFEE MACHINES.

The RM in Figure I.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 Figure I.4 was applied to four representative capsule coffee machines models currently available on the market (Figure I.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.


C1


C2


C3


C4

FIGURE I.5 SELECTED MARKET CAPSULE COFFEE MACHINES.

The RM (Figure I.4) was applied to C1, C2, C3, and C4 capsule coffee machines and the results are available in the Supplementary Material file (Table SI.1, Table SI.2, Table SI.3 and Table SI.4 respectively). Table I.4 shows the RI and RIi for each appliance.

TABLE I.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

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 I.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 I.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 Figure I.6 shows. Proper organisation of parts increases the ease of disassembly and consequently reduces the disassembly depth of each part.

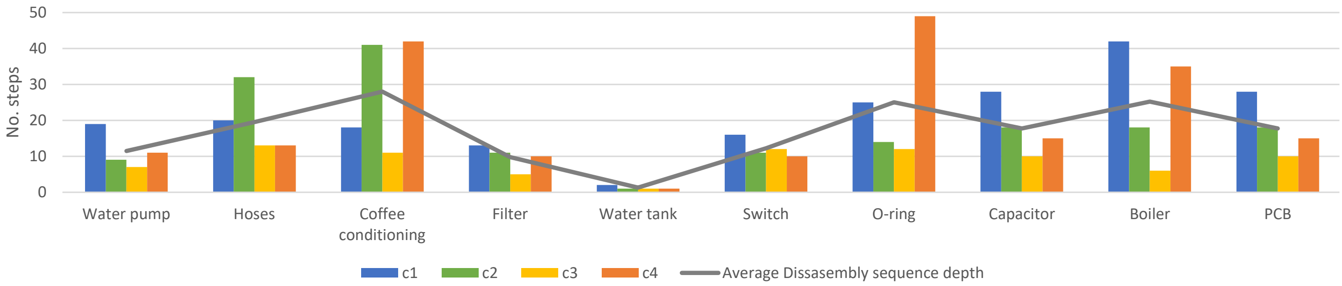

FIGURE I.6 DISASSEMBLY SEQUENCE DEPTH.

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

TABLE I.5 FASTENER TYPE AND SKILL ABILITY IN THE CASE STUDY OF 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										

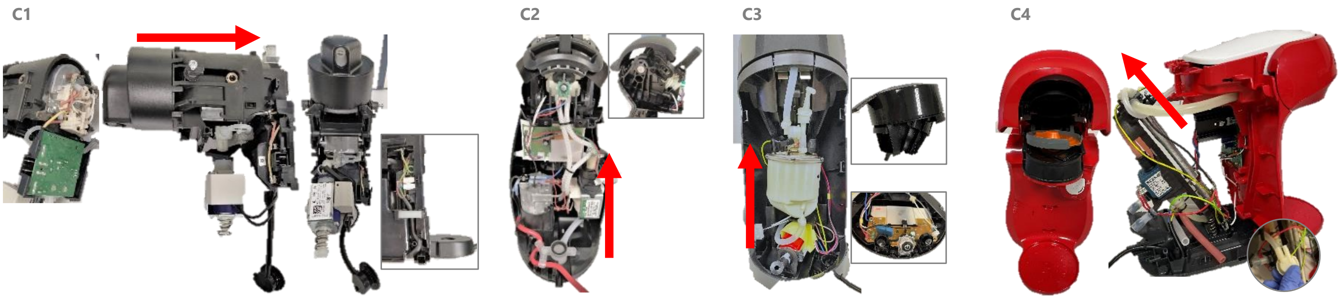

FIGURE I.7 INTERNAL ARCHITECTURE.

- 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 EN 45554 (2020) 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. 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 only 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 Figure I.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.

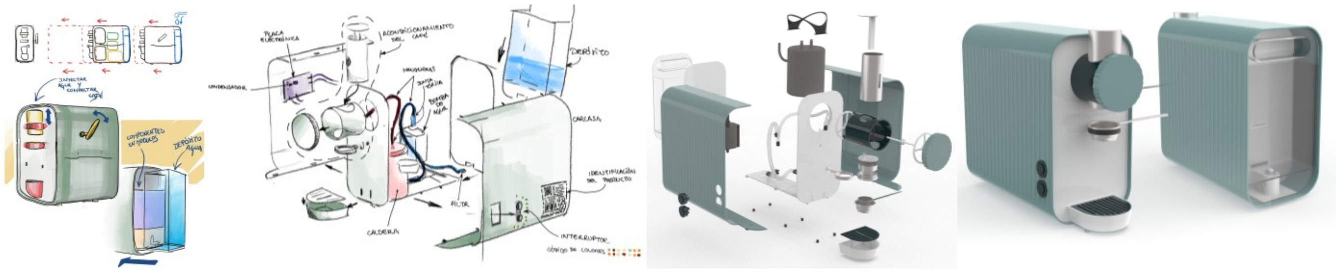

FIGURE I.8 DESIGN PROCESS OF CAPSULE COFFEE MACHINE (C5) IMPROVING ITS RI.

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 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 (Figure I.4) was applied to the new design for a capsule coffee machine (C5) described in Figure I.8. The RI obtained for C5 was 8.83, as shown in Figure I.9 (in light blue) and Table SI.5 in the Supplementary Material file (Table SI.5). The pictograms and the scale from A to D (A ≥ 7.5; 7.5 > B ≥ 5.0; 5.0 > C ≥ 2.5; D > 2.5) used in Figure I.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 RI_i 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 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.

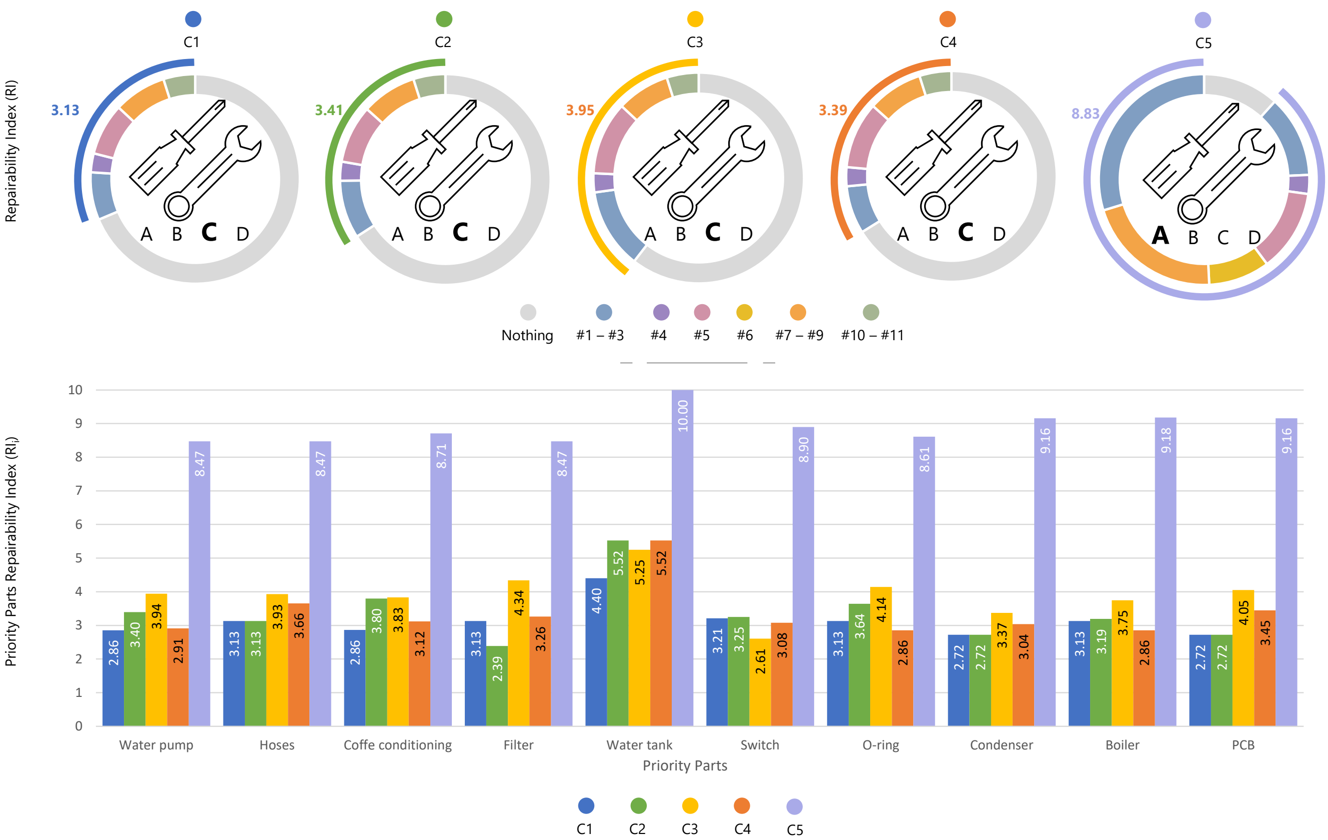

FIGURE I.9 REPAIR INDEX (RI) AND PRIORITY PART REPAIR INDEX (RI_i).

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 I.6. The present proposal fulfils the recommendation by BEUC (2022), which suggests incorporating criteria related to the price of spare parts.

TABLE I.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

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 seconds, whereas for C2 it stands at 521 seconds. 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 I.7.

TABLE I.7 SCORE MATRIX TO ASSESS DISASSEMBLY TIME.

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

In order to assess the impact of incorporating the improvements regarding the cost of the spare parts and disassembly depth, as illustrated in Table I.6 and Table I.7, these parameters were incorporated into the RM, creating the reformulated Repair Matrix (rRM), as shown in Figure I.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 SI.6 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.

		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}	

FIGURE I.10 REFORMULATED REPAIR MATRIX (RRM) FOR CAPSULE COFFEE MACHINES.

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 Table SI.7, Table SI.8, Table SI.9 and Table SI.11 of the Supplementary Material, while the comparison between RI and rRI are reported in Table I.8. The results show that, for each capsule coffee machine, the rRI has slightly decreased compared to the RI, although the order is maintained (from highest to lowest RI or rRI).

TABLE I.8 RI AND RRI FOR THE CASE STUDY.

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

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 I.3. The results in Section 4 and Section 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 I.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 SI.13 of the Supplementary Material.

TABLE I.9 SENSITIVITY ANALYSIS.

Repair Index	Wp_j (Table I.3)	C1	C2	C3	C4	C5	Order (High RI > Low RI)
RI (Figure I.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 (Figure I.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

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 I.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 I.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 Table SI.14, Table SI.15, Table SI.17 and Table SI.18 of the Supplementary Material. As can be observed, AsMeR method exhibits higher values compared to RI and rRI (Table I.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.

TABLE I.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

6 CONCLUSION

This paper provides a matrix (RM) that simplifies and facilitates the application of the UNE 45554 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 (ppi), weighting factor of each priority part, and scale (Sc), need to be identified using the information sources suggested in Table I.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 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.

7 ACKNOWLEDGEMENTS

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9 SUPPLEMENTARY MATERIAL

TABLE SI.1 RM OF C1.

		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	11.20%	Disassembly depth for the part i (Di)		19	20	18	13	2	16	25	28	42	28	0.05
				Disassembly reference depth for the part i ((Dref)		12	20	28	10	1	12	25	18	25	18	
						0.0	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	#2	Fasteners type	5.45%	Reusable	10											
				Removable	5	5.00	10.00	5.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.47
				Not removable and and not reusable	0											
	#3	Tools needed	3.96%	Toolless	10											
				Common general purpose	7.5											
				Professional product group specific tools	5	5.00	5.00	5.00	5.00	10.00	5.00	5.00	5.00	5.00	5.00	0.22
				Propietary tools	2.5											
				Not viable with any existing tool	0											
	#4	Working environment	2.91%	Home / no requirements	10											
				Specialised workshop	5	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.29
				Production environment	0											
	#5	Skill level	16.28%	Apprentice	10											
				Generalist	7.5											
				Professional	5	5.00	5.00	2.50	5.00	10.00	5.50	5.00	2.50	5.00	2.50	0.80
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support	#6	Diagnostic support and interfaces	9.41%	Visually intuitive interface	10											
				Coded interface with public reference table	7.5											
				Publicly available hardware / software interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Proprietary interface	2.5											
				Not viable with any type of interface	0											
Spare Parts	#7	Spare parts availability	10.53%	Publicly available	10											
				Available to independent suppliers	7.5											
				Available to suppliers	5	7.50	7.50	7.50	7.50	10.00	7.50	7.50	7.50	7.50	7.50	0.82
				Available for manufacturer	2.5											
				Spare part not available	0											
	#8	Spare parts interface	0.00%	Standard part with standard interface	10											
				Exclusive part with standard interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Exclusive part with non-standard interface	0											
	#9	Spare parts availability duration	10.53%	Long-term availability	10											
				Mid-term availability	6.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Short-term availability	3.3											
				No information on duration of availability	0											
Information	#10	Information type	14.86%	Comprehensive information available	10											
				Basic information available	5					0						0.00
				No information available	0											
	#11	Information availability	14.86%	Publicly available	10											
				Available to independent suppliers	6.6					3.3						0.49
				Available to suppliers	3.3											
				Available for manufacturer	0											
	#12	Return optios	0.00%	Exhaustive return options	10											
				Basic return options	5					0						0
				No return option	0											
	#13	Data management	0.00%	Integrated data not stored	10											
				Under request	5					0						0.00
				Not available	0											
	#14	Restart type	0.00%	Integrated restart	10											
				External restart	6.6					0						0.00
				Service restart	3.3											
				No restart	0											
																RI
					S_i	0.45	0.48	0.34	0.34	0.42	0.29	0.27	0.18	0.20	0.16	3.13
					RI_i	2.86	3.13	2.86	3.13	4.40	3.21	3.13	2.72	3.13	2.72	

TABLE SI.2 RM OF C2.

		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				Disassembly depth for the part i (Di)		9	32	41	11	1	11	14	18	18	18	
	#1	Disassembly sequence depth	11.20%	Disassembly reference depth for the part i ((Dref)		12	20	28	10	1	12	25	18	25	18	0.23
						2.4	0.0	0.0	0.0	10.0	1.1	4.6	0.0	3.0	0.0	
				Reusable	10											
	#2	Fasteners type	5.45%	Removable	5	10.00	10.00	10.00	0.00	10.00	10.00	10.00	10.00	5.00	10.00	0.47
				Not removable and and not reusable	0											
				Toolless	10											
				Common general purpose	7.5											
	#3	Tools needed	3.96%	Professional product group specific tools	5	5.00	5.00	5.00	0.00	10.00	5.00	5.00	5.00	5.00	5.00	0.20
				Propietary tools	2.5											
				Not viable with any existing tool	0											
				Home / no requirements	10											
	#4	Working environment	2.91%	Specialised workshop	5	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.29
				Production environment	0											
				Apprentice	10											
				Generalist	7.5											
	#5	Skill level	16.28%	Professional	5	5.00	5.00	7.50	5.00	10.00	5.00	5.00	2.50	5.00	2.50	0.89
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support				Visually intuitive interface	10											
				Coded interface with public reference table	7.5											
	#6	Diagnostic support and interfaces	9.41%	Publicly available hardware / software interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Proprietary interface	2.5											
				Not viable with any type of interface	0											
Spare Parts				Publicly available	10											
				Available to independent suppliers	7.5											
	#7	Spare parts availability	10.53%	Available to suppliers	5	7.50	7.50	10.00	7.50	10.00	7.50	7.50	7.50	7.50	7.50	0.85
				Available for manufacturer	2.5											
				Spare part not available	0											
				Standard part with standard interface	10											
	#8	Spare parts interface	0.00%	Exclusive part with standard interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Exclusive part with non-standard interface	0											
				Long-term availability	10											
	#9	Spare parts availability duration	10.53%	Mid-term availability	6.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Short-term availability	3.3											
				No information on duration of availability	0											
Information				Comprehensive information available	10											
	#10	Information type	14.86%	Basic information available	5	0										0.00
				No information available	0											
				Publicly available	10											
	#11	Information availability	14.86%	Available to independent suppliers	6.6	3.3										0.49
				Available to suppliers	3.3											
				Available for manufacturer	0											
				Exhaustive return options	10											
	#12	Return optios	0.00%	Basic return options	5	0										0
				No return option	0											
				Integrated data not stored	10											
	#13	Data management	0.00%	Under request	5	0										0.00
				Not available	0											
				Integrated restart	10											
	#14	Restart type	0.00%	External restart	6.6	0										0.00
				Service restart	3.3											
				No restart	0											
																RI
					S_i	0.54	0.48	0.45	0.26	0.53	0.29	0.32	0.18	0.20	0.16	3.41
					RI_i	3.40	3.13	3.80	2.39	5.52	3.25	3.64	2.72	3.19	2.72	

TABLE SI.3 RM OF C3.

		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 sequience depth	11.20%	Disassembly depth for the part i (Di)		7	13	11	5	1	12	12	10	6	10	0.57
				Disassembly reference depth for the part i ((Dref)		12	20	28	10	1	12	25	18	25	18	
						4.3	3.5	6.3	5.4	10.0	0.2	5.4	4.6	7.9	4.6	
	#2	Fasteners type	5.45%	Reusable	10											
				Removable	5	5.00	10.00	10.00	10.00	5.00	0.00	10.00	5.00	5.00	10.00	0.39
				Not removable and and not reusable	0											
	#3	Tools needed	3.96%	Toolless	10											
				Common general purpose	7.5											
				Professional product group specific tools	5	10.00	5.00	5.00	10.00	10.00	5.00	5.00	5.00	5.00	5.00	0.27
				Propietary tools	2.5											
				Not viable with any existing tool	0											
	#4	Working environment	2.91%	Home / no requirements	10											
				Specialised workshop	5	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.29
				Production environment	0											
	#5	Skill level	16.28%	Apprentice	10											
				Generalist	7.5											
				Professional	5	7.50	7.50	5.00	7.50	10.00	5.00	7.50	5.00	5.00	7.50	1.12
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support	#6	Diagnostic support and interfaces	9.41%	Visually intuitive interface	10											
				Coded interface with public reference table	7.5											
				Publicly available hardware / software interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Proprietary interface	2.5											
				Not viable with any type of interface	0											
Spare Parts	#7	Spare parts availability	10.53%	Publicly available	10											
				Available to independent suppliers	7.5											
				Available to suppliers	5	7.50	7.50	7.50	7.50	10.00	7.50	7.50	7.50	7.50	7.50	0.82
				Available for manufacturer	2.5											
				Spare part not available	0											
	#8	Spare parts interface	0.00%	Standard part with standard interface	10											
				Exclusive part with standard interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Exclusive part with non-standard interface	0											
	#9	Spare parts availability duration	10.53%	Long-term availability	10											
				Mid-term availability	6.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Short-term availability	3.3											
				No information on duration of availability	0											
Information	#10	Information type	14.86%	Comprehensive information available	10											
				Basic information available	5	0										0.00
				No information available	0											
	#11	Information availability	14.86%	Publicly available	10											
				Available to independent suppliers	6.6	3.3										0.49
				Available to suppliers	3.3											
				Available for manufacturer	0											
	#12	Return optios	0.00%	Exhaustive return options	10											
				Basic return options	5	0										0
				No return option	0											
	#13	Data management	0.00%	Integrated data not stored	10											
				Under request	5	0										0.00
				Not available	0											
	#14	Restart type	0.00%	Integrated restart	10											
				External restart	6.6	0										0.00
				Service restart	3.3											
				No restart	0											
																RI
					S_i	0.62	0.61	0.46	0.47	0.50	0.23	0.36	0.22	0.24	0.23	3.95
					RI_i	3.94	3.93	3.83	4.34	5.25	2.61	4.14	3.37	3.75	4.05	

TABLE SI.4 RM OF C4.

		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				Disassembly depth for the part i (Di)		11	13	42	10	1	10	49	15	35	15	
	#1	Disassembly sequence depth	11.20%	Disassembly reference depth for the part i ((Dref)		12	20	28	10	1	12	25	18	25	18	0.22
						0.5	3.5	0.0	0.0	10.0	2.0	0.0	1.6	0.0	1.6	
				Reusable	10											
	#2	Fasteners type	5.45%	Removable	5	5.00	5.00	5.00	5.00	10.00	5.00	5.00	5.00	5.00	5.00	0.30
				Not removable and and not reusable	0											
				Toolless	10											
				Common general purpose	7.5											
	#3	Tools needed	3.96%	Professional product group specific tools	5	5.00	5.00	5.00	5.00	10.00	5.00	5.00	5.00	5.00	5.00	0.22
				Propietary tools	2.5											
				Not viable with any existing tool	0											
				Home / no requirements	10											
	#4	Working environment	2.91%	Specialised workshop	5	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.29
				Production environment	0											
				Apprentice	10											
				Generalist	7.5											
	#5	Skill level	16.28%	Professional	5	5.00	7.50	5.00	7.50	10.00	5.00	5.00	5.00	5.00	7.50	1.02
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support				Visually intuitive interface	10											
				Coded interface with public reference table	7.5											
	#6	Diagnostic support and interfaces	9.41%	Publicly available hardware / software interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Proprietary interface	2.5											
				Not viable with any type of interface	0											
Spare Parts				Publicly available	10											
				Available to independent suppliers	7.5											
	#7	Spare parts availability	10.53%	Available to suppliers	5	7.50	7.50	10.00	7.50	10.00	7.50	7.50	7.50	7.50	7.50	0.85
				Available for manufacturer	2.5											
				Spare part not available	0											
				Standard part with standard interface	10											
	#8	Spare parts interface	0.00%	Exclusive part with standard interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Exclusive part with non-standard interface	0											
				Long-term availability	10											
	#9	Spare parts availability duration	10.53%	Mid-term availability	6.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Short-term availability	3.3											
				No information on duration of availability	0											
Information				Comprehensive information available	10											
	#10	Information type	14.86%	Basic information available	5					0						0.00
				No information available	0											
				Publicly available	10											
	#11	Information availability	14.86%	Available to independent suppliers	6.6					3.3						0.49
				Available to suppliers	3.3											
				Available for manufacturer	0											
				Exhaustive return options	10											
	#12	Return optios	0.00%	Basic return options	5					0						0
				No return option	0											
				Integrated data not stored	10											
	#13	Data management	0.00%	Under request	5					0						0.00
				Not available	0											
				Integrated restart	10											
				External restart	6.6											
	#14	Restart type	0.00%	Service restart	3.3					0						0.00
				No restart	0											
																RI
					S_i	0.46	0.57	0.37	0.35	0.53	0.28	0.25	0.20	0.18	0.20	3.39
					RI_i	2.91	3.66	3.12	3.26	5.52	3.08	2.86	3.04	2.86	3.45	

TABLE SI.5 RM OF C5.

		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 sequience depth	11.20%	Disassembly depth for the part i (Di)		18	22	20	12	1	7	22	6	10	6	0.35
				Disassembly reference depth for the part i ((Dref)		12	20	28	10	1	12	25	18	25	18	
						0.0	0.0	3.0	0.0	10.0	4.7	1.3	7.0	6.3	7.0	
	#2	Fasteners type	5.45%	Reusable	10	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.55
				Removable	5											
				Not removable and and not reusable	0											
	#3	Tools needed	3.96%	Toolless	10	10.00	10.00	7.50	10.00	10.00	7.50	10.00	7.50	10.00	7.50	0.36
				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	2.91%	Home / no requirements	10	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.29
				Specialised workshop	5											
				Production environment	0											
	#5	Skill level	16.28%	Apprentice	10	7.50	7.50	7.50	7.50	10.00	7.50	7.50	7.50	7.50	7.50	1.26
				Generalist	7.5											
				Professional	5											
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support	#6	Diagnostic support and interfaces	9.41%	Visually intuitive interface	10	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.94
				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	10.53%	Publicly available	10	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	1.05
				Available to independent suppliers	7.5											
				Available to suppliers	5											
				Available for manufacturer	2.5											
				Spare part not available	0											
	#8	Spare parts interface	0.00%	Standard part with standard interface	10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Exclusive part with standard interface	5											
				Exclusive part with non-standard interface	0											
	#9	Spare parts availability duration	10.53%	Long-term availability	10	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	1.05
				Mid-term availability	6.6											
				Short-term availability	3.3											
				No information on duration of availability	0											
Information	#10	Information type	14.86%	Comprehensive information available	10	10										1.49
				Basic information available	5											
				No information available	0											
	#11	Information availability	14.86%	Publicly available	10	10										1.49
				Available to independent suppliers	6.6											
				Available to suppliers	3.3											
				Available for manufacturer	0											
	#12	Return optios	0.00%	Exhaustive return options	10	0										0
				Basic return options	5											
				No return option	0											
	#13	Data management	0.00%	Integrated data not stored	10	0										0.00
				Under request	5											
				Not available	0											
	#14	Restart type	0.00%	Integrated restart	10	0										0.00
				External restart	6.6											
				Service restart	3.3											
				No restart	0											
					S_i	1.34	1.31	1.04	0.92	0.96	0.80	0.75	0.60	0.59	0.52	**RI** 8.83
					RI_i	8.47	8.47	8.71	8.47	10.00	8.90	8.61	9.16	9.18	9.16	

TABLE SI.6 SPARE PARTS COST AND THE AVERAGE CONSUMER PRICE OF PART i.

	Catalogue price	Water pump	Hoses	Coffee conditioning	Filter	Water tank	Switch	O-ring	Capacitor	Boiler	PCB
C1	100,90 €					8,00 € 8%					
C2	89,00 €			5,00 € 6%		5,70 € 6%					
C3	70,99 €			9,99 € 14%		13,99 € 20%					
C4	109,99	29,44 € 27%	5,35 € 5%	69,13 € 63%	10,36 € 9%	22,40 € 20%	6,70 € 6%			73,89 € 67%	43,85 € 40%

TABLE SI.7 rRM OF C1.

		p_j	Wp_j		Sc	Water pump	Hoses	Coffee conditioning	Filter	Water tank	Switch	O-ring	Capacitor	Boiler	PCB	S_j
					Wpp_i	15.8%	15.5%	11.9%	10.8%	9.6%	9.0%	8.7%	6.6%	6.4%	5.7%	
Product design	#1	Disassembly sequience depth	10.5%	Disassembly Time for the part i (Di)		420.60	402.00	396.60	319.64	13.60	374.56	427.84	516.12	647.16	516.12	0.01
				Disassembly Time for the part i (Dref)		289.21	375.92	434.25	217.08	9.10	291.72	366.94	390.47	397.31	390.47	
						0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	#2	Fastener type	5.1%	Reusable	10											
				Removable	5	5.00	10.00	5.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.44
				Not removable and and not reusable	0											
	#3	Tools needed	3.7%	Toolless	10											
				Common general purpose	7.5											
				Professional product group specific tools	5	5.00	5.00	5.00	5.00	10.00	5.00	5.00	5.00	5.00	5.00	0.20
				Propietary tools	2.5											
				Not viable with any existing tool	0											
	#4	Working environment	2.7%	Home / no requirements	10											
				Specialised workshop	5	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.27
				Production environment	0											
	#5	Skill level	15.2%	Apprentice	10											
				Generalist	7.5											
				Professional	5	5.00	5.00	2.50	5.00	10.00	5.50	5.00	2.50	5.00	2.50	0.75
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support	#6	Diagnostic support and interfaces	8.8%	Visually intuitive interface	10											
				Coded interface with public reference table	7.5											
				Publicly available hardware / software interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Proprietary interface	2.5											
				Not viable with any type of interface	0											
Spare Parts	#7	Spare parts availability	9.8%	Publicly available	10											
				Available to independent suppliers	7.5											
				Available to suppliers	5	7.50	7.50	7.50	7.50	10.00	7.50	7.50	7.50	7.50	7.50	0.76
				Available for manufacturer	2.5											
				Spare part not available	0											
	#8	Spare parts interface	0.0%	Standard part with standard interface	10											
				Exclusive part with standard interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Exclusive part with non-standard interface	0											
	#9	Spare parts availability duration	9.8%	Long-term availability	10											
				Mid-term availability	6.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				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											
				Average consumer price of pat i is between 5% and 10% of catalogue price (10% included)	6.6	0.00	0.00	0.00	0.00	6.60	0.00	0.00	0.00	0.00	0.00	0.04
				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	#10	Information type	13.9%	Comprehensive information available	10											
				Basic information available	5						0					0.00
				No information available	0											
	#11	Information availability	13.9%	Publicly available	10											
				Available to independent suppliers	6.6						3.3					0.46
				Available to suppliers	3.3											
				Available for manufacturer	0											
	#12	Return optios	0.0%	Exhaustive return options	10											
				Basic return options	5						0					0
				No return option	0											
	#13	Data management	0.0%	Integrated data not stored	10											
				Under request	5						0					0.00
				Not available	0											
	#14	Restart type	0.0%	Integrated restart	10											
				External restart	6.6						0					0.00
				Service restart	3.3											
				No restart	0											
																RI
					S_i	0.42	0.45	0.28	0.32	0.44	0.27	0.25	0.17	0.19	0.15	2.94
					RI_i	2.67	2.93	2.38	2.93	4.55	3.00	2.93	2.55	2.93	2.55	

TABLE SI.8 rRM OF C2.

		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				Disassembly Time for the part i (Di)		371.44	628.96	683.88	347.28	6.40	354.00	409.84	521.04	471.36	521.04	
	#1	Disassembly sequience depth	10.5%	Disassembly Time for the part i (Dref)		289.21	375.92	434.25	217.08	9.10	291.72	366.94	390.47	397.31	390.47	0.03
						0.0	0.0	0.0	0.0	3.3	0.0	0.0	0.0	0.0	0.0	
				Reusable	10											
	#2	Fasteners type	5.1%	Removable	5	10.00	10.00	10.00	0.00	10.00	10.00	10.00	10.00	5.00	10.00	0.44
				Not removable and and not reusable	0											
				Toolless	10											
				Common general purpose	7.5											
	#3	Tools needed	3.7%	Professional product group specific tools	5	5.00	5.00	5.00	0.00	10.00	5.00	5.00	5.00	5.00	5.00	0.18
				Propietary tools	2.5											
				Not viable with any existing tool	0											
				Home / no requirements	10											
	#4	Working environment	2.7%	Specialised workshop	5	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.27
				Production environment	0											
				Apprentice	10											
				Generalist	7.5											
	#5	Skill level	15.2%	Professional	5	5.00	5.00	7.50	5.00	10.00	5.00	5.00	2.50	5.00	2.50	0.83
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support				Visually intuitive interface	10											
				Coded interface with public reference table	7.5											
	#6	Diagnostic support and interfaces	8.8%	Publicly available hardware / software interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Proprietary interface	2.5											
				Not viable with any type of interface	0											
Spare Parts				Publicly available	10											
				Available to independent suppliers	7.5											
	#7	Spare parts availability	9.8%	Available to suppliers	5	7.50	7.50	10.00	7.50	10.00	7.50	7.50	7.50	7.50	7.50	0.79
				Available for manufacturer	2.5											
				Spare part not available	0											
				Standard part with standard interface	10											
	#8	Spare parts interface	0.0%	Exclusive part with standard interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Exclusive part with non-standard interface	0											
				Long-term availability	10											
	#9	Spare parts availability duration	9.8%	Mid-term availability	6.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Short-term availability	3.3											
				No information on duration of availability	0											
				Average consumer price of part i is less than or equal to 5% of catalogue price	10											
	#10	Spare parts cost	6.5%	Average consumer price of pat i is between 5% and 10% of catalogue price (10% included)	6.6	0.00	0.00	6.60	0.00	6.60	0.00	0.00	0.00	0.00	0.00	0.09
				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				Comprehensive information available	10											
	#10	Information type	13.9%	Basic information available	5					0						0.00
				No information available	0											
				Publicly available	10											
	#11	Information availability	13.9%	Available to independent suppliers	6.6					3.3						0.46
				Available to suppliers	3.3											
				Available for manufacturer	0											
				Exhaustive return options	10											
	#12	Return optios	0.0%	Basic return options	5					0						0
				No return option	0											
				Integrated data not stored	10											
	#13	Data management	0.0%	Under request	5					0						0.00
				Not available	0											
				Integrated restart	10											
	#14	Restart type	0.0%	External restart	6.6					0						0.00
				Service restart	3.3											
				No restart	0											
																RI
					S_i	0.46	0.45	0.47	0.24	0.47	0.26	0.25	0.17	0.17	0.15	3.10
					RI_i	2.93	2.93	3.98	2.23	4.90	2.93	2.93	2.55	2.67	2.55	

TABLE SI.9 rRM OF C3.

	#	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 sequience depth	10.5%	Disassembly Time for the part i (Di)		115.56	198.72	84.00	57.20	6.40	251.72	154.88	218.92	97.56	218.92	
				Disassembly Time for the part i (Dref)		289.21	375.92	434.25	217.08	9.10	291.72	366.94	390.47	397.31	390.47	0.57
						6.0	4.7	8.1	7.4	3.3	1.4	5.8	4.4	7.6	4.4	
	#2	Fasteners type	5.1%	Reusable	10											
				Removable	5	5.00	10.00	10.00	10.00	5.00	0.00	10.00	5.00	5.00	10.00	0.37
				Not removable and and not reusable	0											
	#3	Tools needed	3.7%	Toolless	10											
				Common general purpose	7.5											
				Professional product group specific tools	5	10.00	5.00	5.00	10.00	10.00	5.00	5.00	5.00	5.00	5.00	0.25
				Propietary tools	2.5											
				Not viable with any existing tool	0											
	#4	Working environment	2.7%	Home / no requirements	10											
				Specialised workshop	5	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.27
				Production environment	0											
	#5	Skill level	15.2%	Apprentice	10											
				Generalist	7.5											
				Professional	5	7.50	7.50	5.00	7.50	10.00	5.00	7.50	5.00	5.00	7.50	1.05
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support	#6	Diagnostic support and interfaces	8.8%	Visually intuitive interface	10											
				Coded interface with public reference table	7.5											
				Publicly available hardware / software interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Proprietary interface	2.5											
				Not viable with any type of interface	0											
Spare Parts	#7	Spare parts availability	9.8%	Publicly available	10											
				Available to independent suppliers	7.5											
				Available to suppliers	5	7.50	7.50	7.50	7.50	10.00	7.50	7.50	7.50	7.50	7.50	0.76
				Available for manufacturer	2.5											
				Spare part not available	0											
	#8	Spare parts interface	0.0%	Standard part with standard interface	10											
				Exclusive part with standard interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Exclusive part with non-standard interface	0											
	#9	Spare parts availability duration	9.8%	Long-term availability	10											
				Mid-term availability	6.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				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											
				Average consumer price of pat i is between 5% and 10% of catalogue price (10% included)	6.6	0.00	0.00	3.30	0.00	3.30	0.00	0.00	0.00	0.00	0.00	0.05
				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	#10	Information type	13.9%	Comprehensive information available	10											
				Basic information available	5	0										0.00
				No information available	0											
	#11	Information availability	13.9%	Publicly available	10											
				Available to independent suppliers	6.6	3.3										0.46
				Available to suppliers	3.3											
				Available for manufacturer	0											
	#12	Return optios	0.0%	Exhaustive return options	10											
				Basic return options	5	0										0
				No return option	0											
	#13	Data management	0.0%	Integrated data not stored	10											
				Under request	5	0										0.00
				Not available	0											
	#14	Restart type	0.0%	Integrated restart	10											
				External restart	6.6	0										0.00
				Service restart	3.3											
				No restart	0											
																RI
					S_i	0.61	0.59	0.47	0.46	0.42	0.23	0.34	0.21	0.22	0.21	3.77
					RI_i	3.87	3.80	3.99	4.27	4.43	2.56	3.91	3.13	3.46	3.77	

TABLE SI.10 rRM OF C4.

		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 sequience depth	10.5%	Disassembly Time for the part i (Di)		249.24	273.16	572.52	144.20	10.00	186.60	475.20	305.80	373.16	305.80	0.17
				Disassembly Time for the part i (Dref)		289.21	375.92	434.25	217.08	9.10	291.72	366.94	390.47	397.31	390.47	
						1.4	2.7	0.0	3.4	0.0	3.6	0.0	2.2	0.6	2.2	
	#2	Fasteners type	5.1%	Reusable	10											
				Removable	5	5.00	5.00	5.00	5.00	10.00	5.00	5.00	5.00	5.00	5.00	0.28
				Not removable and and not reusable	0											
	#3	Tools needed	3.7%	Toolless	10											
				Common general purpose	7.5											
				Professional product group specific tools	5	5.00	5.00	5.00	5.00	10.00	5.00	5.00	5.00	5.00	5.00	0.20
				Propietary tools	2.5											
				Not viable with any existing tool	0											
	#4	Working environment	2.7%	Home / no requirements	10											
				Specialised workshop	5	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.27
				Production environment	0											
	#5	Skill level	15.2%	Apprentice	10											
				Generalist	7.5											
				Professional	5	5.00	7.50	5.00	7.50	10.00	5.00	5.00	5.00	5.00	7.50	0.96
				Manufacturer	2.5											
				Not viable with any skill	0											
Manufacturer support	#6	Diagnostic support and interfaces	8.8%	Visually intuitive interface	10											
				Coded interface with public reference table	7.5											
				Publicly available hardware / software interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Proprietary interface	2.5											
				Not viable with any type of interface	0											
Spare Parts	#7	Spare parts availability	9.8%	Publicly available	10											
				Available to independent suppliers	7.5											
				Available to suppliers	5	7.50	7.50	10.00	7.50	10.00	7.50	7.50	7.50	7.50	7.50	0.79
				Available for manufacturer	2.5											
				Spare part not available	0											
	#8	Spare parts interface	0.0%	Standard part with standard interface	10											
				Exclusive part with standard interface	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Exclusive part with non-standard interface	0											
	#9	Spare parts availability duration	9.8%	Long-term availability	10											
				Mid-term availability	6.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				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											
				Average consumer price of pat i is between 5% and 10% of catalogue price (10% included)	6.6	0.00	10.00	0.00	6.60	3.30	3.30	0.00	0.00	0.00	0.00	0.19
				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	#10	Information type	13.9%	Comprehensive information available	10											
				Basic information available	5					0						0.00
				No information available	0											
	#11	Information availability	13.9%	Publicly available	10											
				Available to independent suppliers	6.6					3.3						0.46
				Available to suppliers	3.3											
				Available for manufacturer	0											
	#12	Return optios	0.0%	Exhaustive return options	10											
				Basic return options	5					0						0
				No return option	0											
	#13	Data management	0.0%	Integrated data not stored	10											
				Under request	5					0						0.00
				Not available	0											
	#14	Restart type	0.0%	Integrated restart	10											
				External restart	6.6					0						0.00
				Service restart	3.3											
				No restart	0											
																RI
					S_i	0.44	0.62	0.35	0.41	0.42	0.29	0.23	0.19	0.17	0.19	3.32
					RI_i	2.81	3.99	2.91	3.83	4.33	3.26	2.67	2.90	2.73	3.28	

TABLE SI.11 rRM OF C5.

		p_j	Wp_j		Sc	Water pump	Hoses	Coffee conditioning	Filter	Water tank	Switch	O-ring	Capacitor	Boiler	PCB	S_j
					Wpp_i	15.8%	15.5%	11.9%	10.8%	9.6%	9.0%	8.7%	6.6%	6.4%	5.7%	
Product design	#1	Disassembly sequience depth	10.5%	Disassembly Time for the part i (Di)		152.60	186.20	204.88	117.80	4.60	123.52	186.20	109.00	89.80	109.00	0.58
				Disassembly Time for the part i (Dref)		289.21	375.92	434.25	217.08	9.10	291.72	366.94	390.47	397.31	390.47	
						4.7	5.1	5.3	4.6	5.6	5.8	4.9	7.2	7.8	7.2	
	#2	Fasteners type	5.1%	Reusable	10	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.51
				Removable	5											
				Not removable and and not reusable	0											
	#3	Tools needed	3.7%	Toolless	10	10.00	10.00	7.50	10.00	10.00	7.50	10.00	7.50	10.00	7.50	0.34
				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	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.27
				Specialised workshop	5											
				Production environment	0											
	#5	Skill level	15.2%	Apprentice	10	7.50	7.50	7.50	7.50	10.00	7.50	7.50	7.50	7.50	7.50	1.18
				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	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.88
				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	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.98
				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	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				Exclusive part with standard interface	5											
				Exclusive part with non-standard interface	0											
	#9	Spare parts availability duration	9.8%	Long-term availability	10	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.98
				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	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.65
				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	#10	Information type	13.9%	Comprehensive information available	10	10										1.39
				Basic information available	5											
				No information available	0											
	#11	Information availability	13.9%	Publicly available	10	10										1.39
				Available to independent suppliers	6.6											
				Available to suppliers	3.3											
				Available for manufacturer	0											
	#12	Return optios	0.0%	Exhaustive return options	10	0										0
				Basic return options	5											
				No return option	0											
	#13	Data management	0.0%	Integrated data not stored	10	0										0.00
				Under request	5											
				Not available	0											
	#14	Restart type	0.0%	Integrated restart	10	0										0.00
				External restart	6.6											
				Service restart	3.3											
				No restart	0											
																RI
					S_i	1.43	1.41	1.08	0.98	0.92	0.82	0.79	0.61	0.60	0.53	9.16
					RI_i	9.07	9.10	9.03	9.05	9.54	9.09	9.09	9.24	9.39	9.24	

TABLE SI.12 RI AND rRI.

	C1	C2	C3	C4	C5
RI	3.13	3.41	3.95	3.39	8.83
rRI	2.94	3.10	3.77	3.32	9.16

TABLE SI.13 SENSITIVITY ANALYSIS.

Parameters (RI)		Telephone interviews importance order							Importance order average	Weighting factor (Wp_j)	Standard deviation (SD)	Importance order average + SD	Wp_j + SD	Importance order average - SD	Wp_j - SD
		A	B	C	D	E	F	G							
#1	Disassembly sequence depth	7	4	0	8	8	4	0	4.4	11.2%	3.5	7.9	12.1%	1.0	7.0%
#2	Fastener type	5	3	0	1	6	0	0	2.1	5.43%	2.5	4.7	7.2%	-0.4	-2.9%
#3	Tools needed	0	2	0	3	3	3	0	1.6	4%	1.5	3.1	4.7%	0.1	0.4%
#4	Working environment	4	0	0	2	2	0	0	1.1	2.9%	1.6	2.7	4.2%	-0.4	-3.1%
#5	Skill level	6	5	8	6	7	5	8	6.4	16.3%	1.3	7.7	11.8%	5.2	37.4%
#6	Diagnostic support and interfaces	0	6	6	7	1	6	0	3.7	9.4%	3.2	6.9	10.6%	0.5	3.7%
#7	Spare parts availability	0	7	0	4	4	7	7	4.1	10.5%	3.1	7.3	11.2%	1.0	7.3%
#8	Spare parts interface	0	0	0	0	0	0	0	0.0	0.0%	0.0	0.0	0.0%	0.0	0.0%
#9	Spare parts availability duration	0	7	0	4	4	7	7	4.1	10.5%	3.1	7.3	11.2%	1.0	7.3%
#10	Information type	8	8	7	5	5	8	0	5.9	14.9%	2.9	8.8	13.5%	2.9	21.4%
#11	Information availability	8	8	7	5	5	8	0	5.9	14.9%	2.9	8.8	13.5%	2.9	21.4%
#12	Return options	0	0	0	0	0	0	0	0.0	0.0%	0.0	0.0	0.0%	0.0	0.0%
#13	Data management	0	0	0	0	0	0	0	0.0	0.0%	0.0	0.0	0.0%	0.0	0.0%
#14	Restart type	0	0	0	0	0	0	0	0.0	0.0%	0.0	0.0	0.0%	0.0	0.0%
									39.4	100%		65.1	100%	13.8	100%

Parameters (rRI)		Telephone interviews importance order							Importance order average	Weighting factor (Wp_j)	Standard deviation (SD)	Importance order average + SD	Wp_j + SD	Importance order average - SD	Wp_j - SD
		A	B	C	D	E	F	G							
#1	Disassembly sequence depth	7	4	0	8	8	4	0	4.4	10.5%	3.5	7.9	11.3%	1.0	6.7%
#2	Fastener type	5	3	0	1	6	0	0	2.1	5.1%	2.5	4.7	6.7%	-0.4	-2.8%
#3	Tools needed	0	2	0	3	3	3	0	1.6	3.7%	1.5	3.1	4.4%	0.1	0.4%
#4	Working environment	4	0	0	2	2	0	0	1.1	2.7%	1.6	2.7	3.9%	-0.4	-3.0%
#5	Skill level	6	5	8	6	7	5	8	6.4	15.2%	1.3	7.7	11.0%	5.2	35.7%
#6	Diagnostic support and interfaces	0	6	6	7	1	6	0	3.7	8.8%	3.2	6.9	9.9%	0.5	3.6%
#7	Spare parts availability	0	7	0	4	4	7	7	4.1	9.8%	3.1	7.3	10.4%	1.0	7.0%
#8	Spare parts interface	0	0	0	0	0	0	0	0.0	0.0%	0.0	0.0	0.0%	0.0	0.0%
#9	Spare parts availability duration	0	7	0	4	4	7	7	4.1	9.8%	3.1	7.3	10.4%	1.0	7.0%
#10	Spare parts cost	0	4.67	0	2.67	2.67	4.67	4.67	2.8	6.5%	2.1	4.8	6.9%	0.7	4.7%
#11	Information type	8	8	7	5	5	8	0	5.9	13.9%	2.9	8.8	12.5%	2.9	20.4%
#12	Information availability	8	8	7	5	5	8	0	5.9	13.9%	2.9	8.8	12.5%	2.9	20.4%
#13	Return options	0	0	0	0	0	0	0	0.0	0.0%	0.0	0.0	0.0%	0.0	0.0%
#14	Data management	0	0	0	0	0	0	0	0.0	0.0%	0.0	0.0	0.0%	0.0	0.0%
#15	Restart type	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
									42.2	100%		69.9	100%	14.5	100%

TABLE SI.14 ASMER OF C1.

	Repair score					
	Step 1	Step 2	Step 3	Step 4	Step 5	
Information	100%	20%	20%	58%	100%	55%
Design	80%	50%	20%	47%	100%	48%
Service	70%	40%	20%	25%	40%	36%
	83%	37%	20%	40%	75%	46%

TABLE SI.15 ASMER OF C2.

	Repair score					
	Step 1	Step 2	Step 3	Step 4	Step 5	
Information	100%	20%	20%	58%	100%	55%
Design	100%	50%	20%	47%	100%	53%
Service	70%	40%	20%	25%	40%	36%
	91%	37%	20%	40%	75%	48%

TABLE SI.16 ASMER OF C3.

	Repair score					
	Step 1	Step 2	Step 3	Step 4	Step 5	
Information	50%	50%	20%	42%	100%	47%
Design	80%	50%	35%	80%	100%	61%
Service	70%	40%	40%	25%	40%	40%
	69%	47%	33%	47%	75%	50%

TABLE SI.17 ASMER OF C4.

	Repair score					
	Step 1	Step 2	Step 3	Step 4	Step 5	
Information	50%	50%	20%	42%	100%	47%
Design	47%	50%	35%	47%	100%	45%
Service	70%	40%	40%	25%	40%	40%
	54%	47%	33%	36%	75%	44%

TABLE SI.18 ASMER OF C5.

	Repair score					
	Step 1	Step 2	Step 3	Step 4	Step 5	
Information	100%	100%	100%	83%	100%	96%
Design	100%	100%	75%	80%	100%	87%
Service	100%	100%	100%	60%	100%	85%
	100%	100%	88%	72%	100%	89%

Article II

Supporting repairability analysis through graph-based visualisation

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ABSTRACT

Repairability is a key aspect of circular economy strategies, contributing to product longevity and resource efficiency. However, existing assessment methods often lack the ability to quantitatively and visually analyse product architecture. This study proposes a graph-based modelling approach for repairability assessment, combining network theory metrics with structural visualisation. Based on the EN 45554 standard, the Repair Matrix (RM) is used to assign repair-related attributes to product components and their connections. These attributes are represented as nodes and edges within a network, enabling both visual exploration and quantitative analysis. A three-stage methodology is developed: (i) input data structuring, (ii) visual graph construction using Gephi software and (iii) analytical output. In addition, a novel graph-based Repair Index (RI) is introduced to quantify repairability at the system level. The approach is applied to a capsule coffee machine as a case study. The results demonstrate that graph metrics such as degree, modularity, eccentricity and betweenness centrality effectively reveal structural complexity and critical components. The proposed method offers a scalable and interpretable framework that enhances design-for-repair strategies by highlighting component dependencies and optimising disassembly logic. Overall, this work contributes to the development of more repairable and sustainable product architectures, supporting circular economy objectives.

KEYWORDS
Circular economy, Design for repairability, EN 45554, Repair Index, Graph-based modelling, Network metrics, product architecture

1 INTRODUCTION

The recent publication of the "Right to Repair" directive (European Parliament, 2024) and Regulation (EU) 2024/1781 (European Union, 2024) represents a significant step forward in promoting sustainable consumption. These developments support both the Circular Economy Action Plan (European Commission, 2020) and the European Green Deal (European Commission, 2019). As products play a central role in this ecological transition, Regulation (EU) 2024/1781 encourages production and consumption patterns that align with the EU's overarching sustainability objectives, particularly in relation to climate, environment, energy, resource use and biodiversity (European Union, 2024). Moreover, the regulation introduces ecodesign requirements aimed at enhancing product reparability and durability while reducing environmental impact, thereby fostering greater reuse and repair of products.

In line with this European framework, various initiatives have been developed to assess product repairability. These include standards such as ONR 192102 (2014) and EN 45554 (2020); methodologies proposed by iFixit (Flipsen et al., 2019, 2016; Suovanen, 2023), AsMeR (Bracquené et al., 2018), the Repair Score System (RSS)(Cordella et al., 2019; Spiliotopoulos et al., 2022) or the Repair Matrix (RM) (Blanco-Espeleta et al., 2024); as well as national initiatives such as the French Durability Index (Ministère de la Transition écologique, 2020; The French Agency for Ecological Transition, 2021). These methods focus primarily on design-related parameters such as ease of disassembly, tools required and joint types. However, they often lack a direct connection between disassembly procedures and the underlying product architecture, complicating structural comparisons across different products.

Understanding product architecture and disassembly processes is increasingly recognised as essential to achieving sustainability and circular economy goals. Designers and engineers must consider component connectivity, accessibility and disassembly sequencing to enable maintenance and recovery. As highlighted by Parajuly et al. (2023), product design and infrastructure are confirmed to be key drivers of the ability to perform repair, reinforcing the critical role of structural configuration in facilitating repair-oriented practices. Early approaches to mapping product architecture relied on diagrams and schematic models such as the *liaisons* concept introduced by Bourjault (1998), while De Fazio and Whitney (1987) developed algorithms for computing possible assembly sequences based on these diagrams. However, such representations lacked flexibility to capture alternative disassembly paths or real-world constraints.

To overcome these limitations, graph-based modelling techniques have emerged as powerful tools in structural analysis of product architectures. Graphs systematically represent functional and physical relationships between components, facilitating analysis of assembly, disassembly and maintenance strategies (Ji et al., 2022). The introduction of AND/OR graphs by De Mello and Sanderson (1986) enabled representation of multiple assembly and disassembly sequences, which was further developed for optimising end-of-life processes (Cao and Sanderson, 1998). Recent studies confirm their value: Agrawal et al. (2016) used graph- and matrix-based approaches to model disposition routes in reverse logistics; Alrufaifi et al. (2024) applied centrality metrics to evaluate how wear and failures modify disassembly graphs; Formentini and Ramanujan (2023) developed the Design for Circular Disassembly (DfCD) methodology to map disassembly processes. Complementary visual tools such as the Disassembly Map (De Fazio et al., 2021a) and the Peony Diagram (Huang et al., 2025) further enhance the visualisation of component hierarchies and disassembly constraints. While these tools offer valuable visual insights into product disassembly and component dependencies, they often lack standardised metrics for quantitative evaluation and rarely incorporate key repair-oriented parameters, such as failure probability, joint types or spare part availability.

In this context, graph theory emerges as a promising and underexplored approach that enables a more rigorous and systematic assessment of repairability performance. As a mathematical tool, graph theory enables the representation of complex systems through nodes and edges, where nodes can correspond to product parts and edges to physical or functional relationships. Such graph-based models facilitate both visual and quantitative analysis of product architecture, enabling the identification of critical components, dependency chains and potential bottlenecks. Unlike conventional scoring matrices, graph-based models preserve the architectural logic of the product, thereby integrating parameters such as accessibility, sequencing and part centrality directly into repairability assessments. Moreover, this modelling approach is compatible with visualisation and metric-based analysis tools, such as those provided by the open-source software Gephi (Bastian et al., 2009), further expanding its analytical potential.

Despite the wide range of network metrics available in graph theory to evaluate aspects such as connectivity, centrality, clustering and structural depth, there remains a notable lack of a dedicated metric specifically designed to assess the repairability of a product as represented by its graph. This highlights the need for a tailored metric that integrates key repair-related parameters into a unified and interpretable score, capable of capturing the complexity and accessibility inherent in product architecture.

Given this context, the main objective of this study is to assess the potential of graph-based modelling and network metrics as tools for evaluating product repairability. To fulfil this general aim, the study pursues the following specific objectives:

- To identify the types of input data and attributes required to define a graph that represents the architecture of a product in relation to its repairability.
- To determine which tools and metrics, available within graph analysis environments, are most relevant to assessing structural repairability.
- To explore appropriate visualisation strategies that enhance the interpretability of graph-based representations in the context of repairability analysis.
- To design a new graph-based metric to quantify product repairability at the network level.
- To explore the applicability and usefulness of this approach through its implementation in a real product case study.

To address these objectives, a three-stage methodology was developed: ((I) input data structuring, (II) graph visual structuring and (III) analytical output. The process begins with the compilation of relevant data at the part, connection and system levels, which is then used to model the product architecture as a graph. This graph is subsequently analysed using a set of visualisation tools and structural network metrics, leading to the calculation of a new graph-based Repair Index (RI) metric. Finally, the methodology is applied to a real-world case study, a capsule coffee machine, to illustrate its practical implementation and validate its analytical capabilities.

2 METHOD

To perform the repairability assessment through graph-based modelling, a three-stage methodological approach was followed: (I) input data, (II) graph visualisation and (III) outputdata. These stages are shown in Figure II.1.

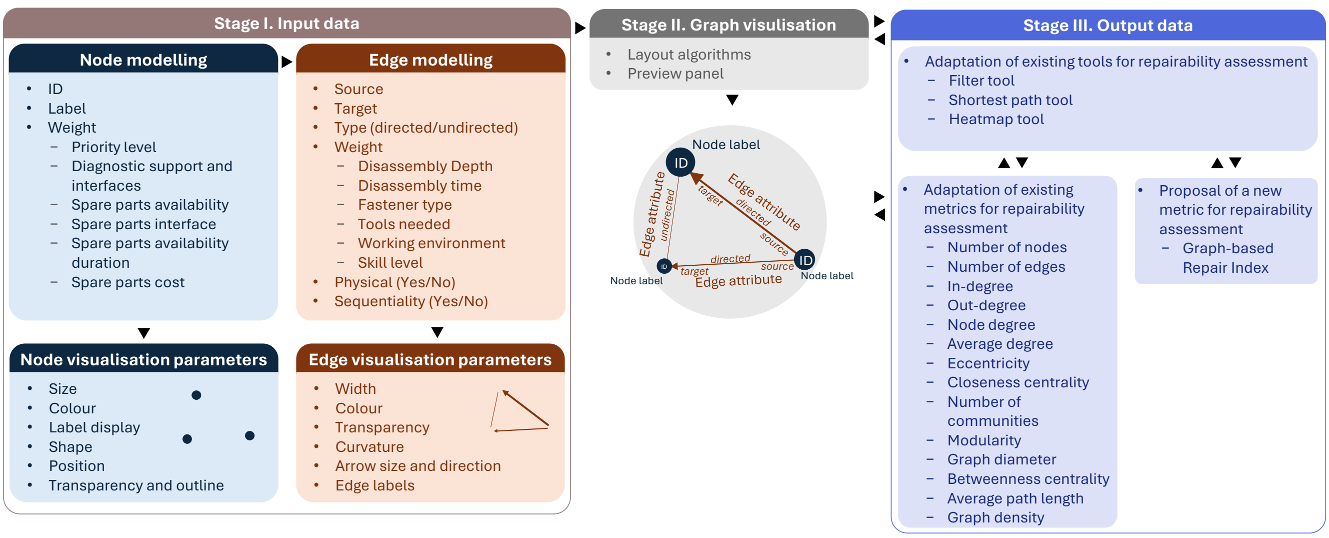


FIGURE II.1 METHODOLOGY.

STAGE I. INPUT DATA

The methodology builds upon the general framework established by EN 45554 (2020), which outlines a method for assessing the ability to repair, reuse and upgrade energy-related products. The standard introduces a series of parameters and the concept of priority parts, those most likely to fail or critical to product functionality. However, EN 45554 provides a non-restrictive structure, requiring adaptation to each product category. To address this, proposed the RM (Blanco-Espeleta et al., 2024) was applied to formalise a scoring scale for each parameter and establishes complementary parameters. The parameters used are presented in Table II.1.

TABLE II.1 REPAIR MATRIX (RM) PARAMETERS.

Parameters for the priority parts	(P1) disassembly sequence/time depth	(P6) diagnostic support and interfaces
	(P2) fastener type	(P7) spare parts availability
	(P3) tools needed	(P8) spare parts interface
	(P4) working environment	(P9) spare parts availability duration
	(P5) skill level	(P10) spare parts cost
Parameters for the product	(P11) information type	(P14) data management
	(P12) information availability	(P15) restart type
	(P13) return options	

In this stage, the product architecture is modelled as a network in which each part is represented as a node and disassembly or dependency relationships are represented as edges. Two datasets were created accordingly:

- For node modelling, each part was represented with a unique identifier and assigned relevant attributes from the RM: part priority level (Wpp_i), diagnostic support (P6), spare parts availability (P7), spare parts interface (P8), availability duration (P9) and spare part cost (P10).
- For edge modelling, connections between parts were defined through attributes including disassembly sequence depth and time (P1), fastener type (P2), required tools (P3), working environment (P4) and skill level (P5). Each edge also indicated whether the connection was physical or logical and whether the disassembly followed a sequential logic.

These datasets were compiled in Excel sheets and imported into Gephi for subsequent modelling and analysis.

STAGE II. GRAPH VISUALISATION

The second stage involved generating a graphical representation of the product architecture in Gephi. Layout algorithms were used to position nodes based on their relationships, supporting interpretation of the network structure. The ForceAtlas2 algorithm (Jacomy et al., 2014) was selected for this purpose, as it spatially organises nodes according to repulsive and attractive forces, naturally revealing clusters and centrality patterns.

Visual attributes of nodes and edges were configured to support repairability analysis. Node size and colour were mapped to repair-related attributes, while edge thickness and directionality reflected disassembly parameters. The resulting visualisation highlighted key aspects such as part accessibility, disassembly complexity and component dependencies.

STAGE III. OUTPUT DATA

In the final stage, Gephi's analytical tools were employed to extract quantitative insights from the network. The filter tool enabled selective visualisation of network segments, the shortest path tool was used to identify optimal disassembly routes and the heatmap tool provided accessibility gradients from a selected part.

Additionally, conventional network metrics were calculated to characterise the structural complexity and repairability of the product. Metrics included number of nodes and edges, average degree, graph density, diameter and average path length. Node-level metrics such as degree, eccentricity (Brandes, 2001), closeness centrality and betweenness centrality were used to identify critical components and potential bottlenecks. The number of communities algorithm (Blondel et al., 2008; Lambiotte et al., 2009) provided further insight into the modularity of the product architecture.

3 RESULTS AND DISCUSSION

3.1 INPUT DATA

3.1.1 Node modelling

In the context of network theory, a node represents an individual entity within a system. In this study, each node corresponds to a distinct product part.

Each node was defined with a unique identifier (ID), a label and attributes derived from the RM. The node weight reflects the repairability performance of the part, using the following parameters:

- Part priority level (Wpp_i), indicating the importance of the part in relation to failure modes and functional relevance. Non-priority parts are assigned a weight of zero.
- Diagnostic support (P6), representing the availability of aids for failure diagnosis.
- Spare parts availability (P7), indicating the level of spare part availability.
- Spare parts interface (P8), reflecting compatibility and ease of integration.
- Spare parts availability duration (P9), representing the number of years spare parts are available post-sale.
- Spare parts cost (P10), representing the economic burden associated with replacement.

These attributes were compiled in the node sheet and imported into Gephi. In the visualisation process, node size and colour were mapped to the assigned weights, supporting the interpretation of repairability-related indicators within the network structure. An example of the node modelling and visualisation approach is shown in Figure II.2.

For example, in the case of the spare parts cost RM score, a larger node size is observed for Node 1 (Part A), since the cost of this part is less than 5% of the total product price and therefore, according to the RM, it obtains a score of 10. This score is represented as the weight of Node 1. In contrast, Node 2 appears much smaller, as its score (weight) is only 3.3, corresponding to a spare part cost between 10% and 20% of the product price. Additionally, there is a slightly closer proximity between Nodes 2 and 3 (Parts B and C), due to their lower weights (3.3 and 6.6 respectively), which affects the spatial distribution of the network under the layout algorithm. This reflects the influence of node weight not only on visual attributes such as size, but also on positioning within the network graph.

Node modelling

Priority level
The relative importance of a specific component in the overall product.

ID	Label	Weight	
1	Part A	0	Non-priority part
2	Part B	0.2	Priority part
3	Part C	0.8	Priority part

Diagnostic support and interfaces RM score
Presence and type of diagnostic systems that support fault detection.

ID	Label	Weight	
1	Part A	10	Intuitive
2	Part B	5	Public available
3	Part C	0	Not viable

Spare parts availability RM score
Considers if spare parts are available on the market.

ID	Label	Weight	
1	Part A	7.5	Suppliers
2	Part B	10	Publicly available
3	Part C	2.5	Manufacturer

Spare parts interface RM score
Refers to the ease of integrating replacement parts.

ID	Label	Weight	
1	Part A	10	Standard part/interface
2	Part B	0	Non-standard interface
3	Part C	5	Exclusive part

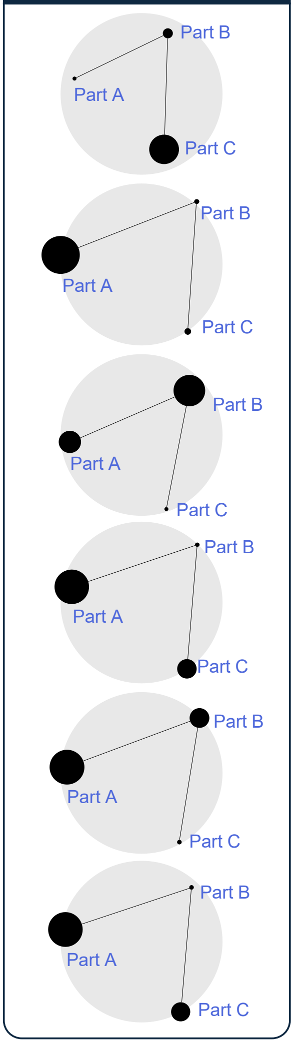
Spare parts availability duration RM score
Indicates the length of time that spare parts are available after the product is discontinued.

ID	Label	Weight	
1	Part A	6.6	Mid-term
2	Part B	3.3	Short-term
3	Part C	0	No information

Spare parts cost RM score
Evaluates the cost of spare parts relative to the product price.

ID	Label	Weight	
1	Part A	10	≤ 5%
2	Part B	3.3	Between 10% and 20%
3	Part C	6.6	Between 5% and 10%

Node visualisation



For these examples, as the score (weight) increases, the nodes expand in size and are distributed more widely across the layout.

FIGURE II.2 NODE MODELLING AND VISUALISATION FOR REPAIRABILITY ASSESSMENT.

3.1.2 Edge modelling

In relation to the edge modelling, in graph-based modelling, an edge represents the connection or relationship between two nodes, as Figure II.3 shows. In this study, each edge corresponds to a physical or functional dependency between product parts. These connections play a critical role in the structural configuration of the product, therefore, in the analysis of its repairability.

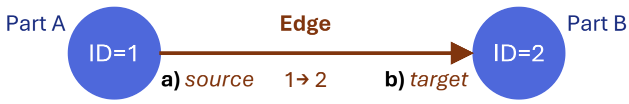


FIGURE II.3 EXAMPLE OF AN EDGE BETWEEN PARTS.

Each edge is defined by a source, a target, a type, a weight, physical design, sequentially and a set of attributes:

- The source, identified with an "a" in Figure II.3
- refers to the part from which the connection originates.
- The target, identified with a "b" in Figure II.3, indicates the part to which the connection leads.
- The type of edge determines whether the connection is directed or undirected, a distinction that is critical when modelling disassembly dependencies. Directed edges indicate that a specific sequence must be followed, meaning the source part must be removed before the target. In contrast, undirected edges imply that the removal order is interchangeable, with no predefined hierarchy. This differentiation is particularly relevant for capturing constraints related to accessibility, embeddedness, or spatial obstruction. As illustrated in Figure II.3, directed edges are represented with arrows, signalling mandatory sequencing in the disassembly process, whereas undirected edges appear without arrows, denoting symmetrical or non-sequential relationships.

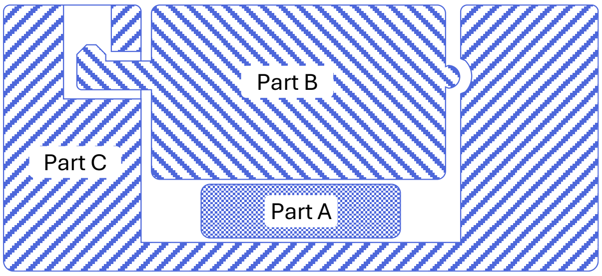


FIGURE II.4 EXAMPLE OF A PHYSICAL CONNECTION (PART B & PART C) AND SEQUENTIAL CONNECTION (PART B & PART A).

- The physical attribute determines whether the source and target parts are physically connected. For instance there could be cases where disassembly of one part (Part B on Figure II.4) is required to access another (Part A on Figure II.4), even if no physical joint exists between them.
- The sequentially defines the order in which parts must be disassembled. All directed edges are considered sequential, while undirected edges are non-sequential.
- The weight assigned to each edge plays a central role in the repairability assessment. It can integrate several parameters derived from EN 45554 (2020), each associated with a specific attribute, as is shown on Figure II.5:
  - Disassembly depth (P1), defined as the minimum number of steps required to remove a part (EN 45554, 2020). In this context, if disconnecting an edge implies a new step in the disassembly process, the edge is assigned a weight of 1; otherwise, the value is 0. The corresponding attribute for this weight is the disassembly action, such as "remove" or "change of tool".
  - Disassembly time (P1), which quantifies the time required to disconnect the parts linked by the edge. In this case, the weight corresponds to the measured or estimated disconnection time (in seconds) and visual attributes can reflect this temporal cost.
  - Fastener type (P2). The value is derived from a RM score based on the type of joint (e.g. snap-fit, screw, adhesive). Similarly, the tools required to perform the disconnection are scored and assigned as edge weights (e.g. screwdriver, spudger, hand tool).
  - The working environment needed for disassembly (P3), is considered through a score that reflects the context required (e.g. home, workshop).

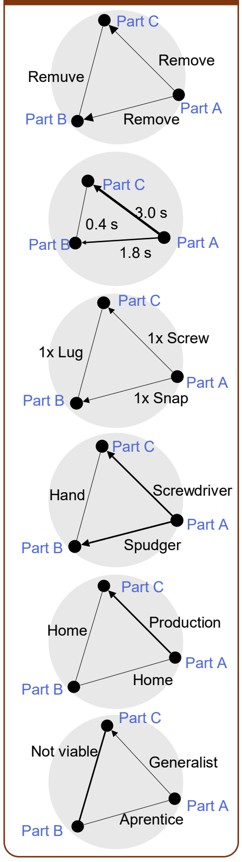
– The skill level (P4) is integrated as a weight to indicate the level of expertise needed (e.g. apprentice, generalist, professional).

The visual representation of edges in Gephi is adapted according to their weight (see Figure II.5). Edges associated with longer disassembly times or deeper disassembly sequences may be displayed as longer and thicker lines, indicating a greater effort or complexity. Conversely, lower-weighted edges can be rendered thinner or with shorter spans. Edge colour can also be mapped to a gradient scale to visually distinguish varying degrees of difficulty or relevance.

Edge modelling

Attribute	Source → Target	Type	Physical	Sequentiality	Weight	
Disassembly depth Refers to the minimum number of steps required to remove a specific part.	1 → 2	Directed	No	Yes	1	Remove
	1 → 3	Directed	Yes	Yes	1	Remove
	2 → 3	Undirected	Yes	No	1	Remove
Disassembly time The time required to remove a specific component from the product.	1 → 2	Directed	No	Yes	1.8	1.8 s
	1 → 3	Directed	Yes	Yes	3.0	3.0 s
	2 → 3	Undirected	Yes	No	0.4	0.4 s
Fastener type RM score Type of connection between components.	1 → 2	Directed	No	Yes	10	Snap
	1 → 3	Directed	Yes	Yes	10	Screw
	2 → 3	Undirected	Yes	No	10	Lug
Tools needed RM score Tools required for repair.	1 → 2	Directed	No	Yes	7.5	Spudger
	1 → 3	Directed	Yes	Yes	7.5	Screwdriver
	2 → 3	Undirected	Yes	No	10	Hand
Working environment RM score Type of setting necessary to perform the repair.	1 → 2	Directed	No	Yes	10	Home
	1 → 3	Directed	Yes	Yes	0	Production
	2 → 3	Undirected	Yes	No	10	Home
Skill level RM score Level of expertise needed for the repair.	1 → 2	Directed	No	Yes	10	Aprentice
	1 → 3	Directed	Yes	Yes	7.5	Generalist
	2 → 3	Undirected	Yes	No	0	Not viable

Edge visualisation



For these examples, the higher the score (weight) or the disassembly time/depth, the longer the edges—meaning nodes are positioned further apart. Lower scores result in thicker edges. Similarly, greater disassembly time or depth also leads to thicker edges.

FIGURE II.5 EDGE MODELLING AND VISUALISATION FOR REPAIRABILITY ASSESSMENT.

For example, in the case of Disassembly time, edge thickness is used to visually represent the weight associated with each connection, which corresponds to the time required to remove a part. For example, the edge from Part A to Part C (1 to 3) is visibly thicker, as the disassembly time is 3.0 seconds, the highest among the three edges. In contrast, the edge from Part B to Part C (2 to 3) is much thinner, with a disassembly time of only 0.4 seconds. The layout also reflects that Parts B and C appear closer to each other, influenced by the lower weight of their connecting edge. This illustrates how edge weights, derived from disassembly times, not only influence the visual appearance (thickness and labels) but also affect the spatial arrangement of parts in the network.

3.2 GRAPH VISUALISATION

The visual structuring of the network supports the interpretation of repairability-related indicators. Through visualisation, designers can quickly identify patterns such as component modularity, disassembly complexity and part accessibility.

The ForceAtlas2 layout algorithm (Jacomy et al., 2014) was applied to spatially organise the network based on the relationships between components. This algorithm positions nodes according to the forces exerted by their connections, allowing the formation of visual clusters that reflect the structural logic of the product.

Visual attributes including node size, node colour, edge width and edge colour were mapped to the corresponding parameters from the RM. This approach enhances the visual analysis of the network and facilitates the identification of components and connections with a significant influence on repairability.

An example of the visual structuring is shown in Figure II.6.

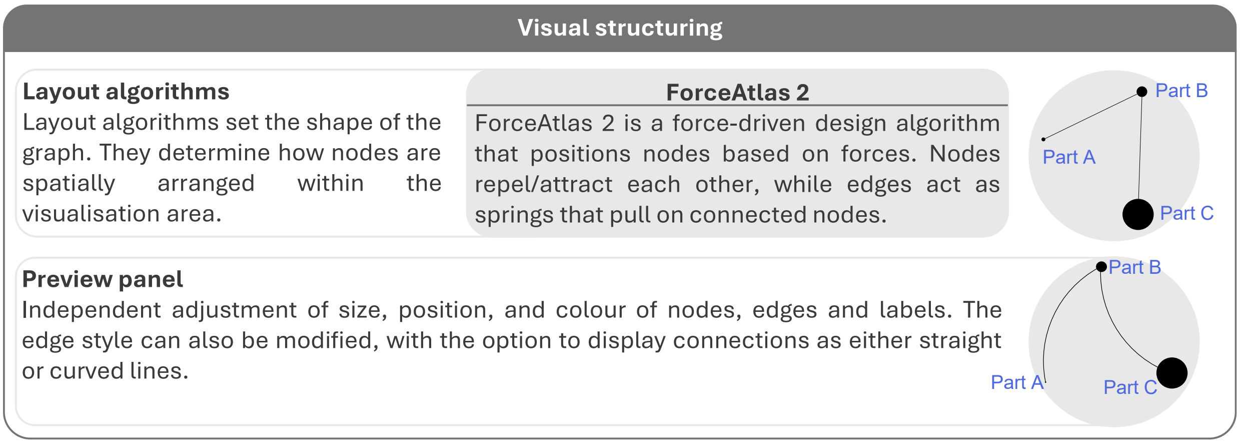


FIGURE II.6 VISUAL STRUCTURING FOR REPAIRABILITY ASSESSMENT.

3.3 OUTPUT DATA

The final stage of the methodology involved extracting quantitative and qualitative insights from the network through a combination of analytical tools, graph-based metrics and a newly developed graph-based RI. These outputs provide a multi-level assessment of the product's repairability performance.

3.3.1 Adaptation of existing tools for repairability assessment

The tools identified as especially relevant for repairability assessment are:

- The filter tool enables visualisation or exclusion of nodes and edges based on user-defined criteria. This is particularly useful for isolating subsets of the network, such as displaying only physical connections between parts. In the example shown in Figure II.7, a filter is applied to show only physical edges, where a physical joint links the source and target parts, simplifying the interpretation of structural dependencies relevant to disassembly.
- The shortest path tool calculates and visually highlights the shortest path between two selected nodes, taking into account the weights assigned to each edge. The output includes the path with the lowest cumulative value and a colour-coded visualisation. As shown in Figure II.7, the disassembly path with the shortest time (based on edge weights) is highlighted in red. This tool is particularly valuable for identifying optimal disassembly sequences, such as those requiring the least time, the fewest tools or the most reversible joints.
- The heatmap tool provides a colour-gradient visualisation of node distances from a selected source node, based on edge weights or structural proximity. This representation enables rapid identification of parts that are deeply embedded or

structurally central. As demonstrated in Figure II.7, nodes are coloured based on their proximity to Part A, revealing zones of higher or lower accessibility.

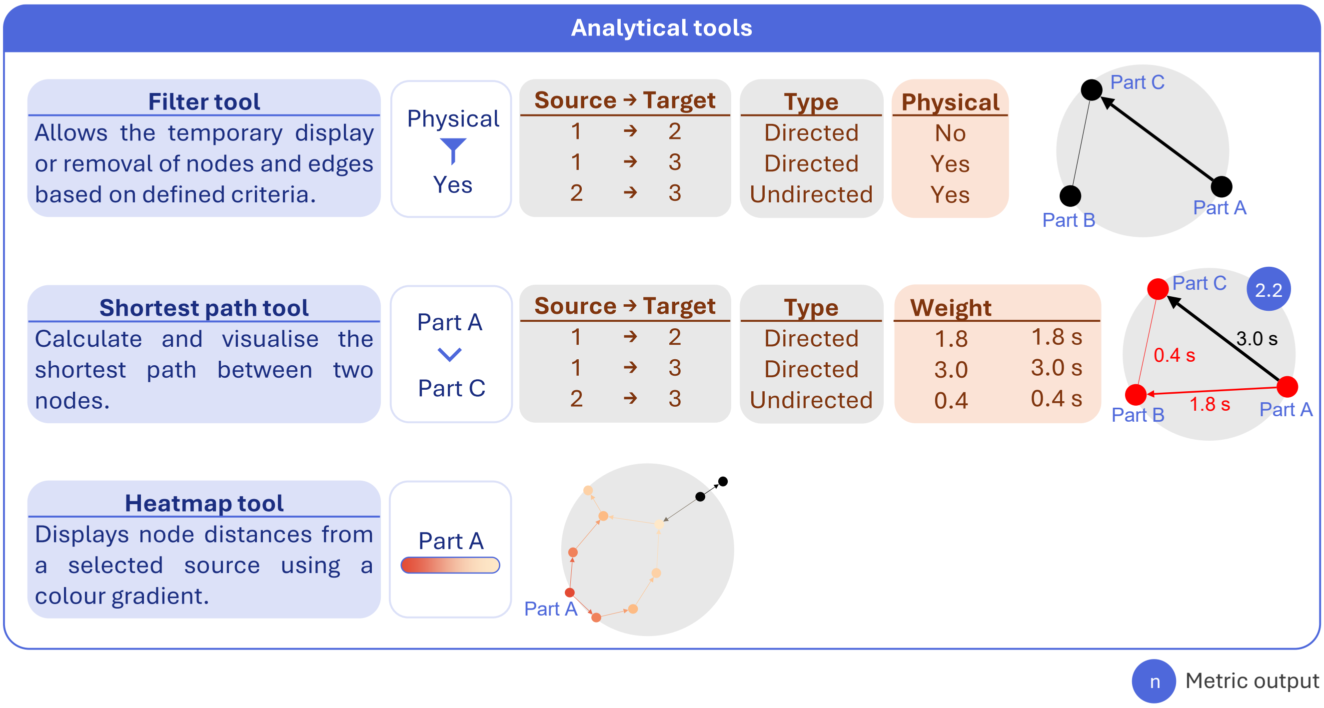


FIGURE II.7 ANALYTICAL TOOLS FOR REPAIRABILITY ASSESSMENT.

3.3.2 Adaptation of existing tools for repairability assessment

In addition to the interactive tools, a set of graph-based metrics was used to quantify structural aspects of the product architecture that influence repairability. These metrics were selected and interpreted for disassembly complexity, part accessibility and modularity.

At the graph level, metrics provide a general overview of structural complexity, connectivity and accessibility:

– The number of nodes and edges indicate system complexity and part interdependencies.

– Average degree and graph density quantify overall connectivity. Higher values suggest stronger inter-part dependencies, while lower values may indicate more modular designs.

– Graph diameter and average path length reflect structural depth and part accessibility. Higher values suggest lower accessibility, whereas shorter paths are associated with more straightforward disassembly processes.

At the node level, metrics support the identification of key components in the repairability context:

– In-degree, out-degree and total degree quantify the number of direct connections a node has, identifying parts that are either difficult to access (high in-degree) or structurally influential (high out-degree).

– Eccentricity (Brandes, 2001) reflects how far a node is from the most distant part of the graph, useful for detecting isolated or deeply embedded parts.

– Closeness centrality (Brandes, 2001) identifies nodes that are, on average, nearer to all other parts, ideal candidates for intervention points.

- Betweenness centrality (Brandes, 2001) reveals nodes that lie along many shortest paths, highlighting potential bottlenecks in disassembly or repair operations.

Finally, the number of communities was calculated using the modularity algorithm (Blondel et al., 2008; Lambiotte et al., 2009). High modularity is associated with a more modular architecture, supporting design-for-repair strategies, suggesting that certain parts may be removed as a unit without disrupting the entire system. Figure II.8 provides an overview of these metrics applied to the product case study.

FIGURE II.8 GRAPH-BASED METRICS FOR REPAIRABILITY ASSESSMENT.

3.3.3 Proposal of a new metric for repairability assessment

Building on the RM and the network representation, a novel graph-based RI metric was developed to quantify product repairability in a comprehensive and interpretable way.

Each parameter from the RM was mapped to specific elements and functionalities within the network model, as summarised in Table II.2.

TABLE II.2 CORRESPONDENCE BETWEEN REPAIR MATRIX (RM) AND GEPHI FUNCTIONALITIES.

Repair Matrix		Gephi features
Wpp_i	Weighting factor of each priority part	Edge information
P1	Disassembly sequence/time depth	Edge information + Shortest path tool
P2	Fastener type	Edge information + Filter tool
P3	Tools needed	Edge information + Filter tool
P4	Working environment	Edge information + Filter tool
P5	Skill level	Edge information + Filter tool
P6	Diagnostic support and interfaces	Node information
P7	Spare parts availability	Node information
P8	Spare parts interface	Node information
P9	Spare parts availability duration	Node information
P10	Spare parts cost	Node information
P11	Information type	Product information for the metric
P12	Information availability	Product information for the metric
P13	Return options	Product information for the metric
P14	Data management	Product information for the metric
P15	Restart type	Product information for the metric

This structure allows integrating repairability parameters at three levels of the network:

- Edge-related parameters were analysed through edge weights and relevant analytical tools. These parameters included disassembly sequence depth and time (P1), fastener type (P2), required tools (P3), working environment (P4) and skill level required (P5). These attributes influence accessibility and disassembly complexity across the network.

- Node-related parameters were assigned as node weights. These included diagnostic support (P6), spare parts availability (P7), spare parts interface (P8), availability duration (P9) and spare parts cost (P10). These attributes reflect the repairability performance of individual components.

- Global product-level parameters (P11 to P15), covering aspects such as documentation, software availability, maintenance information and manufacturer support, were incorporated as additional inputs in the Graph-based RI metric calculation at the overall product level.

The Graph-based RI metric can be expressed either as a continuous value ranging from 0 to 10, or as a categorical grade (A to E), following the scale proposed by the European Commission (2023). The metric also allows parameter-level breakdowns, enabling targeted analysis of strengths and weaknesses in product repairability. Figure II.9 shows an example of the visualisation of selected node and edge attributes relevant to the Graph-based RI metric calculation.

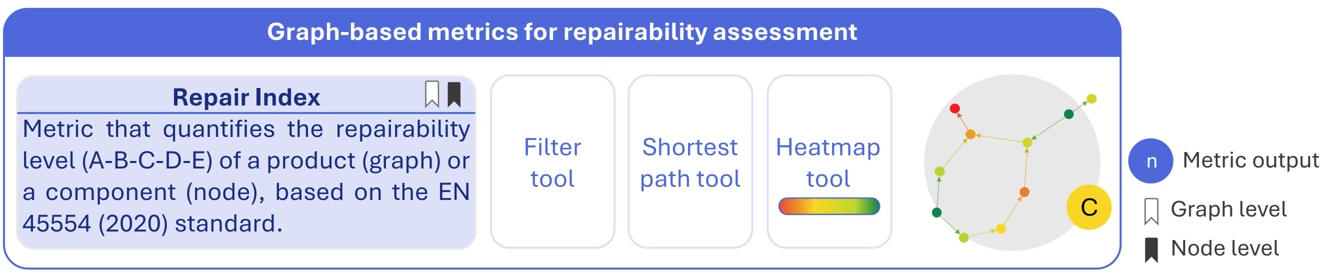


FIGURE II.9 GRAPH-BASED RI METRIC.

3.4 APPLICATION TO A CASE STUDY

The graph-based approach was applied to the capsule coffee machine selected as the case study. The objective was to evaluate its repairability performance based on the network representation of the product architecture. Figure II.10 shows the capsule coffee machine selected for analysis (a) with its priority parts (b).

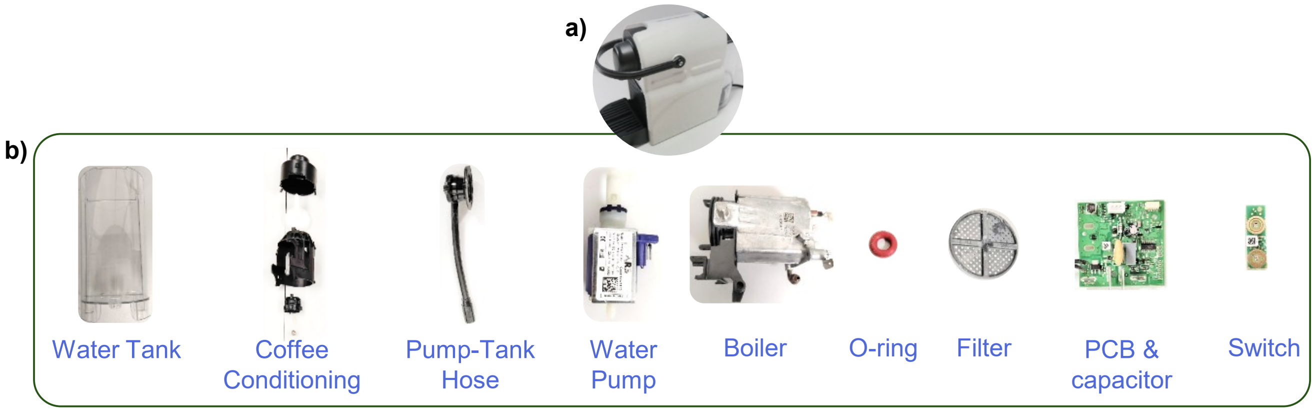


FIGURE II.10 SELECTED CASE STUDY. CAPSULE COFFEE MACHINE AND ITS PRIORITY PARTS.

3.4.1 Input data

Nodes modelling

Node modelling was carried out by preparing an Excel file in which each row corresponds to a part of the capsule coffee machine and each column represents a relevant attribute (see Table II.3). These include the part ID, label and weighted parameters linked to the repairability assessment. For the representation, the weight assigned to each node corresponds to the part's priority level. It is important to note that only priority parts are assigned a value weight, as only these are considered relevant for calculating the Graph-based RI metric and visualising repairability-related attributes. Non-priority parts are included in the graph to preserve structural coherence, but their weight is set to non-value.

TABLE II.3 NODES INPUT DATA FOR A CAPSULE COFFEE MACHINE.

Id	Label	Weight	Diagnostic support and interfaces	Spare parts availability	Spare parts interface	Spare parts availability duration	Spare parts cost
0	Capsule coffee machine	100	0	7.5	-	0	0
1	Water Tank	9.6	0	10	-	0	6.6
2	Tank Intake Trim	0	-	-	-	-	-
3	Inner Right Casing	0	-	-	-	-	-
4	Inner Left Casing	0	-	-	-	-	-
5	Tray Cluster	0	-	-	-	-	-
6	Conditioning System Comp.	0	-	-	-	-	-
7	Boiler	6.4	0	7.5	-	0	0
8	Lever	-	-	-	-	-	-
9	Right Shaft	-	-	-	-	-	-
10	Left Shaft	-	-	-	-	-	-
11	Right Casing	-	-	-	-	-	-
12	Left Casing	-	-	-	-	-	-
13	Clamp	-	-	-	-	-	-
14	Power Cable	-	-	-	-	-	-
15	Rear Casing Cluster + Switch	-	-	-	-	-	-
16	Button Panel	-	-	-	-	-	-
17	Rear Casing	-	-	-	-	-	-
18	Switch	9	0	7.5	-	0	0
19	Coffee Conditioning	11.9	0	7.5	-	0	0
20	Boiler + PCB Cluster	-	-	-	-	-	-
21	PCB	5.7	0	7.5	-	0	0
22	Capacitor	6.6	0	7.5	-	0	0
23	Sensors	-	-	-	-	-	-
24	Boiler-Pump Hose	-	-	-	-	-	-
25	Pump-Tank Hose	15.5	0	7.5	-	0	0
26	Filter	10.8	0	7.5	-	0	0
27	Water Pump	15.8	0	7.5	-	0	0
28	Pump Protector	-	-	-	-	-	-
29	Pump Positioner	-	-	-	-	-	-
30	Injector	-	-	-	-	-	-
31	O-ring	8.7	0	7.5	-	0	0

Edges modelling

Similarly, edge modelling was conducted through a dedicated Excel sheet in which each row represents a connection between parts (see Table II.4). Column fields include source, target, connection type (directed or undirected), weighted parameters linked to the repairability assessment, physical connection and sequentiality. For the representation, the weight assigned to each edge corresponds to the disassembly time, calculated using the eDIM (Peeters et al., 2018) methodology.

TABLE II.4 EDGES INPUT DATA FOR A CAPSULE COFFEE MACHINE.

Source	Target	Type	Weight	Physical	sequentiality	Disassembly sequence dep	eDIM (s)	Fastener	Nº Fasteners	Fastener score	Tools	Tools score	Working environment	Working environment score	Skill level	Skill level score
1	2	Undirected	0.47	Yes	No	0	0.47	Lug	4	10	Hand	10	Home	10	-	-
1	3	Undirected	0.47	Yes	No	0	0.47	Lug	1	10	Hand	10	Home	10	-	-
1	4	Undirected	0.47	Yes	No	0	0.47	Lug	1	10	Hand	10	Home	10	-	-
0	1	Directed	0	No	Yes	1	0	-	-	-	-	-	-	-	Apprentice	10
5	4	Undirected	1.4	Yes	No	0	1.4	Loose fit	1	10	Hand	10	Home	10	-	-
1	5	Directed	0	No	Yes	1	0	-	-	-	-	-	-	-	-	-
6	4	Undirected	4.7	Yes	No	0	4.7	Lug	2	10	Hand	10	Home	10	-	-
6	4	Undirected	4.7	Yes	No	0	4.7	Cantilever Snap	1	10	Spudger	7,5	Home	10	-	-
6	7	Undirected	3.27	Yes	No	0	3.27	Loose fit	1	10	Hand	10	Home	10	Professional	0.71
5	6	Directed	0.47	No	Yes	1	0.47									
8	9	Undirected	4.6	Yes	No	0	4.6	Screw	1	10	Screwdriver	10	Home	10	-	-
8	10	Undirected	4.6	Yes	No	0	4.6	Screw	1	10	Screwdriver	10	Home	10	-	-
6	8	Directed	0	No	Yes	1	0	-	-	-	-	-	-	-	-	-
12	4	Undirected	19.37	Yes	No	0	19.37	Cantilever Snap	7	10	Spudger	7,5	Home	10	-	-
12	4	Undirected	0.47	Yes	No	0	0.47	Lug	11	10	Hand	10	Home	10	-	-
8	12	Directed	0.477	No	Yes	1	0.477	-	-	-	-	-	-	-	-	-
12	11	Directed	6.87	Yes	Yes	1	6.87	Cantilever Snap	2	10	Spudger	7,5	Home	10	-	-
11	3	Undirected	24.37	Yes	No	0	24.37	Cantilever Snap	9	10	Spudger	7,5	Home	10	-	-
11	3	Undirected	0.48	Yes	No	0	0.48	Lug	10	10	Hand	10	Home	10	-	-
13	3	Undirected	0.87	Yes	No	0	0.87	Cantilever Snap	1	10	Hand	10	Home	10	-	-
11	13	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
14	21	Undirected	6.87	Yes	No	0	6.87	Faston cable	2	10	Tweezers	7,5	Home	10	Manufacturer	0.5
14	7	Undirected	4.37	Yes	No	0	4.37	Faston cable	1	10	Tweezers	7,5	Home	10	Professional	0.71
13	14	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
2	3	Directed	6.87	Yes	Yes	1	6.87	Cantilever Snap	2	10	Spudger	7,5	Home	10	-	-
2	4	Undirected	6.87	Yes	No	0	6.87	Cantilever Snap	2	10	Spudger	7,5	Home	10	-	-
14	2	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
3	4	Directed	16.87	Yes	Yes	1	16.87	Cantilever Snap	6	10	Spudger	7,5	Home	10	-	-
3	4	Directed	0.47	Yes	Yes	1	0.47	Guide	3	10	Hand	10	Home	10	-	-
3	4	Directed	0.47	Yes	Yes	1	0.47	Lug	2	10	Hand	10	Home	10	-	-
3	17	Undirected	0.47	Yes	No	0	0.47	Lug	2	10	Hand	10	Home	10	-	-
17	4	Undirected	0.47	Yes	No	0	0.47	Lug	2	10	Hand	10	Home	10	-	-
3	4	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
15	21	Undirected	0.47	Yes	No	0	0.47	Press fit	1	10	Hand	10	Home	10	Manufacturer	0.5
4	15	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
16	17	Undirected	2.07	Yes	No	0	2.07	Cantilever Snap	4	10	Hand	10	Home	10	-	-
15	16	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
18	17	Undirected	4.37	Yes	No	0	4.37	Cantilever Snap	1	10	Spudger	7,5	Home	10	-	-
18	17	Undirected	4.37	Yes	No	0	4.37	IDC	1	10	Tweezers	7,5	Home	10	-	-
18	17	Undirected	0.47	Yes	No	0	0.47	Guide	2	10	hand	10	Home	10	-	-
16	18	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	Professional	5
26	25	Undirected	0.47	Yes	No	0	0.47	Press fit	1	10	Hand	10	Home	10	Professional	2.5
3	26	Undirected	0.47	Yes	No	0	0.47	Guide	1	10	Hand	10	Home	10	Professional	2.5
4	26	Directed	0.47	Yes	Yes	1	0.47	Cantilever Snap	1	10	Hand	10	Home	10	Professional	2.5
4	26	Directed	0.47	Yes	Yes	1	0.47	Guide	1	10	Hand	10	Home	10	Professional	2.5
28	27	Undirected	6.87	Yes	No	0	6.87	Cantilever Snap	2	10	Spudger	7,5	Home	10	Professional	1.67
4	28	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
9	7	Undirected	0.87	Yes	No	0	0.87	Press fit	1	10	Hand	10	Home	10	Professional	0.71
9	19	Undirected	0.47	Yes	No	0	0.47	Loose fit	1	10	Hand	10	Home	10	Manufacturer	0.83
15	9	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
10	7	Undirected	0.47	Yes	No	0	0.47	Press fit	1	10	Hand	10	Home	10	Professional	0.71
10	19	Directed	0.47	Yes	Yes	1	0.47	Loose fit	1	10	Hand	10	Home	10	Manufacturer	0.83
9	10	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
29	27	Directed	0.47	Yes	Yes	1	0.47	Loose fit	1	10	Hand	10	Home	10	Professional	1.67
4	29	Undirected	0.47	Yes	No	0	0.47	Guide	2	10	Hand	10	Home	10	-	-
28	29	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
4	25	Directed	0.47	Yes	Yes	1	0.47	Guide	2	10	Hand	10	Home	10	Professional	2.5
27	24	Undirected	4.37	Yes	No	0	4.37	Clamp	1	10	Tweezers	7,5	Home	10	-	-
27	21	Undirected	6.87	Yes	No	0	6.87	Faston cable	2	10	Tweezers	7,5	Home	10	Manufacturer	0.5
25	27	Undirected	0.87	Yes	No	0	0.87	Press fit	1	10	Hand	10	Home	10	Professional	1.67
20	19	Undirected	0.47	Yes	No	0	0.47	Loose fit	1	10	Hand	10	Home	10	Manufacturer	0.83
10	20	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
21	7	Undirected	6.87	Yes	No	0	6.87	Faston cable	2	10	Tweezers	7,5	Home	10	Professional	0.71
21	23	Undirected	4.37	Yes	No	0	4.37	IDC	1	10	Tweezers	7,5	Home	10	-	-
18	21	Undirected	4.37	Yes	No	0	4.37	IDC	1	10	Tweezers	7,5	Home	10	Manufacturer	0.5
20	21	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	Manufacturer	0.5
21	22	Directed	63.27	Yes	Yes	1	63.27	Solder	1	0	Solder gun	7,5	Home	10	Manufacturer	2.5
30	7	Directed	9.37	Yes	Yes	1	9.37	Cantilever Snap	3	10	Spudger	7,5	Home	10	Professional	0.71
20	30	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
30	31	Directed	3.27	Yes	Yes	1	3.27	Loose fit	1	10	Tweezers	7,5	Home	10	Professional	5
20	24	Undirected	0.47	No	No	0	0.47	-	-	-	-	-	-	-	-	-
20	23	Directed	0.47	No	Yes	1	0.47	-	-	-	-	-	-	-	-	-
7	24	Undirected	4.37	Yes	No	0	4.37	Clamp	1	10	Tweezers	7,5	Home	10	-	-
7	23	Undirected	4.37	Yes	No	0	4.37	Faston cable	1	10	Tweezers	7,5	Home	10	-	-
23	7	Undirected	4.37	Yes	No	0	4.37	Screw	1	10	Screwdriver	7,5	Home	10	Professional	0.71

3.4.2 Graph visualisation

The layout of the graph was structured in Gephi using the ForceAtlas2 algorithm (Jacomy et al., 2014), which provides a force-directed spatialisation of the nodes. This approach ensures that closely related parts are visually grouped, making the product architecture interpretable and analytically consistent.

Figure II.11 shows the graph-based visualisation of the capsule coffee machine used for repairability assessment. Visual attributes of nodes and edges were configured to reflect their repair-related characteristics. Node size, label size and colour were mapped to parameters such as part priority and RM attributes. Priority parts were displayed with larger node sizes and more vivid colours to enhance their visual prominence. Edges were displayed with varying thickness and directionality according to their weights, particularly disassembly time. Directed edges were represented with arrows to indicate disassembly sequence constraints.

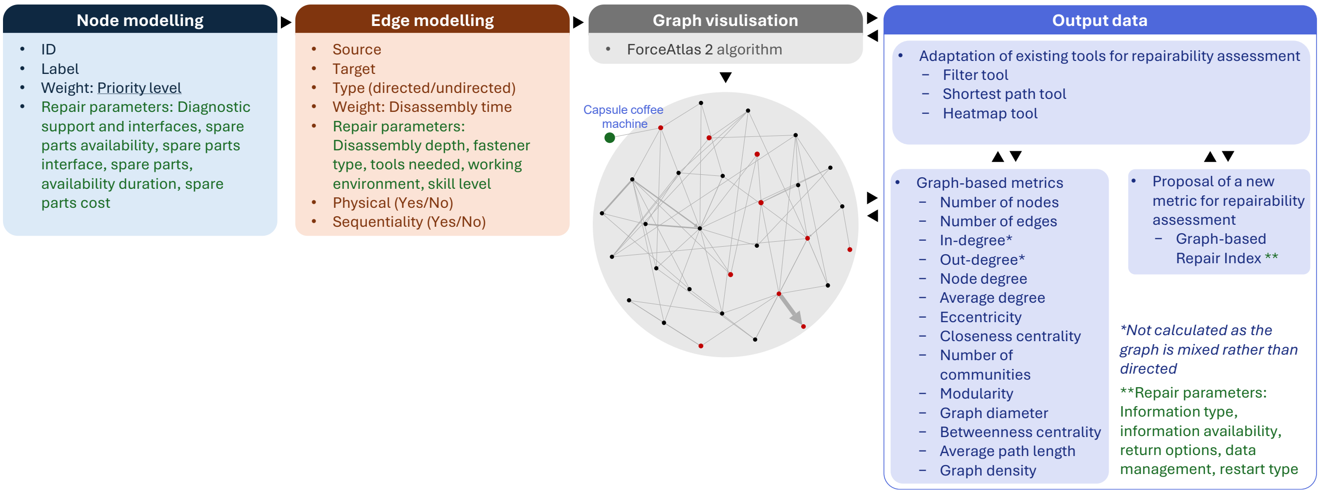


FIGURE II.11 GRAPH-BASED MODELLING FOR REPAIRABILITY ASSESSMENT OF A CAPSULE COFFEE MACHINE.

Figure II.12 illustrates the visualisation of node priority and accessibility characteristics within the network. This visualisation facilitates the rapid identification of key structural and repair-relevant features. Highly connected nodes, such as the boiler, appear centrally positioned with multiple directed paths, indicating their critical role in the disassembly process. Conversely, less connected or peripheral components are positioned at the edges of the graph. The visual structuring supports an intuitive understanding of component accessibility, potential disassembly bottlenecks and modularity within the product architecture.

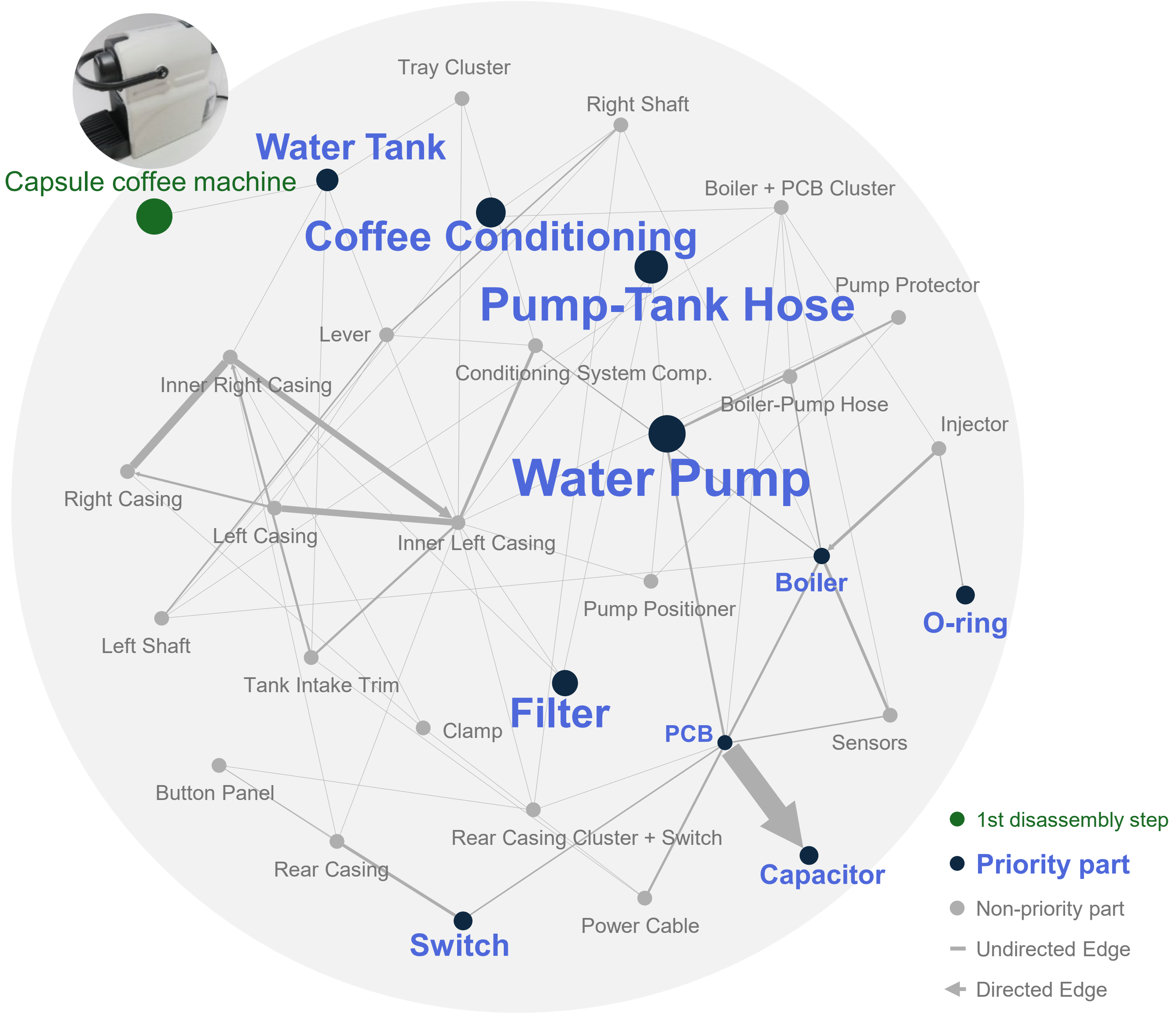


FIGURE II.12 CAPSULE COFFEE MACHINE GRAPH.

3.4.3 Graph-based repairability assessment

Once the graph was modelled and visually structured, the repairability assessment proceeded through the application of graph-based metrics, interactive tools and the graph-based RI metric, providing a multi-level view of the product's repairability.

Graph-level metrics offer an overview of the product architecture. The network comprises 32 nodes and 62 edges. The average degree is 4, indicating moderate interconnectivity. A modularity value of 0.57 reveals well-clustered subassemblies. The diameter of 17 shows the maximum disassembly steps required, while an average path length of 2.61 suggests that most parts can be reached in a few steps. The graph density of 0.13 reflects a sparse yet cohesive structure. Figure II.13 presents the graph-level metrics calculated for the product.

A graph-based RI metric was then computed. Product-level parameters complementing part- and edge-level attributes are shown in Table II.5. The overall RI is 2.94, corresponding to a category C on the repairability scale. The filter tool was used to isolate sequential edges for the computation of diameter, path length and RI, ensuring consistency with actual disassembly processes.

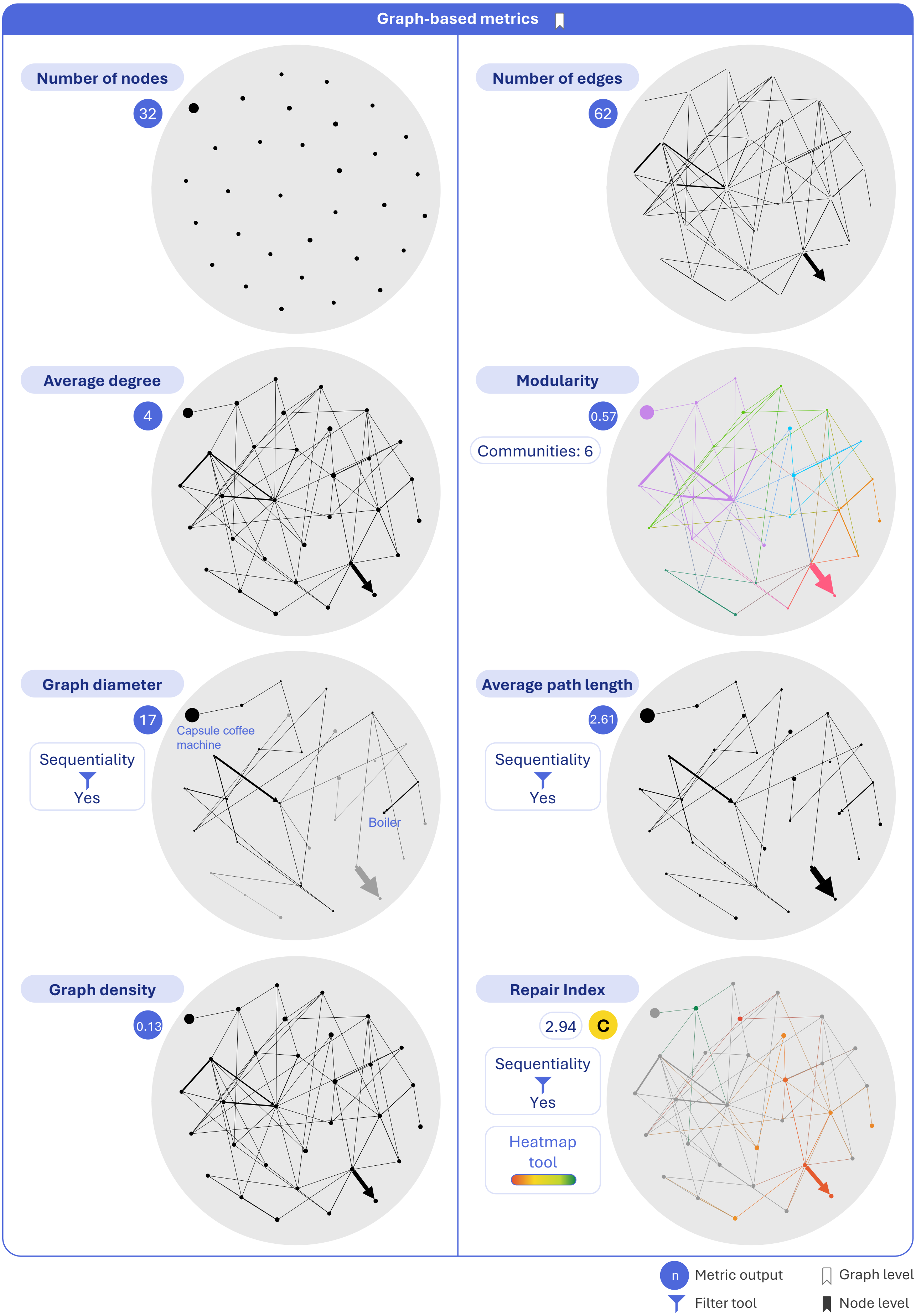


FIGURE II.13 GRAPH-BASED REPAIRABILITY ASSESSMENT OF CAPSULE COFFEE MACHINES: GRAPH-LEVEL METRICS

TABLE II.5 PRODUCT-LEVEL PARAMETERS USED IN RI CALCULATION.

	Information type	Information availability	Return options	Data management	Restart type
Graph	-	3.3	-	-	-

Node-level metrics highlight components with critical roles in disassembly and repair. Figure II.14 presents the worst-performing priority part for each metric. The boiler and PCB exhibit the highest degree and eccentricity (17), indicating poor accessibility and critical connectivity. The capacitor and O-ring also display high eccentricity. The modularity analysis confirms distinct subassemblies. The water tank, with the lowest closeness centrality (0.10), is the least central part, while the PCB shows the highest betweenness centrality (97.38), acting as a structural bottleneck. Figure II.14 presents the node-level metrics for the product.

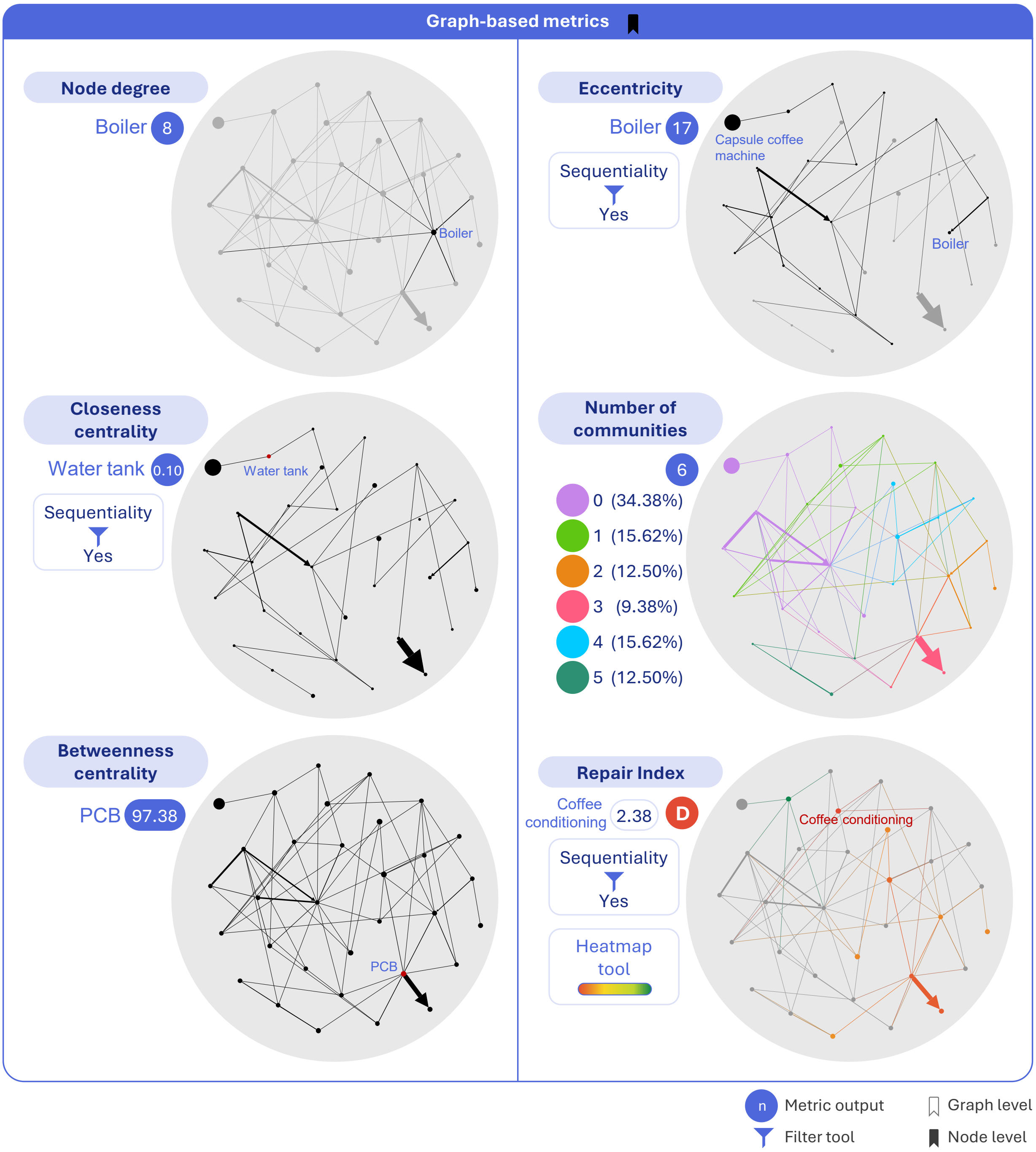


FIGURE II.14 GRAPH-BASED REPAIRABILITY ASSESSMENT OF CAPSULE COFFEE MACHINES: NODE-LEVEL METRICS.

A parameter-level analysis of the RI was conducted to assess priority parts. Table II.6 summarises the results. The coffee conditioning unit scores lowest (2.38, category D), while parts such as the water tank and pump-tank hose perform better.

TABLE II.6 NODE-LEVEL METRICS AND REPAIR INDEX VALUES FOR PRIORITY PARTS OF THE CAPSULE COFFEE MACHINE.

	Grade	Eccentricity	Closeness centrality	Betweenness centrality	Community	Repair Index
Water Tank	5	16	0.10	32.17	2	4.55
Switch	3	14	0.16	12.84	3	3.0
Coffee Conditioning	3	15	0.16	0.5	1	2.38
PCB	8	16	0.15	97.38	5	2.55
Capacitor	1	17	0.13	0	5	2.55
Pump-Tank Hose	3	12	0.19	8.51	4	2.93
Filter	3	12	0.19	1.85	2	2.93
Water Pump	5	14	0.14	37.10	4	2.67
O-ring	1	17	0.13	0	0	2.93
Boiler	8	17	0.13	91.61	0	2.93

The metrics reveal a moderately complex structure with distinct subassemblies. High diameter and eccentricity indicate several deeply embedded parts, limiting accessibility and increasing disassembly time. Improving modularity and reducing diameter could enhance repairability by shortening disassembly paths and reducing dependency chains.

At the node level, parts with high betweenness or eccentricity, such as the PCB and boiler, are critical redesign targets. These findings underline the importance of addressing structural bottlenecks and optimising component layout.

The graph-based methodology developed here shows strong potential for repairability assessment. By integrating network metrics with visual representations, it provides actionable insights for design-for-repair strategies. Its scalability and compatibility with the RM further enhance its practical value. Future work should focus on automating data integration and validating the approach across a broader range of products.

4 CONCLUSIONS

By modelling product architecture through nodes and edges, each enriched with repair-relevant attributes, this approach allows for both a quantitative and visual exploration of how design decisions influence reparability. Specifically, the use of Gephi's analytical tools and layout algorithms enables the identification of critical parts, disassembly bottlenecks and accessibility limitations, as well as the detection of structural patterns such as clustering or centrality. Therefore, this study demonstrates the value of graph-based modelling as a tool for assessing the repairability of products from a structural perspective.

The proposed methodology, structured in three stages, input data structuring, graph visual construction and analytical output, proves to be robust and adaptable. When applied to the case study of a capsule coffee machine, the approach was able to translate EN 45554 based repairability parameters into a visual and metric-driven model. The resulting network allowed for the computation of a graph-based Repair Index metric, alongside the interpretation of key metrics such as modularity, average path length and betweenness centrality. These indicators facilitated both system-wide diagnosis and the identification of specific parts that hinder repairability.

A significant strength of this method lies in its scalability and potential for application to any product category, especially when supported by the standardised structure provided by the Repairability Matrix (RM). The flexibility to represent various EN 45554 parameters, including disassembly effort, spare part logistics and information availability, within a unified graph environment represents a methodological advancement over traditional scoring systems or static diagrams.

Moreover, the combination of macro-level graph insights and micro-level node analysis offers a powerful decision-support tool for designers, policymakers and manufacturers. Visual ranking and filtering enable an intuitive exploration of structural complexity, while metrics grounded in network science translate these insights into actionable repair strategies. As demonstrated, this approach is particularly useful for identifying high-priority parts that should be redesigned to reduce dependency, improve accessibility, or enhance modularity.

Nonetheless, the approach also presents some limitations, particularly the manual nature of data entry and the dependence on accurate modelling of product structure. Future work should focus on integrating graph-based repairability modelling directly into CAD environments to enable real-time, parametric evaluations during the early phases of design. This would significantly increase the applicability and efficiency of the method, allowing design-for-repair principles to be implemented more systematically.

In summary, this study presents a novel, scalable and interpretable methodology for assessing product repairability using graph-based modelling. It contributes to the advancement of design practices that are aligned with the principles of the circular economy and supports the broader transition toward more repairable and sustainable consumption systems.

5 ACKNOWLEDGEMENTS

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Article III

Right to repair in practice: Environmental and economic performance of coffee machine repairs

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ABSTRACT

The European Commission's recent adoption of the 'Right to Repair' promotes product repairability to reduce waste and conserve raw materials. This European framework also requires that consumers be provided with clear, accessible information on their options to repair or replace broken appliances, emphasising the environmental and economic advantages of repair. Focusing on the product category of 'capsule coffee machines', this research aims to provide consumers with comprehensive information to support decision-making regarding repair costs and environmental performance. The study's novel approach integrates Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methodologies, enabling a holistic evaluation of the environmental and economic impacts of repair versus replacement decisions. Additionally, it introduces repairability indices for specific components and presents the findings in a consumer-friendly format, aligned with the European 'Right to Repair' initiative. To this end, four capsule coffee machines were selected as a case study. A diagnosis of the current repair landscape was conducted using data from the Open Repair Alliance, which provided information on priority parts, failure rates, failure ages, and repair success rates. Repairability indices for each machine and its priority components were then calculated in accordance with the EN 45554 standard. Finally, replacement and repair scenarios were analysed to assess their environmental and economic performance. The results indicated that prioritising the repair of components with high failure rates and ease of repair offers significant environmental and economic benefits. This transparent information can be provided to consumers, enabling them to decide between repairing or replacing their equipment. In theoretical terms, this framework enhances understanding of integrated sustainability assessments by combining environmental and economic analyses. In practical terms, it provides actionable insights for manufacturers and policymakers to design products for repairability. For society, it empowers consumers to make informed decisions that foster sustainable consumption and production.

KEYWORDS

Circular Economy, Repair Index, EN 45554, LCA, LCC, EEE, Visual communication

1 INTRODUCTION

The recent publication of the 'Right to Repair' (European Parliament, 2024a) and Regulation (EU) 2024/1781 (European Union, 2024) marks a significant step forward in promoting sustainable consumption, while also supporting the Circular Economy Action Plan (European Commission, 2023a) and the European Green Deal (European Commission, 2019). According to the European Commission (2023a), the premature disposal of reparable goods contributes to increased waste generation and greenhouse gas emissions, as well as higher demand for valuable resources in the production of new products. Additionally, it is estimated that consumers waste approximately €12 billion annually by choosing replacement over repair (European Commission, 2023a). To promote sustainable consumption, this framework aims to increase the repair and reuse of viable defective products, both within and beyond legal warranties.

Currently, information regarding product reparability is only available at retail points in countries with relevant legislation in place. France took the initiative in 2020 by introducing a repairability index for certain product categories (Ministère de la Transition écologique, 2020). From 2025 onwards, the durability index will replace the repairability index for certain product categories in France (The French Agency for Ecological Transition, 2021). At the European level, Belgium followed suit by proposing a regulation from the Federal Minister of Environment, introducing a repairability index and a durability index similar to the French system (Zakia Khattabi, 2023). Additionally, the Spanish Ministry of Consumer Affairs conducted a public consultation in 2021 regarding the future regulation of the repair index for electrical and electronic devices (MC (Spanish Ministry of Consumer), 2021). Prior to these regulatory frameworks, other initiatives providing methods for calculating repairability had already emerged, including standards such as ONR 192102 (2014) and EN 45554 (2020), as well as methods developed by research units such as iFixit (Flipsen et al., 2016), AsMeR (Bracquené et al., 2018), and the Repair Score System (RSS) (Cordella et al., 2019).

In parallel, voluntary initiatives also exist that focus on promoting open and accessible repair at the user level. The Open Repair Alliance (2024) is an international network dedicated to supporting organisations involved in community repair while also striving to optimise the collection and publication of data on the repair of electrical and electronic equipment (EEE). Currently, it comprises seven databases from non-profit organisations that champion collective repair initiatives and collect data related to repairs using a collaborative standard format known as the Open Repair Data Standard (ORDS). This enables relevant information on out-of-warranty repairs to be documented and shared with both commercial repairers and users, promoting demand for more repairable products, enhancing informational support, and facilitating access to repair services. However, the ORDS format is not designed with consumer comprehension in mind and must therefore be adapted to incorporate intuitive data presentation methods that specifically address consumer needs, thereby empowering informed decision-making.

To enable consumers to make better-informed decisions, information regarding a product's repairability should extend beyond the repair index itself. Understanding the environmental and economic implications of repairing versus replacing a faulty product is crucial. Notably, 77% of consumers are willing to repair rather than replace (European Commission, 2020b). In this regard, the recent Regulation (EU) 2024/1781 (European Union, 2024) emphasises that, to allow consumers to effectively assess and compare products, the format, content, and display of repairability scores should include easy-to-understand language or pictograms. Furthermore, according to Directive (EU) 2024/825 (European Parliament, 2024b), manufacturers should provide additional relevant information on repair, including, but not limited to, the estimated cost of spare parts.

Within this framework, there is a need to define reliable information for consumers that aligns with European regulations and helps them make informed purchasing decisions at the point of sale, as well as determine whether to replace or repair a product when it fails. This study responds to that need by integrating environmental and economic criteria into repairability assessment and applying it to the specific case of capsule coffee machines, a product group not previously analysed in depth despite its growing market relevance and short lifespan. With this approach, the present study aims to identify and generate information that facilitates consumer decision-making regarding repair by considering the environmental and economic performance of products. This will be applied to the case study of the 'capsule coffee machines' product category, appliances that fall under the small EEE (sEEE) category and are present in the majority of Spanish households (Blanco-Espeleta et al., 2024). According to Baldé et al. (2024) small EEE constitutes the largest category of e-waste in terms of mass, accounting for 20 billion kg in 2022, or almost one-third of the world's total e-waste. In particular, capsule coffee machines show a clear growth trend in the European market, with annual sales increasing from 3.01 million units in 2010 to a projected 11.04 million in 2025, and the installed stock rising from 12.55 to 62.06 million units over the same period (Spiliotopoulos et al., 2025). Coffee machines are among the most frequently repaired small household appliances, yet their repair success rate remains relatively low, around 50-55%, placing them among the least successfully repaired product categories (Spiliotopoulos et al., 2025). This category has also been highlighted by R2R Europe (2024) due to the frequent disposal of machines caused by minor faults, the lack of explicit requirements for repairable design and the limited availability of spare parts and replaceable components.

In particular, capsule coffee machines show a strong growth trend in the European market, with annual sales increasing from 3.01 million units in 2010 to a projected 11.04 million units in 2025, and the installed stock rising from 12.55 to 62.06 million units in the same period (Spiliotopoulos et al., 2025). Despite their popularity, their actual average lifetime remains limited to 5–7 years, significantly below the consumer-expected 8.7 years. A recent JRC study (Spiliotopoulos et al., 2025) ranks coffee machines among the top product groups most in need of a reparability scoring system, based on failure rates, market penetration, and repair feasibility. Additionally, European Commission (2016) estimates that repair could extend their lifespan by up to four years, making them one of the most repair-benefiting products after vacuum cleaners. However, this product category remains largely understudied in the academic literature on repairability.

To achieve the aim of the study, a diagnosis of the current repair landscape for the 'capsule coffee machines' product category is conducted to identify priority parts and their frequency of failure. Subsequently, the repairability indices of a representative sample of capsule coffee machines and their priority parts are calculated, and the environmental and economic performance of repairing each priority part is compared with that of replacing the entire capsule coffee machine with a new one. Finally, the information obtained is represented graphically to enhance consumer comprehension. In this regard, a consumer study (European Commission, 2020c) suggests that colour-coding the reparability scale and including numerical scores could significantly improve understanding, thereby assisting consumers in making decisions when a priority part of a capsule coffee machine fails.

Although the environmental and economic aspects of repairability have begun to be explored in scientific literature, much of the research has focused on developing repairability indices, often overlooking more comprehensive environmental and economic analyses that compare scenarios across different products within the same category or identify patterns within these categories. While studies such as Boldoczki et al. (2020) and Cordella et al. (2021) have provided valuable insights into specific aspects of repair and replacement, the present study is novel in its integrated approach, combining both Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methodologies, to offer a holistic evaluation of repairability. Moreover, most previous research focuses on smartphones, ICT devices, or large appliances, and tends to operate at the product level. In contrast, this study applies a component-level perspective to a widely used but under-analysed product group: capsule coffee machines.

This integrated framework addresses the limitations of previous research by translating technical repairability data into accessible, consumer-friendly information, while also providing a solid basis for further investigations into the links between product design, environmental impacts, and economic performance.

The research presents an innovative contribution by combining Life Cycle Assessment (LCA) methodology (ISO 14040, 2006) and Life Cycle Cost (LCC) methodology (Swarr et al., 2011) to examine repair versus replacement decisions specifically for capsule coffee machines, an understudied category within household Electrical and Electronic Equipment (EEE). Building on recent efforts to quantify repairability, the study utilises real-world repair data from the Open Repair Alliance, drawing directly from actual consumer repair experiences. By applying the EN 45554 (2020) repair standard and an adapted Repair Matrix (RM) (Blanco-Espeleta et al., 2024) it enables the calculation of repairability indices not only for the overall product but also for individual priority components. This component-level perspective allows for a more detailed and realistic assessment of both environmental and economic impacts over time. This multidimensional approach, based on real-world failure data, applied standards, and dual sustainability metrics, offers a distinct and policy-relevant methodology aligned with the emerging EU 'Right to Repair' framework.

2 LITERATURE REVIEW

Since the announcement of the 'Right to Repair' (European Parliament, 2020), several actions related to repairability have been developed, focusing on promoting repairability and increasing consumer awareness, as well as advancing scientific understanding in this area.

Aimed at increasing consumer awareness of repairability, various non-profit organisations, including the Anstiftung Foundation, Fixit Clinic, iFixit, The Repair Cafe Foundation, and The Restart Project, organise collective repair activities among consumers and collect data on the repairs carried out. The Open Repair Alliance (2024) gathers and shares this information, as illustrated in Figure III.1 A total of 102,446 entries are recorded across all the databases. It was observed that Repair Cafe International and The Restart Project are the organisations with the highest number of records, accounting for approximately 80% of all entries in the Open Repair Alliance (2024) (Figure III.1a). This data has experienced significant growth in recent years, with the total number of entries across all databases increasing by 83% between 2021 and 2023. The Restart Project database showed the highest growth (163%), followed by Anstiftung (110%). Analysing the data by country, the United Kingdom (27.4%) and the Netherlands (27.3%) have the highest number of entries (Figure III.1b). When analysing the data by product category, Figure III.1c shows that small household EEE items, such as vacuum cleaners, coffee machines, laptops, and lamps, are those most frequently brought to these repair workshops for repair. For each entry in the database, information can be obtained regarding the repaired product, the repair process, and the provider. Specifically, for the product, the data includes the product category, brand, year of manufacture, and product age. Regarding the repair, the data covers the repair status, the issue, and any barriers encountered during the repair process, if applicable. Concerning the repair process, it includes the event date and the country. Additionally, it incorporates information about the data provider responsible for organising, compiling, and sending the data, as well as the registration date. It is important to note that ORDS is designed for data collection by technicians, which can result in information that may be non-intuitive and difficult for consumers to analyse. This highlights the need to adapt the data collection model to provide consumers with clear and direct information, enabling them to make well-informed repair decisions.

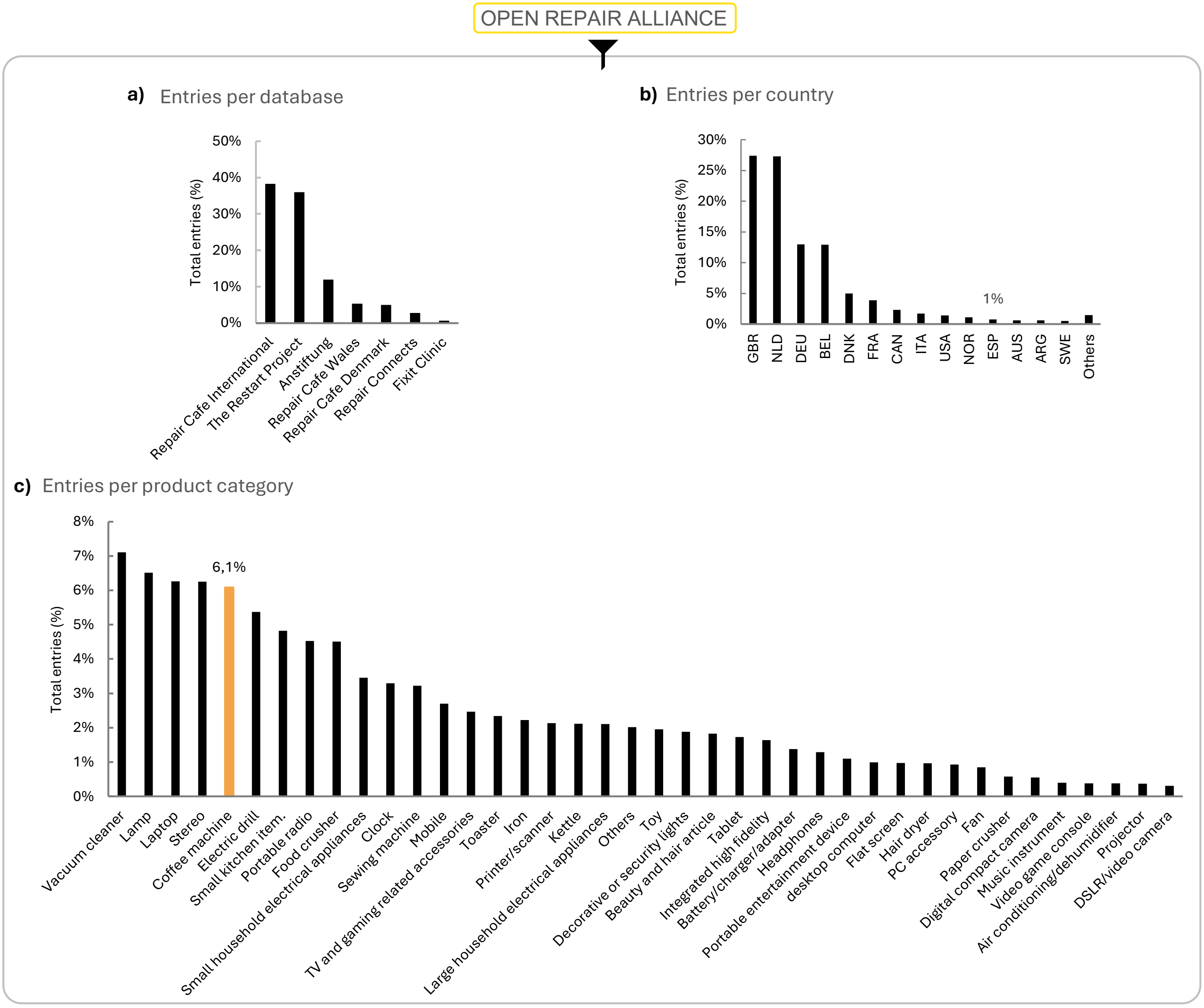

FIGURE III.1 INFORMATION FROM REPAIRS COMPILED BY THE OPEN REPAIR ALLIANCE.

Focusing on the actions of scientists, various studies have been conducted to analyse the environmental and/or economic performance of repair-related scenarios within the framework of the circular economy. To gain insight into this field, a literature review was carried out using the Scopus and Google Scholar databases, employing combinations of specific search strings such as 'life cycle assessment', 'life cycle cost', 'repair', 'repairability', 'EEE', 'remanufacture', 'reuse', 'product', and 'circular economy' within the title, keywords, or abstract of each article, covering the period from 2020 (the year of the announcement of the 'Right to Repair' in the European Parliament) to the present. Reviews prior to this date can be found in Boldoczki et al. (2020). For each article encountered, the abstract was inspected to identify those focused on analysing, comparing, or applying LCA, LCC, or repair methods within various scenarios aligned with circular strategies. After conducting a content analysis of the selected studies, the findings, summarised in Table III.1, highlighted several key aspects: the type of scenario analysed (Repair, Early replacement, Reuse, Remanufacture or refurbishing, and Upgradeability); and specific life cycle elements, such as the primary aspects of the LCA study, Life Cycle Inventory (LCI) database, Life Cycle Impact Assessment (LCIA) method, the units used for the LCC analysis and the product category analysed.

In addition to offering a broad overview of methods and product categories, the review also reveals several gaps. First, it shows that the majority of studies operate at the product level, providing generalised insights without applying repairability indices at the component level. Second, it highlights the lack of environmental and economic analyses that take into account the technical reparability of individual components, a key factor influencing real repair behaviour. Finally, while smartphones and ICT products are frequently studied, small household appliances such as capsule coffee machines remain underrepresented despite their prevalence and growing importance in EU policy discussions (Spiliotopoulos et al., 2025).

TABLE III.1 LITERATURE REVIEW.

Reference	Scenarios					Life cycle aspect			LCA		LCC	Product Category
	Repair	Early replacement	Reuse	Upgradeability	Remanufacture or refurbishing	Comparison with updated products	Energy efficiency	Lifetime extension after repair	LCI database	LCIA method	Unit	
Bovea et al. (2020a)	x	x	x	—	—	—	—	—	Ecoinvent	CML-midpoint	—	Vacuum cleaner, hand blender, coffee maker, heater, juicer, iron, sandwich maker, hairdryer, toaster
Boldoczki et al. (2020)	x	x	x	—	—	x	x	x	Ecoinvent 3.5	ReCiPe-midpoint	—	Washing machine, refrigerator, range, freezer, PC, printer, monitor, laptop
Leiden et al. (2020)	x	x	x	—	—	—	—	—	Ecoinvent 3.1	ReCiPe-endpoint	—	Surgery instrument set
Cordella et al. (2021)	x	x	x	—	x	—	—	x	Ecoinvent 3.5	n/a	EUR	Smartphones
Pamminger et al. (2021a)	x	—	—	—	x	—	—	—	Ecoinvent 3.5	EPD	—	Smartphone
Rizan et al. (2022)	x	x	x	—	—	—	—	—	Ecoinvent 3.6	ReCiPe-midpoint & endpoint	GBP	Surgical scissors
Rizan and Bhutta (2022)	—	x	x	—	—	—	—	x	Ecoinvent 3.6	ReCiPe-midpoint & endpoint	GBP	Hybrid laparoscopic clip appliers, scissors, ports
Proske (2022)	x	—	—	x	—	x	—	x	Ecoinvent 3.6	CML- midpoint	—	Smartphone
Mann et al. (2022)	—	—	—	—	x	—	—	—	n/a	ReCiPe-midpoint & endpoint	—	Computer
Jerome et al. (2023)	x	—	—	—	—	—	x	x	Ecoinvent 3.8	EF3.0-midpoint	—	High-voltage electric motors
Kouloumpis et al. (2023)	x	x	x	—	—	—	—	x	Ecoinvent	ReCiPe-midpoint	—	Laptop, desktop computer, printer, monitor, mobile phone, vacuum cleaner
Barkhausen et al. (2024)	x	x	—	—	—	—	x	x	n/a	n/a	—	Electric motors
Sandez et al. (2024a)	x	x	—	—	—	—	—	x	Ecoinvent	Environmental Footprint	—	Kettles

In the scenarios analysed, focusing on studies that consider repair, early replacement, and reuse, Bovea et al. (2020) propose a methodology to identify the optimal end-of-life scenario (repair & reuse versus replacement) for sEEE. The results indicate that, across all analysed categories, the repair/reuse option generally proves to be more environmentally beneficial than replacement, except in cases of motor or Printed Circuit Board (PCB) failures. Moreover, in relation to kettles, Sandez et al. (2024b) states that extending lifetimes through repair can reduce the total environmental impact compared to not doing so. One study examining the same scenarios with different types of EEE (four large household appliances and four small electrical devices), considering factors such as energy efficiency and product lifespan extension, also concludes that whether reuse is preferable to replacement depends on the environmental impact category, product efficiency, and expected duration of use (Boldoczki et al., 2020). Another study, focusing on high-voltage electric motors used in industrial applications and considering energy efficiency, notes that the benefit of extending use through repair is limited and uncertain compared to replacing them with more efficient technology (Jerome et al., 2023). Also concerning electric motors, Barkhausen et al. (2024) notes that early replacement of inefficient but functional products can reduce environmental impacts. Additionally, Kouloumpis et al. (2023) analyses six categories of EEE under repair and reuse scenarios, showing that the greatest reduction in environmental impact occurs through repair compared to replacement. However, in the case of vacuum cleaners, the environmental impact of repair may exceed that of replacement, emphasising the importance of the energy efficiency of the replacement product (Kouloumpis et al., 2023). Leiden et al. (2020) analyses the same scenarios (repair, premature replacement, and reuse), but focused on surgical instruments, and concludes that the environmental impact of the disposable system is significantly lower across all studied environmental impact categories and the single-score indicator, due to the fact that the selected cleaning and sterilisation process for reusable instruments accounts for up to 90% of the greenhouse gas emissions. Continuing with the same scenarios but focusing on different medical materials, Rizan and Bhutta (2022) finds that the carbon footprint of hybrid surgical instruments, which contain both single-use and reusable components, is approximately one-quarter that of their single-use counterparts, with the economic cost being roughly half. Furthermore, Proske (2022), considering scenarios of repair and upgradeability for mobile phones, such as battery replacements, repairability, and camera upgrades, concludes that these options are environmentally favourable compared to obsolescence.

Despite the diversity of products and scenarios analysed, most of these studies assess reparability at the product level, without applying component-level indices or integrating them into environmental or economic comparisons.

Therefore, repairing and reusing products are effective strategies for minimising waste and conserving resources. However, the benefits of these strategies vary depending on the type of product and its intended use, emphasising the need for specific life cycle assessments. Regarding studies that consider remanufacturing scenarios for mobile phones, Cordella et al. (2021) states that remanufactured and second-hand devices could have greater environmental benefits. However, these benefits depend on factors such as travel distances, replaced parts, and the materials involved. Additionally, for the same product category, Pamminger et al. (2021b) concludes that remanufacturing or refurbishing and repair result in a significant reduction in Global Warming Potential compared to the baseline scenario, specifically, a reduction of 25% by remanufacturing instead of purchasing a new smartphone, 55% through refurbishing and 71% through repair. Moreover, Mann et al. (2022) distinguishes between centralised and decentralised refurbishing, concluding that a decentralised refurbishing network has a smaller environmental impact than a centralised one in the case of computers. This conclusion is based on the fact that centralised refurbishing relies on a facility in the Middle East, while decentralised refurbishing utilises plants near collection locations.

Regarding the application of the LCA methodology, Ecoinvent (2024) is the most commonly used database for modelling the LCI across the different scenarios analysed. With regard to LCIA, the ReCiPe method (Huijbregts et al., 2016) and CML method (Frischknecht et al., 2021) are the most frequently applied for obtaining environmental indicators for each impact category (mid-point), with global warming being the most commonly assessed aspect. However, the Environmental Footprint, recently proposed by the EC (European Commission, 2021), has already been used by Jerome et al. (2023) and Sandez et al. (2024b).

In terms of the application of the LCC methodology, only three of the reviewed studies analyse the economic consequences of implementing circular economy measures on products. However, economic performance is not integrated with environmental performance. Nevertheless, Cordella et al. (2021) suggests that, for mobile phones, scenarios involving repair, reuse, and refurbishing are economically attractive to consumers when considering factors such as the purchase price of new products, operating costs, the cost of more durable devices, repair costs, and the purchase price of used devices. However, these scenarios may also lead to rebound effects, resulting in increased spending (Zink and Geyer, 2017). Additionally, in the case of medical equipment, considering the costs associated with purchasing a new product, disposal, and repair, opting for repair or reuse at the end of its functional life, rather than replacing it with a new product, can reduce overall financial costs (Rizan et al., 2022; Rizan and Bhutta, 2022).

Regarding the product categories analysed in the literature, it is noteworthy that smartphones are featured in three studies, indicating their growing relevance in recent years. Similarly, computing devices, such as laptop and desktop computers, are also examined more than once. The review spans a wide range of categories, from small electronic devices to specialised medical equipment and industrial motors, reflecting diverse applications and uses. However, there is a notable lack of case studies on small household electrical and electronic appliances, such as kitchen gadgets or personal care devices. This is consistent with R2R Europe (2024), which highlights significant gaps in the current regulatory framework for repairability across various product categories in the EU. This gap is particularly pronounced in the case of capsule coffee machines, which remain largely unexamined as a distinct product category in previous repairability studies. This lack of focus on small appliances, despite their growing volume and environmental relevance, reinforces the appropriateness of selecting capsule coffee machines as a representative and policy-relevant case study within sEEE.

In addition, the reviewed studies do not apply component-level repairability indices, such as EN 45554 or the Repair Matrix, in combination with LCA or LCC approaches. Although repairability has been a frequent subject of study in recent years, particularly regarding the development of repair indices in the literature, such as the RI by Blanco-Espeleta et al. (2024), AsMeR by Bracquené et al. (2018), RSS by Cordella et al. (2019), as well as assessments by EU members (Ministère de la Transition écologique, 2021; Zakia Khattabi, 2023), none of the authors in the literature review evaluating repair scenarios consider repairability levels. This oversight occurs both in comparing scenarios across different products within the same category and in identifying patterns within product categories, highlighting the need for a comprehensive assessment of environmental, economic, and repair impacts. Bridging this gap would also involve providing information that supports consumer decision-making, considering both the repairability level of products and their associated environmental and economic benefits. This study seeks to address these gaps by integrating component-level repairability indices, based on EN 45554 and the Repair Matrix, with life cycle assessment and life cycle cost methodologies. This approach is applied to capsule coffee machines, an underexamined yet highly relevant product category, and is intended to inform both consumer decision-making and future policy development.

3 METHOD

To achieve the objectives of this study, a three-stage methodology was implemented, as illustrated in Figure III.2. Stage I involved collecting and preparing information specific to the selected product category. This data was used in Stage II to define the evaluation scenarios. Once the scenarios had been defined, they were analysed from both environmental and economical perspectives in Stage III, using the LCA and LCC methodologies, respectively.

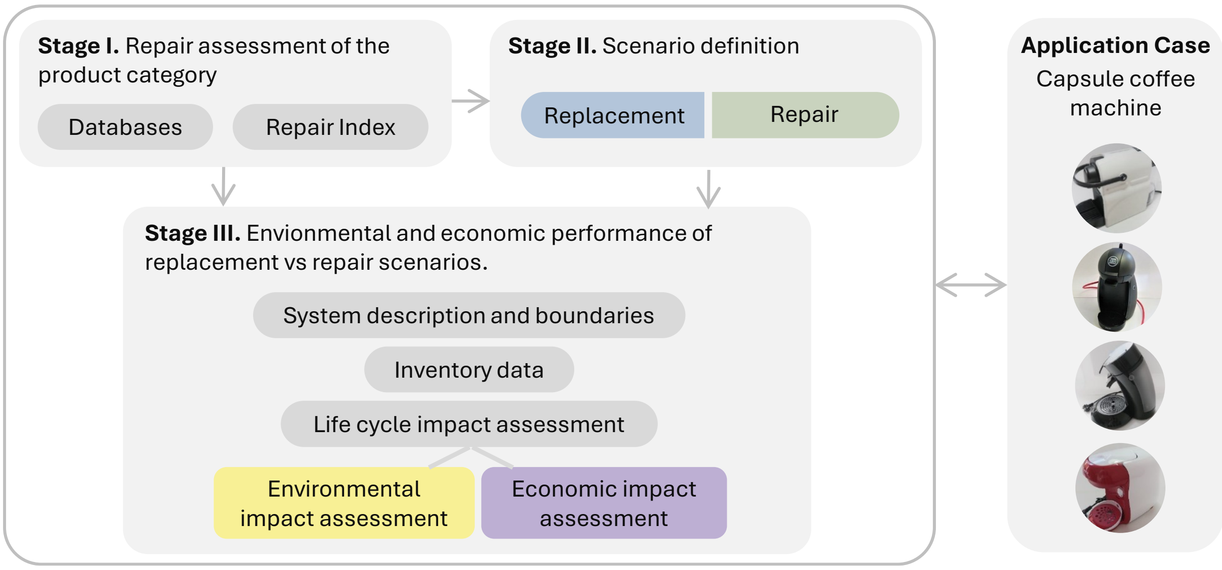

FIGURE III.2 METHODOLOGY.

STAGE I. DATA COLLECTION ON REPAIR

In this stage, the information related to the repairability of the product category was obtained from two different sources: information from repairs compiled by the Open Repair Alliance (2024) and information on the level of repairability, determined by calculating the Repair Index (RI).

Regarding the information from repair databases, the seven databases provided by the Open Repair Alliance (2024), including those from the Anstiftung Foundation, Fixit Clinic, iFixit, The Repair Cafe Foundation, and The Restart Project, were selected and analysed. For each database, entries related to the product category under study were identified, and repair-related information was extracted. Specifically, information on the product brand, year of manufacture, product age, state of repair, problem, repair barrier, date of event, country, data provider and date of registration were obtained for each entry in the databases related to the product category under study. This information was then compiled to calculate an overall average for the entire product category. Based on this data, a list of priority parts, target components that are functionally relevant and associated with typical failures for a specific product category (Spiliotopoulos et al., 2022), was compiled, and the following parameters were calculated for each:

- The failure rate, calculated as the percentage of instances in which a priority part was the cause of product failure.
- The failure age, calculated as the average year of failure of the priority parts.
- The success repair rate, calculated as the percentage of successful repairs of each priority part.
- This specific data was used in both Stage II and Stage III.

Regarding the repair index, although various standards exist, such as ONR 192102 (2014) and EN 45554 (2020); methods developed by research units, such as iFixit (Flipsen et al., 2016), AsMeR (Bracquené et al., 2018) and the Repair Score System (RSS) (Cordella et al., 2019); and national regulations such as the French Reparability Index (FRI) (Ministère de la Transition écologique, 2021), it was decided to apply the Repair Matrix (RM) and the Repair Index (RI) proposed by Blanco-Espeleta et al. (2024), as it allows the Repair Index (RI) to be calculated both holistically and by priority part.

STAGE II. SCENARIO DEFINITION

Based on the information gathered in the previous stage, each scenario to be evaluated had to be defined. To this end, the following parameters were considered:

- Category product lifespan (L_p): the estimated lifetime of the product category, obtained from the European Commission (2011).
- Life Extension (LE): the extension of the product lifespan following repair, obtained from the European Commission (2016).
- Priority part lifespan (L_j): the estimated lifetime of the priority part, obtained in Stage I.
- Considering the failure of a product within the analysed product category, two distinct scenarios were defined:
- Replacement scenario: the substitution of the broken product with an equivalent one.
- Repair scenarios: repair of the priority part causing the failure. For each repair scenario identified in Stage I involving priority parts for the product category under study, different lifetime extensions of the product after repair are considered (LE = 1 year, 2 years, 3 years, or 4 years), as illustrated in Figure III.3. These lifetime extension scenarios ranging from 1 to 4 years are considered based on assumptions from the Study on Socioeconomic Impacts of Increased Reparability (European Commission, 2016), which estimates that mid-life and end-of-life repairs can extend coffee machines use by an additional 4 years. Additionally, this range of lifespan extension scenarios serves as a sensitivity analysis, confirming the robustness of the findings against variations in the repair-induced extension of the product's life. Considering the previously defined variables (L_p and L_j), these may conflict and not always align. Specifically, there will be priority parts whose failure occurs before the end of the product's lifespan ($L_j > L_p$), while others may fail in the same year ($L_j = L_p$), and some may fail later ($L_j < L_p$). Therefore, two extreme situations can arise:
  - The estimated priority part lifespan (L_j) is shorter than the estimated category product lifespan (L_p): $L_j < Lp$ (Figure III.3a).
  - The priority part lifespan (L_j) is greater than the category product lifespan (L_p): $L_j > L_p$ (Figure III.3b).

By consistently using the category product lifespan (L_p) as the time reference and considering it as the functional unit, a comparison of results between the various scenarios defined (repair versus replacement) for each priority part was enabled.

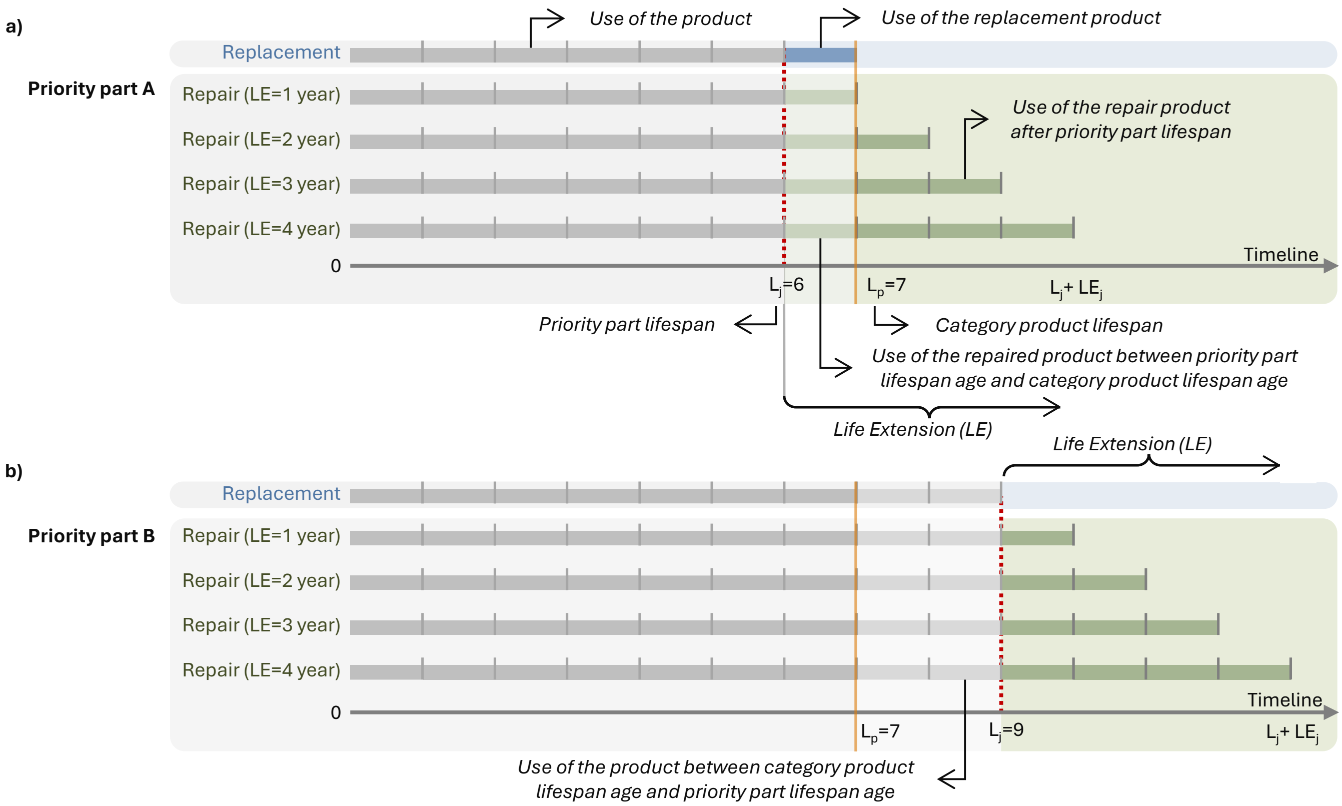

FIGURE III.3 INFORMATION FOR SCENARIO DEFINITION.

STAGE III. ENVIRONMENTAL AND ECONOMIC PERFORMANCE OF REPLACEMENT VERSUS REPAIR SCENARIOS

Following the definition of the replacement and repair scenarios, their environmental and economic performance was evaluated using the LCA and LCC methodologies.

This stage entailed a comparative analysis of the environmental and economic performance between the replacement and repair scenarios, based on the average age of failure for each priority part. First, the goal, scope, and functional unit of the study were defined. Next, the life cycle inventory was compiled. Finally, the life cycle impact assessment was conducted, evaluating both environmental and economic impacts.

Goal, system boundaries and functional unit

The goal of this study was to assess the environmental and economic performance of repairing versus replacing a capsule coffee machine upon its failure. The system boundary was defined as 'cradle to grave', as illustrated in Figure III.4 The selected functional unit was the use of the capsule coffee machine for the duration of its product category lifespan (seven years) (European Commission, 2011), assuming the production of two coffees per day. The consideration of this functional unit enables the comparison of environmental and economic impacts between the different coffee machines, regardless of variations in materials, component design, or technical configuration, as long as they fulfil the same functional performance.

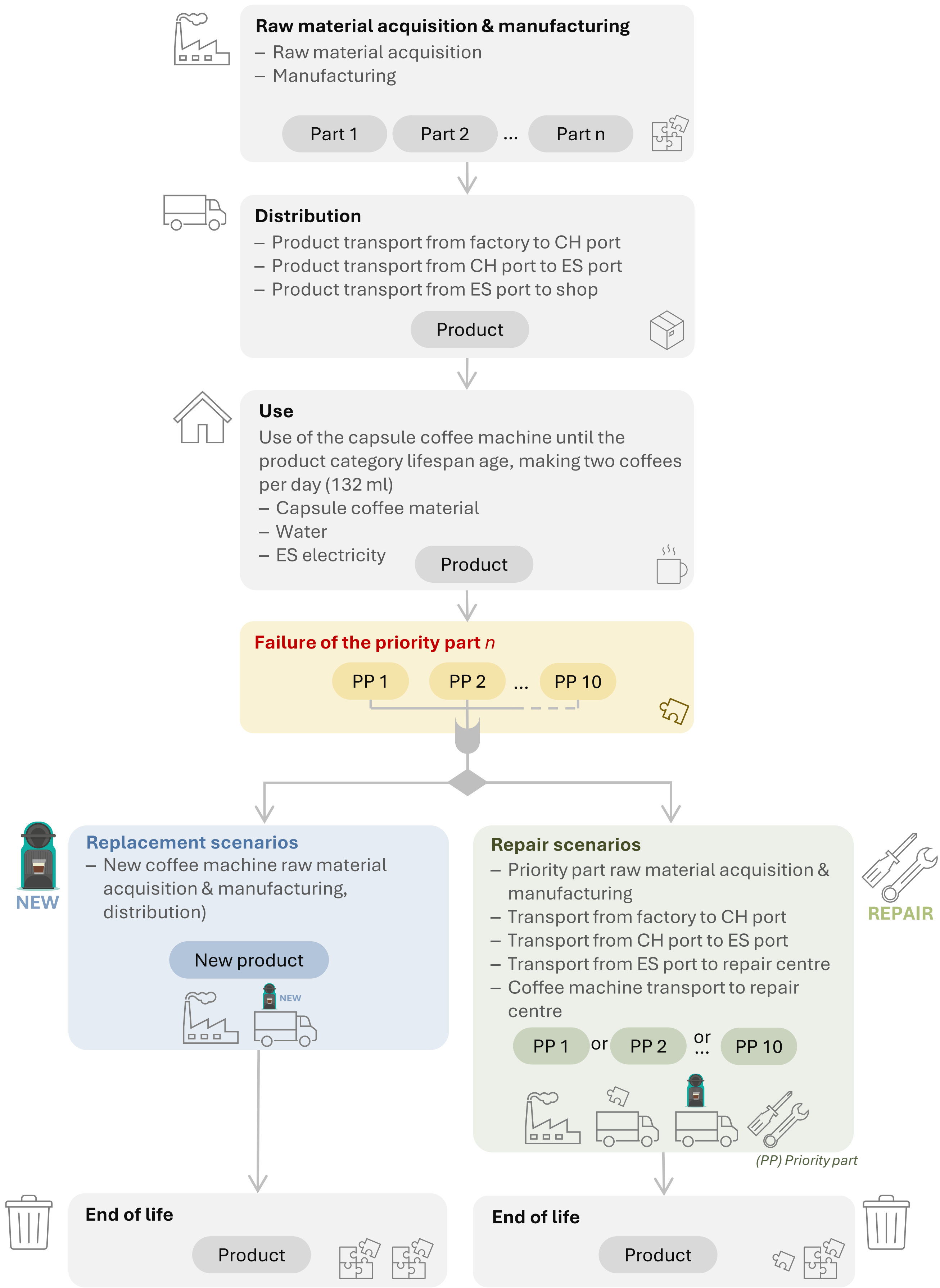

FIGURE III.4 SYSTEM BOUNDARY.

Life Cycle Inventory

The LCI model was developed using a combination of primary data and secondary data from the Ecoinvent (2024) database in SimaPro (2024) software, covering each life cycle stage as outlined below.

Raw material acquisition and manufacturing stage

The Life Cycle Inventory (LCI) for the case study was compiled following the disassembly of the four capsule coffee machines in the laboratory (Figure III.5). Table III.2 presents the material weights and manufacturing processes for each component of the disassembled machines.

TABLE III.2 COMPOSITION OF THE CAPSULE COFFEE MACHINES (kg).

			C1	C2	C3	C4
Material	Plastics	PP	1.70 x 10-1	1.94 x 10-1	7.09 x 10-1	1.20 x 10-2
		ABS	8.15 x 10-1	4.62 x 10-1	3.33 x 10-3	9.93 x 10-1
		SAN	1.23 x 10-1	-	-	1.90 x 10-1
		PVC	4.26 x 10-2	3.80 x 10-3	1.30 x 10-3	-
		Silicone	1.20 x 10-1	1.62E-02	2.68 x 10-2	5.17 x 10-2
		Nylon (PA)	2.58 x 10-1	9.75E-02	1.91 x 10-1	1.25 x 10-1
		NBR (rubber)	2.80 x 10-3	-	-	-
		EPS	9.34 x 10-2	-	-	-
		PE	4.00 x 10-3	5.60 x 10-3	-	-
		SMMA	-	1.39 x 10-1	-	-
		HDPE	-	5.90 x 10-3	-	-
		LDPE	-	2.00 x 10-3	1.19 x 10-2	-
		PC	-	-	2.37 x 10-2	-
		POM	-	-	8.91 x 10-2	-
		PET	-	-	1.15 x 10-3	-
		PS	-	-	-	9.82 x 10-2
		PPS	-	-	-	1.66 x 10-3
	Metal	Steel	1.81 x 10-2	1.07 x 10-1	3.82 x 10-2	1.64 x 10-2
		Aluminium	-	2.97 x 10-2	-	-
		Stainless Steel	-	-	1.96 x 10-1	-
	Paper & cardboard		2.91 x 10-1	2.91 x 10-1	5.41 x 10-1	6.46 x 10-1
	Electronic components	Cable	1.11 x 10-1	1.25 x 10-1	9.07 x 10-2	1.12 x 10-1
		PCB	2.89 x 10-2	4.43 x 10-2	4.40 x 10-2	5.78 x 10-2
		Water pump	3.25 x 10-1	3.63 x 10-1	1.44 x 10-1	1.52 x 10-1
		Switch	1.80 x 10-3	4.00 x 10-3	3.12 x 10-3	7.21 x 10-3
		Thermal fuse	8.90 x 10-3	2.40 x 10-3	2.23 x 10-3	3.80 x 10-3
		Thermostat	-	-	-	1.10 x 10-2
		Sensor	-	1.00 x 10-4	1.38 x 10-3	2.60 x 10-2
		Boiler	4.54 x 10-1	4.50 x 10-1	2.05 x 10-1	1.16 x 10-1
	Others	Fabric	-	-	-	2.24 x 10-3
Total weight			2.87	2.59	2.43	2.33
Processes	Metal injection		-	1.00 x 10-1	-	-
	Metal extrusion		-	2.00 x 10-4	5.94 x 10-2	3.66 x 10-3
	Metal stamping		3.00 x 10-4	8.00 x 10-4	-	1.90 x 10-4
	Aluminium injection		-	-	2.97 x 10-2	-
	Screw machining		1.78 x 10-2	5.90 x 10-3	1.74 x 10-1	1.25 x 10-2
	Plastic injection		1.42	9.13 x 10-3	1.04	1.47
	Plastic extrusion		1.19 x 10-2	1.31 x 10-2	1.32 x 10-2	-
	Plastic expansion		9.34 x 10-2	-	-	-

Distribution stage

To account for the transport of the capsule coffee machines from the factory to their destination, it was assumed that they were manufactured in Asian countries and transported to Europe. The initial distribution segment involved lorry transport from the factory to the port, followed by sea transport from the Asian port to the European port. The last leg of the journey was completed by lorry to reach the final destination. Relevant information is presented in Table III.3.

TABLE III.3 DATA FOR THE DISTRIBUTION STAGE.

Distribution type	Distance (km)	Means of transport
International	200	Lorry 16–36, Euro 3
International	15,000	Container ship
National	150	Lorry 16–36, Euro 5

Use stage

During the use stage, in accordance with the defined functional unit, the capsule coffee machine was operated twice a day, seven days a week, over a period of seven years. The daily coffee consumption per person was set at 132 ml, based on a tracking study of the C1 model, which was used 116 times by various users. For each use, the amount of coffee produced was recorded, resulting in an average of 66 ml per dose. Table III.4 and Table III.5 present the data for the LCI model.

TABLE III.4 DATA FOR USES WITH 1 LITRE OF WATER IN THE TANK.

	C1	C2	C3	C4
Nº capsules	20	17	13	14
Water (ml)	951.80	965.60	892.40	734.20
Electricity (kWh)	0.10	0.08	0.08	0.08
Average Electricity / water (kWh/ml)	0.15	0.07	0.32	0.06
Average coffee (ml)	47.59	56.80	68.65	52.44

TABLE III.5 DATA FOR ANNUAL USE (730 CAPSULES).

		C1	C2	C3	C4
Capsule (kg)	Aluminium	7.45×10^{-1}	2.92×10^{-2}	-	2.98×10^{-1}
	LDPE	-	8.40×10^{-1}	-	-
	PET	-	1.82	-	-
	PP	-	-	-	2.69
	Paper	-	-	1.50×10^{-1}	2.99×10^{-1}
Water (ml)		4.82×10^{1}	4.82×10^{1}	4.82×10^{1}	4.82×10^{1}
Electricity (kWh)		5.06	3.99	4.32	5.25

End-of-life stage

The end-of-life stage comprises transport of the entire used product, including its primary packaging, to a shredding facility (≈100 km via lorry, 16–32 metric tons, Euro 5); shredding, with an electrical energy consumption of 0.06 kWh/kg (Ecoinvent, 2024) and a selection efficiency of 75%; and subsequent transport of the recovered fractions to the respective recycling facilities (≈500 km via lorry, 16–32 metric tons, Euro 5). The avoided burdens from substituting primary materials with secondary materials from recycling were calculated using the 'net scrap' approach (Gallego-Schmid et al., 2018). This method accounts for recycling impacts while granting environmental credits for avoiding virgin materials. These credits apply only to the portion of recycled metals that exceeds the recycled content of the original raw materials.

Life Cycle Impact Assessment

Environmental impact assessment

Considering the scope of the study, the functional unit and the data in Figure III.3, Equations 1 and 2 were defined to calculate the environmental performance of the replacement and repair scenarios, respectively.

$$EI_{Replacement} = \frac{(M_{EI}+P_{EI}+D_{EI}+Eol_{EI})\cdot L_p}{L_j} + U_{EI}\cdot L_p$$ [Eq. 1]

$$EI_{Repair} = \frac{(M_{EI}+P_{EI}+D_{EI}+Eol_{EI})\cdot L_p}{L_j+LE_j} + U_{EI}\cdot L_p + R_j + Eol_j$$ [Eq. 2]

where:

- $EI_{Replacement}$= environmental impact of replacement scenarios.
- EI_{Repair}= environmental impact of repair scenarios.
- M_{EI}= environmental impact of the raw material stage for EEE.
- P_{EI}= environmental impact of the production stage for EEE.
- D_{EI}= environmental impact of the distribution stage for EEE.
- U_{EI}= annual environmental impact of the use stage for EEE.
- Eol_{EI}= environmental impact of the end-of-life treatment of initial EEE.
- Eol_j= environmental impact of the end-of-life treatment of the priority part j.
- L_p= lifespan of the product category.
- L_j= lifespan of the priority part j.
- j= priority part.
- LE_j= lifespan extension of the priority part j.
- R_j= environmental impact of the repair of the priority part j.

The end-point Environmental Footprint (EF) method (European Commission, 2021) was chosen for the Life Cycle Impact Assessment (LCIA).

Economic impact assessment

Similarly, Equations 3 and 4 were defined to calculate the economic performance of the replacement and repair scenarios, respectively.

$$EcI_{Replacement} = \frac{(RP)\cdot L_p}{L_j} + U_{\mathrm{EcI}}\cdot L_p$$ [Eq. 3]

$$EcI_{Repair} = \frac{(RP)\cdot L_p}{L_j+LE_j} + U_{\mathrm{EcI}}\cdot L_p + Re_j$$ [Eq. 4]

Where:

- $EcI_{Replacement}$ = economic impact of replacement scenarios.
- EcI_{Repair} = economic impact of repair scenarios.

- RP= retail price (economic impact of the raw material stage, production stage, distribution stage, and the end-of-life treatment for EEE).
- U_{EcL}= annual economic impact of the use stage for EEE.
- Re_j= economic impact of the repair of the priority part j.
- L_p= lifespan of the product category.
- L_j= lifespan of the priority part j.
- j= priority part.
- LE_j= lifespan extension of the priority part j.

Table III.6 presents the economic factors for the life cycle stages of raw material acquisition, manufacturing, distribution, and end-of-life. For the use stage, costs were set at €0.15/m^3 for tap water and €0.12/kWh for electricity. Repair costs for each priority part were calculated based on spare parts and labour, with an hourly labour rate of €30. Disassembly and reassembly times were determined using the eDIM methodology (Peeters et al., 2018).

TABLE III.6 ECONOMIC PERFORMANCE DATA (€).

			C1	C2	C3	C4
Raw material acquisition, manufacturing, distribution, end-of-life			109.90	89.00	63.99	109.99
Use (annual)	Material		68.62	38.78	21.43	44.17
	Water		0.01	0.01	0.01	0.01
	Electricity		0.61	0.48	0.52	0.63
Scenarios	Coffee cond. repair	Material	31.00	5.00	14.00	70.00
		Labour	3.31	5.70	0.70	4.77
	Filter repair	Material	11.00	7.00	4.20	8.00
		Labour	2.66	2.89	0.48	1.20
	O-ring repair	Material	0.10	0.10	0.10	0.10
		Labour	3.57	3.42	1.29	3.96
	Hoses repair	Material	5.00	5.00	5.00	5.00
		Labour	3.35	5.24	1.66	2.28
	Water tank repair	Material	8.00	5.70	13.99	22.40
		Labour	0.11	0.05	0.05	0.08
	Boiler repair	Material	30.00	90.00	50.00	73.89
		Labour	5.39	3.10	0.81	3.11
	Water pump repair	Material	20.00	19.00	22.00	22.00
		Labour	3.51	3.10	0.96	2.08
	Switch repair	Material	7.00	6.00	6.00	9.00
		Labour	3.12	2.95	2.10	1.56
	Capacitor repair	Material	12.00	7.00	4.00	4.00
		Labour	4.92	4.34	1.82	2.55
	PCB repair	Material	33.00	20.00	15.00	31.00
		Labour	4.92	4.34	1.82	2.55

The life cycle inventory was modelled by integrating primary data from the disassembly of the products under study with secondary data, based on the defined objective, system boundary and functional unit. For the environmental perspective, the Ecoinvent database (Ecoinvent, 2024) provided secondary data for configuring the LCI model, while the Environmental Footprint (European Commission, 2021) served as the Life Cycle Impact Assessment (LCIA) method to calculate environmental performance, using SimaPro (2024) v9 software. Retail prices were applied for the economic perspective.

4 RESULTS AND DISCUSSION

The proposed methodology was applied to a case study of capsule coffee machines. As shown in Figure III.5, the case study included four representative models, each with a different coffee-loading system: aluminium (C1), plastic (C2), pads (C3) and a combination of plastic and aluminium (C4). The market prices of the machines range from €30 to €115. To obtain the necessary data for the various stages of the methodology, the machines were disassembled in the laboratory beforehand. This process aimed to collect information on their components, their placement within the product architecture, the manufacturing processes of the materials, their weights and types, the number of joints, and other relevant details.

FIGURE III.5 CAPSULE COFFEE MACHINES FOR THE CASE STUDY AND THEIR DISASSEMBLY.

4.1 REPAIR ASSESSMENT OF CAPSULE COFFEE MACHINES

Regarding the repair data in the (Open Repair Alliance, 2024) databases, 6,305 entries related to coffee machine repairs were identified, accounting for 6.1% of the total entries (Figure III.1c). These entries are distributed by country and brand, as illustrated in Figure III.6b and c, respectively. Regarding coffee machine repairs, Figure III.6a shows that the Netherlands leads with 55% of the records, followed by Belgium (17.6%), Germany (11.6%), France (5.2%), and the United Kingdom (5.0%). In contrast, Spain accounts for only 0.4% of the recorded coffee machine repairs. In terms of manufacturer or brand identification (Figure III.6b), Philips is the most frequently repaired brand (28.1%), followed by Nespresso (7.9%).

With regard to the repair process of coffee machines (Figure III.6c), the average age at the time of repair is 7.75 years. Parts with higher repair rates, which fall below this average, include the coffee conditioning component (year 6), O-rings (year 6), and the boiler (year 7).

Regarding the success rate of the repair process (Figure III.6e), 71% of the repairs were successful, indicating a high level of repairability for coffee machines. Among these, the most frequently repaired components (Figure III.6f) were the boiler (20%), water pump (14%), switch (11%), and electronic board (9%). For the boiler, the main barrier (Figure III.6) was the lack of spare part availability, along with the high cost of the replacement part. In the case of the water pump, the most commonly reported barrier was also the high cost of the replacement. Difficulties in opening the product and accessing the component were equally reported for the water pump, cables, boiler and hoses.

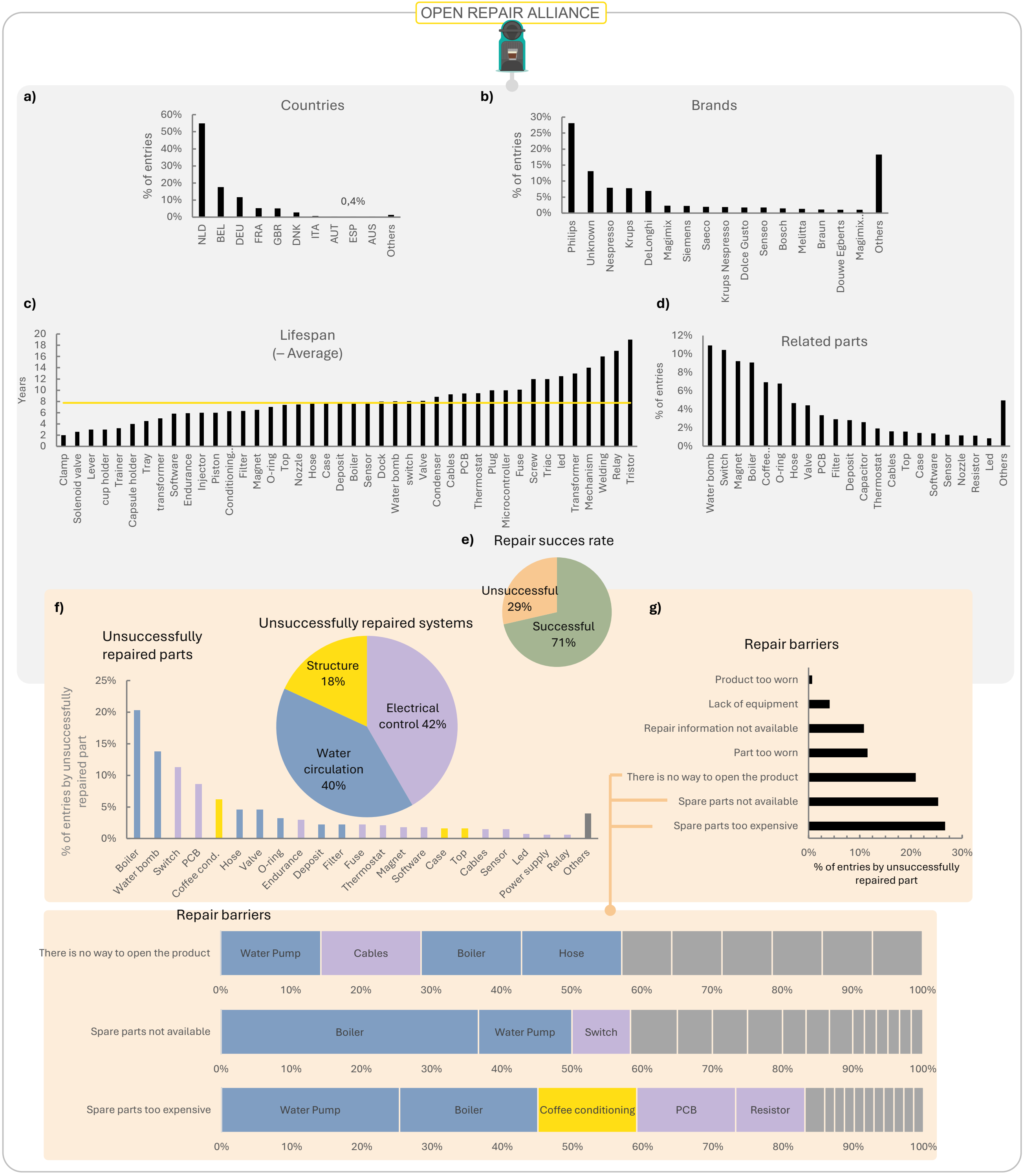

FIGURE III.6 REPAIR DATA FOR COFFEE MACHINES FROM THE OPEN REPAIR ALLIANCE.

Regarding the information extracted from the Repair Index, the Repair Matrix (RM) developed by Blanco-Espeleta et al. (2024), based on EN 45554 (2020), was applied to assess the reparability of capsule coffee machines. This matrix considers fifteen parameters: disassembly sequence depth, fastener type, tools required, working environment, skill level, diagnostic support and interfaces, spare parts availability, spare parts interface, spare parts availability duration, spare parts cost, information type, information availability, return options, data management, and restart type. In the study Repair Index of Energy-Related Products: Application to Capsule Coffee Machines (Blanco-Espeleta et al., 2024) the RM for calculating the RI is adapted specifically to the context of capsule coffee machines. This adaptation involves adjustments to the parameters and their respective weighting factors, the selection and weighting of priority parts, as well as the scoring scale.

It enables the calculation of the Repair Index (RI) for each capsule coffee machine (C1, C2, C3 and C4) and for each of their priority parts.

As a result, Table III.7 presents the information obtained from the repair databases and the Repair Index.

TABLE III.7 DATA FOR THE REPAIR ANALYSIS.

		Priority Part										Coffee machine
		Coffee cond.	Filter	O-ring	Hoses	Water tank	Boiler	Water pump	Switch	Capacitor	PCB	
Failure rate (%)		12%	11%	9%	16%	10%	6%	16%	9%	7%	6%	
Failure age (year)		6	6	7	7	7	7	8	8	9	9	
Success repair rate (%)		78%	82%	88%	76%	81%	45%	69%	74%	97%	37%	
Repair Index	C1	2.38	2.93	2.93	2.93	4.55	2.93	2.67	3.00	2.55	2.55	2.94
	C2	3.98	2.23	2.93	2.93	4.90	2.67	2.93	2.93	2.55	2.55	3.10
	C3	3.99	4.27	3.91	3.80	4.43	3.46	3.87	2.56	3.13	3.77	3.77
	C4	2.91	3.83	2.67	3.99	4.33	2.73	2.81	3.26	2.90	3.28	3.32

4.2 SCENARIO DEFINITION

Based on the parameters defined in Figure III.3, one replacement scenario and four repair scenarios were established for each priority part, as illustrated in Figure III.7 .The priority parts were grouped according to their common failure event (L_j) into the following categories:

- Coffee conditioning component and filter (6 years)
- O-ring, hoses, water tank, and boiler (7 years)
- Water pump, capacitor, and switch (8 years)
- PCB (9 years)

In the product's timeline, the failure event (L_j) of a priority part occurs, at which point the product is either replaced or repaired. Four repair scenarios are considered for all priority parts, extending the product's life by LE = 1 year, LE = 2 years, LE = 3 years, or LE = 4 years. The estimated useful life for capsule coffee machines (L_p) is 7 years (European Commission, 2011), as shown in Figure III.7. This aligns with data from the Open Repair Alliance (2024) repair process databases (Figure III.6c), which indicates that the average age of coffee machines at the time of repair is 7.75 years.

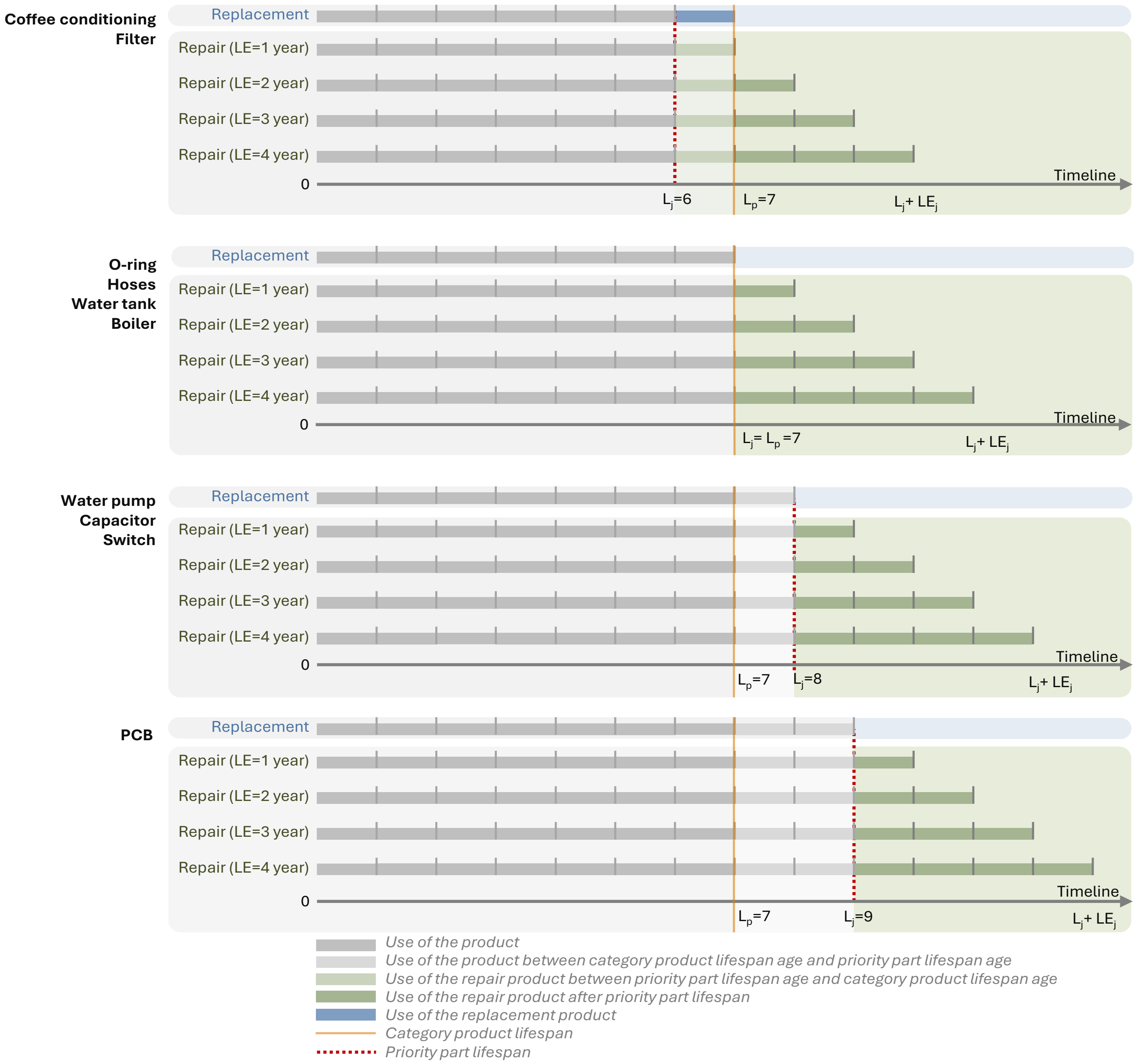

FIGURE III.7 REPLACEMENT AND REPAIR SCENARIOS DEFINED.

4.3 ENVIRONMENTAL AND ECONOMIC PERFORMANCE OF REPLACEMENT VERSUS REPAIR SCENARIOS

By applying Equations (1) and (2) for the environmental impact assessment and Equations (3) and (4) for the economic impact assessment, results were obtained for each of the previously identified priority parts. Figure III.8 provides a specific example for one priority part: the coffee conditioning component. Figure III.8a and Figure III.8b illustrate the environmental and economic impacts of repair, respectively, while Figure III.8c and d show the environmental and economic impacts of replacement, respectively, across the different stages of the life cycle (M, P, D, U, and EoL). The supplementary material (SM) includes the results for the remaining priority parts.

FIGURE III.8 RESULTS FOR THE COFFEE CONDITIONING COMPONENT.

Once the results had been obtained, the data for each capsule coffee machine and each of its priority parts were organised into three figures: Figure III.9 (Repair information), Figure III.10 (Environmental performance of replacement versus repair scenarios) and Figure III.11 (Economic performance of replacement versus repair scenarios).

To aid comprehension, the results were presented graphically from three perspectives: repair, environmental, and economic. Each figure includes various graphical elements, such as images, line types and colours, each carrying a specific meaning. Laboratory images of the priority parts are included to help identify each component. Additionally, each coffee machine is represented by its product photograph, also taken in the laboratory. Different line types are used to distinguish the impacts associated with each end-of-life alternative: a dashed line (- - -) represents the impact of replacement, while a solid line (——) indicates the environmental impact of repair. A colour scale (● ●) is applied to represent the optimal scenario (repair or replacement) for each priority part, based on their respective repair, environmental, or economic performance.

First, Figure III.9 presents the repair information for the capsule coffee machines, which are the focus of the case study. In the colour scale, the best scenarios (grey ●) correspond to the highest values among all the priority parts, while the worst scenarios (orange ●) represent the lowest values. The repairability analysis of capsule coffee machines identifies critical priority parts with failure rates exceeding the average, particularly between years 6 and 8. In year 6 of the product's life, both the coffee conditioning component and the filter exceed the average failure rates, with failure rates of 12% and 11%, respectively. However, the components with the highest failure rates are the hoses and the water pump, which exhibit failure rates of 16% in years 7 and 8, respectively. In terms of repair success rates, most components perform above average; however, the PCB and the boiler are identified as the worst-performing components, closely followed by the water pump.

Regarding the Repair Index (RI), the C3 coffee machine stands out, with most of its components achieving above-average results. A common issue for all coffee machines, however, is low scores derived from the lack of diagnostic support and insufficient repair information.

For priority parts, the water tank is identified as the component with the highest score across all capsule coffee machines, while the capacitor receives the lowest average score. The water tank is designed to be easily removable due to the frequent need for refilling, which results in higher scores for design-related parameters. In contrast, both the capacitor and the boiler rank among the lowest-scoring components. In particular, the consistently low repairability of the boiler can be attributed to factors such as long disassembly times, the requirement for specialised tools, and a design that lacks integrated diagnostic features. These aspects collectively impede efficient repair and suggest potential design changes that manufacturers could implement to enhance repairability.

	Coffee conditioning	Filter	O-ring	Hoses	Water tank	Boiler	Water pump	Switch	Capacitor	PCB	Average
Failure rate (%)	12%	11%	9%	16%	10%	6%	16%	9%	7%	6%	10%
Failure age (year)	6	6	7	7	7	7	8	8	9	9	7
Success repair rate (%)	78%	82%	88%	76%	81%	45%	69%	74%	97%	37%	73%
RI (fron 0 to 10) C1	2.38	2.93	2.93	2.93	4.55	2.93	2.67	3.00	2.55	2.55	2.94
RI (fron 0 to 10) C2	3.98	2.23	2.23	2.93	4.90	2.67	2.93	2.93	2.55	2.55	3.10
RI (fron 0 to 10) C3	3.99	4.27	3.91	3.80	4.43	3.46	3.87	2.56	3.13	3.77	3.77
RI (fron 0 to 10) C4	2.91	3.83	2.67	3.99	4.33	2.73	2.81	3.26	2.90	2.28	3.32

FIGURE III.9 REPAIR INFORMATION OF CAPSULE COFFEE MACHINES.

Second, Figure III.10 illustrates the environmental performance by comparing the impact of replacement (- - -) with that of repair (—) over time. The intersection of the two lines on each graph indicates the number of years the product must be used after repair for the repair to be environmentally beneficial. According to the colour scale, the worst grade (orange ●) is assigned when the replacement scenario is more advantageous than the repair scenario.

Repair consistently emerges as the best option for most critical components across all the capsule coffee machines, with the exception of the boiler, water pump, capacitor, and PCB. Specifically, for the boiler in the C4 model, the environmental improvement percentage for a repaired product compared to replacement is 5% in the first year of extension. In contrast, the C3 model does not show a positive improvement until the second year of extension (4%), while the C2 model achieves this in the third year (1%). The worst-case scenario is the C1 model, which shows only a 2% improvement in the fourth year. A similar trend is observed for the water pump, where the minimum extension needed for environmental benefit aligns with that of the boiler. Conversely, the capacitor provides environmental benefits across all capsule coffee machines within the first year of extension. In contrast, the PCB requires longer extensions for environmental improvements, with the C2, C3 and C4 models needing extensions of 3, 11, and 7 years, respectively.

Third, similar to the representation of environmental performance, the economic performance is depicted in Figure III.11. According to the colour scale, the worst level (orange ●) is assigned when the replacement scenario outperforms the repair scenario.

In this case, repair is consistently the best option for the C2 and C3 capsule coffee machines. However, for the C1 model, even with a 4-year extension of its lifespan through repair, the cost of repairing the water pump remains higher than that of replacement. For the C4 model, the only economically advantageous repair option is for the filter, which requires a minimum 1-year extension.

These findings reveal trade-offs between environmental and economic performance. For example, components like the boiler or water pump in model C1 may offer environmental advantages when repaired, but the associated cost still exceeds that of replacement, even with four years of extended use. Conversely, certain repairs may be economically viable (e.g., filter in C4), but not environmentally beneficial unless the product's use is extended by at least two years. These comparisons highlight the need to jointly consider both indicators to support informed, balanced decision-making.

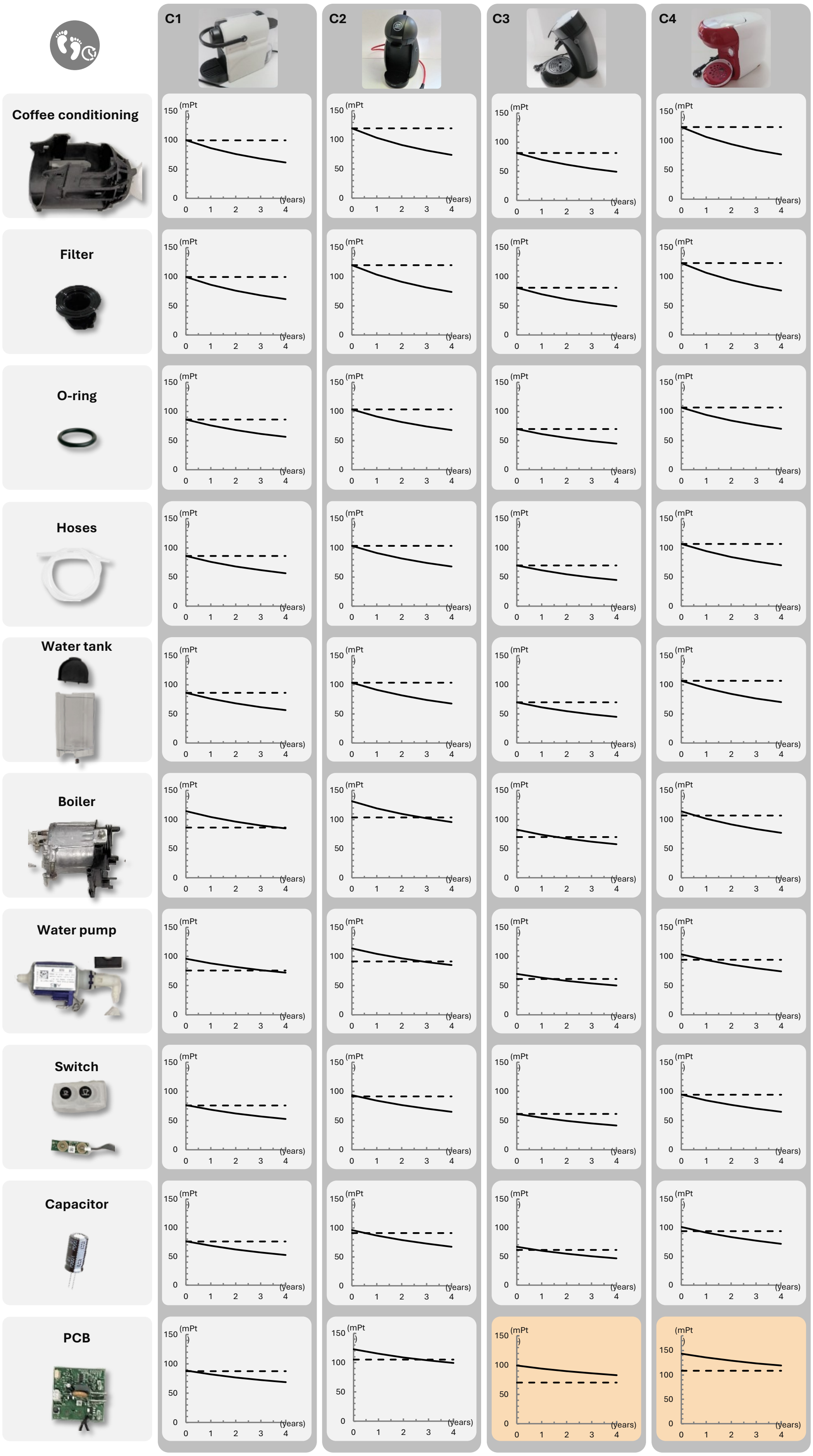

FIGURE III.10 ENVIRONMENTAL PERFORMANCE OF REPLACEMENT (- - -) VERSUS REPAIR SCENARIOS (—).

FIGURE III.11 ECONOMIC PERFORMANCE OF REPLACEMENT (- -) VERSUS REPAIR SCENARIOS (—).

4.4 INFORMATION FOR CONSUMERS

Based on the findings of this study, particularly those presented in Figure III.9- Figure III. 11, the potential for translating this information into practical tools or resources for consumers is explored, addressing one of the most common barriers to repair: the lack of repair information, as identified by the European Commission (2018). This barrier was also highlighted in Figure III.6, based on data reported in the Open Repair Alliance (2024) database, specifically for coffee machines. Effectively communicating these aspects to consumers is crucial for encouraging changes in purchasing habits and promoting smarter, more sustainable consumption decisions.

The European Commission (2018) found that providing information on product reparability and durability influences consumer choices, guiding them towards more repairable and durable options. Insights from the study on *Different Options for Communicating Environmental Information for Products* (European Commission, 2012) emphasise the importance of a global indicator to facilitate easy product comparisons, the value of a colour-coded scheme for quicker comprehension, the need for verified information to build trust and a consumer preference for classification systems using letters over purely technical environmental indicators. The European Commission (2018) concluded that reparability information is equally effective when displayed on the EU energy label or as a separate label. However, including this information on the EU energy label is a particularly viable option, given that the Eurobarometer Special 492 (D.-G. for C. European Commission, 2019) found that 93% of consumers recognise the energy label, and 79% consider it when purchasing electrical appliances.

Figure III.12 presents a preliminary proposal within the context of energy labelling. Figure III.12a provides an example based on the existing energy labelling framework for other product categories, using a black monochromatic scale (A, B, C, D, E). In contrast, Figure III.12b offers an example based on a separate repair label, adopting the colour-coded scheme of the existing energy label with the scale (A, B, C, D). In both cases, the repairability information is expanded to include two additional logos alongside the repair logo: one representing the economic performance of repair versus replacement, and another reflecting the environmental performance of repair versus replacement. The logo used to represent the environmental aspect (environmental footprint) originates from European Commission (2025), while the euro symbol (€) is used for the economic aspect. In both logos, the representation of lifespan extension is indicated by the logo identified as Bovea et al. (2018).

The scale for the economic and environmental logos is as follows:

- A: The repair option is always preferable to replacement, from both an economic and environmental perspective.
- B: The repair option is preferable, from both an environmental and economic perspective, provided it extends the product's lifespan by at least one year.
- C: The repair option is preferable, from both an environmental and economic perspective, provided it extends the product's lifespan by at least two years.
- D: The repair option is preferable, from both an environmental and economic perspective, provided it extends the product's lifespan by at least three years.
- E: The repair option is preferable, from both an environmental and economic perspective, provided it extends the product's lifespan by at least four years.

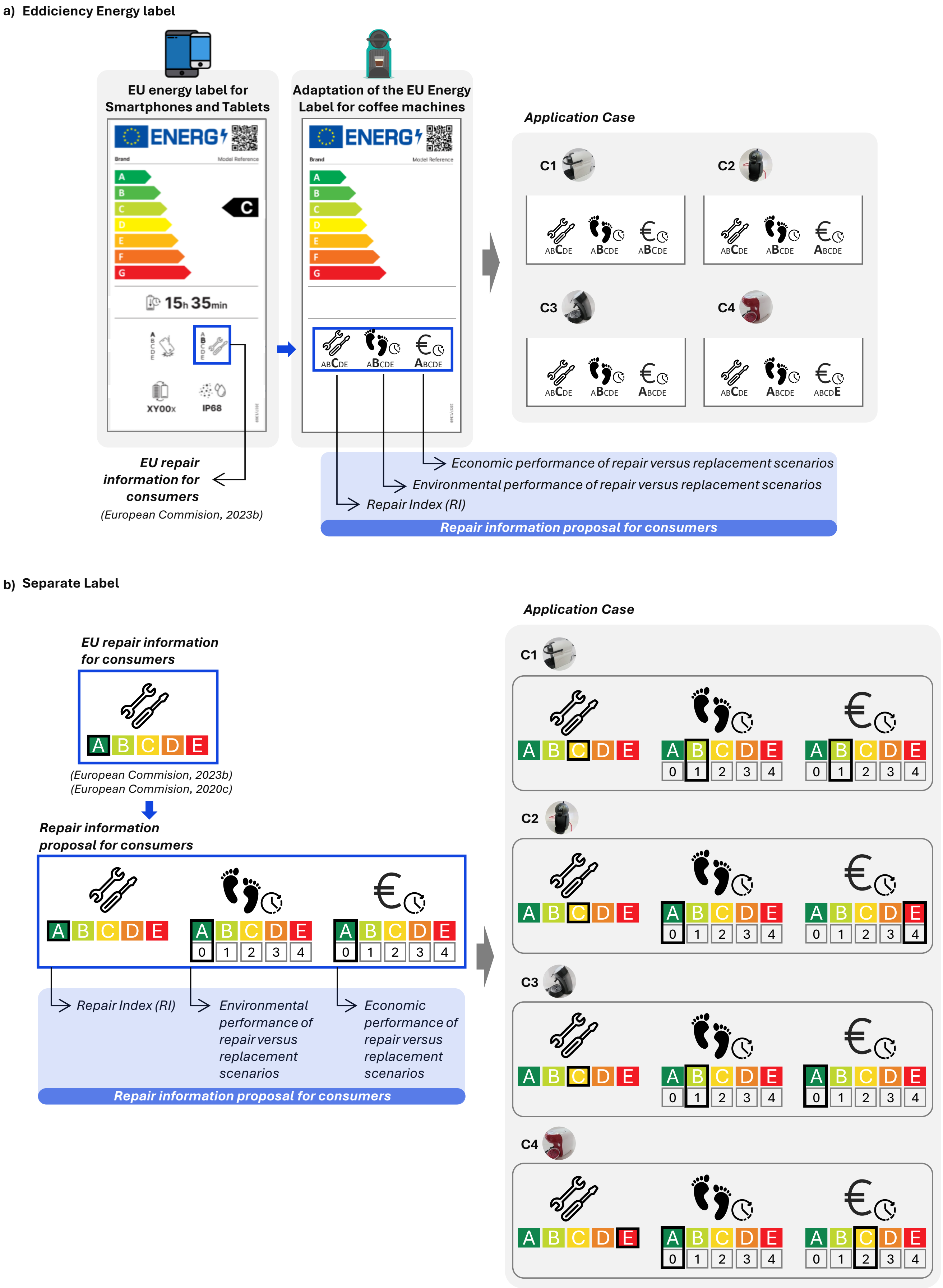

FIGURE III.12 REPAIR INFORMATION FOR CONSUMERS.

In addition to addressing the information barrier, the study's findings hold significant policy implications. An analysis of current repair incentive systems in Europe (Meyer and Molnár, 2024) highlights successful examples in France and Austria. These insights suggest that policymakers could consider mandating repairability indices for products such as capsule coffee machines, as well as establishing minimum design standards to facilitate repair. Furthermore, targeted economic incentives, such as subsidies, tax deductions, or direct incentives for consumers who choose repair over replacement, could be introduced for manufacturers and users who exceed these standards. This would foster a more tangible transition towards a circular economy and help effectively reduce waste.

5 CONCLUSIONS

The aim of this study was to propose a framework for the environmental and economic assessment of repairing energy-related products, with the goal of supporting consumer decision-making on whether to repair or replace a product. Capsule coffee machines were chosen as the case study.

This study advances theoretical understanding by introducing a comprehensive framework that integrates LCA and LCC methodologies into repairability evaluations. The findings contribute to the academic discourse on sustainable production by presenting a novel approach that combines environmental and economic assessments. In practical terms, they offer actionable insights for manufacturers and policymakers, highlighting specific opportunities to optimise product design and enhance repairability while reducing both environmental and economic impacts. Collectively, these insights can inform policy interventions that promote sustainable consumption and production practices.

The analysis shows that prioritising components with high failure rates and favourable repairability, such as the filter in the capsule coffee machines case study, results in significant environmental and economic benefits by conserving resources, reducing waste, and lowering maintenance costs. However, challenges persist for components with lower repair success, such as the boiler, water pump and PCB, which require further design improvements to enhance their repairability. In advancing the right to repair, it is crucial to balance repair costs, repair rates and environmental implications.

At the societal level, this novel approach empowers consumers by presenting repairability information in a clear and accessible way. The study expands the perspective by not only considering the Repair Index (RI), but also by examining the environmental and economic consequences of repairing versus replacing a damaged product, both for the product as a whole and for each of its priority parts.

Nevertheless, it is important to acknowledge certain limitations of this study. The analysis is based on a small, carefully selected sample of four capsule coffee machine models, although they effectively represent a broad range of internal architectures and coffee types available on the market. While variations in repairability, material composition, and failure rates may exist in other models, this focused approach has enabled the development of a comprehensive methodological framework. Additionally, the study relies primarily on data from European sources, which align with regional regulatory frameworks and consumer markets. The incorporation of data from other regions in future studies could provide additional insights. Furthermore, variations in consumer behaviour, especially those driven by rapid technological advancements that encourage the replacement of functional devices, are acknowledged as factors influencing environmental and economic impacts. Differences in consumer repair practices, such as repair frequency, willingness to invest in repairs, and overall repair awareness, may also affect these impacts. In future research, variables such as energy consumption, estimated product lifespan and usage patterns, which in this study were treated as fixed parameters collected from empirical tracking data, will be explored in greater depth as dynamic variables.

Building on these observations, several opportunities for future research emerge. Expanding the sample size, including additional product categories, and broadening the geographical scope would enhance the robustness of the findings. Moreover, future work could expand the scope of LCA and LCC analyses to incorporate diverse user behaviours and emerging repair business models, providing a more comprehensive understanding of the economic and environmental dynamics of repair practices. In addition, exploring the potential of artificial intelligence to revolutionise repair processes, by enabling predictive maintenance, optimising repair workflows, and providing personalised repair recommendations, could significantly enhance the sustainability and cost-effectiveness of repair strategies, particularly in alignment with emerging regulatory trends. Furthermore, investigating the impact of technological advancements, such AI-driven diagnostics and repair processes, on repair rates and their subsequent effects represents another promising avenue for future research. Additionally, the influence of evolving regulatory frameworks on practices should be considered, as new regulations have the potential to strengthen sustainable repair strategies and drive market transformation. Finally, integrating a comprehensive evaluation of the social benefits and impacts associated with repair activities would provide a more holistic perspective on the transformative potential of repairability, fostering a more inclusive and equitable transition towards a circular economy.

6 ACKNOWLEDGEMENTS

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8 SUPPLEMENTARY MATERIAL

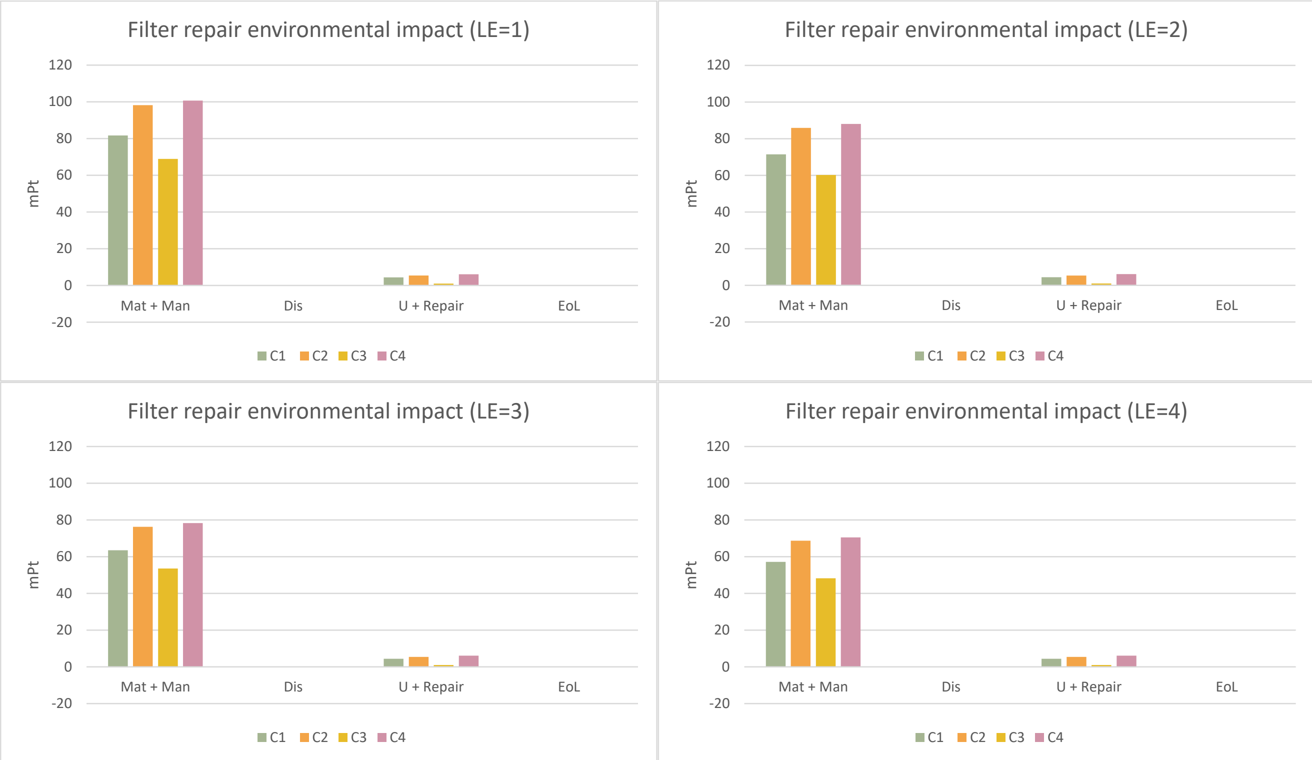

FIGURE SIII.1 FILTER REPAIR ENVIRONMENTAL IMPACT.

FIGURE SIII.2 O-RING REPAIR ENVIRONMENTAL IMPACT.

FIGURE SIII.3 HOSES REPAIR ENVIRONMENTAL IMPACT.

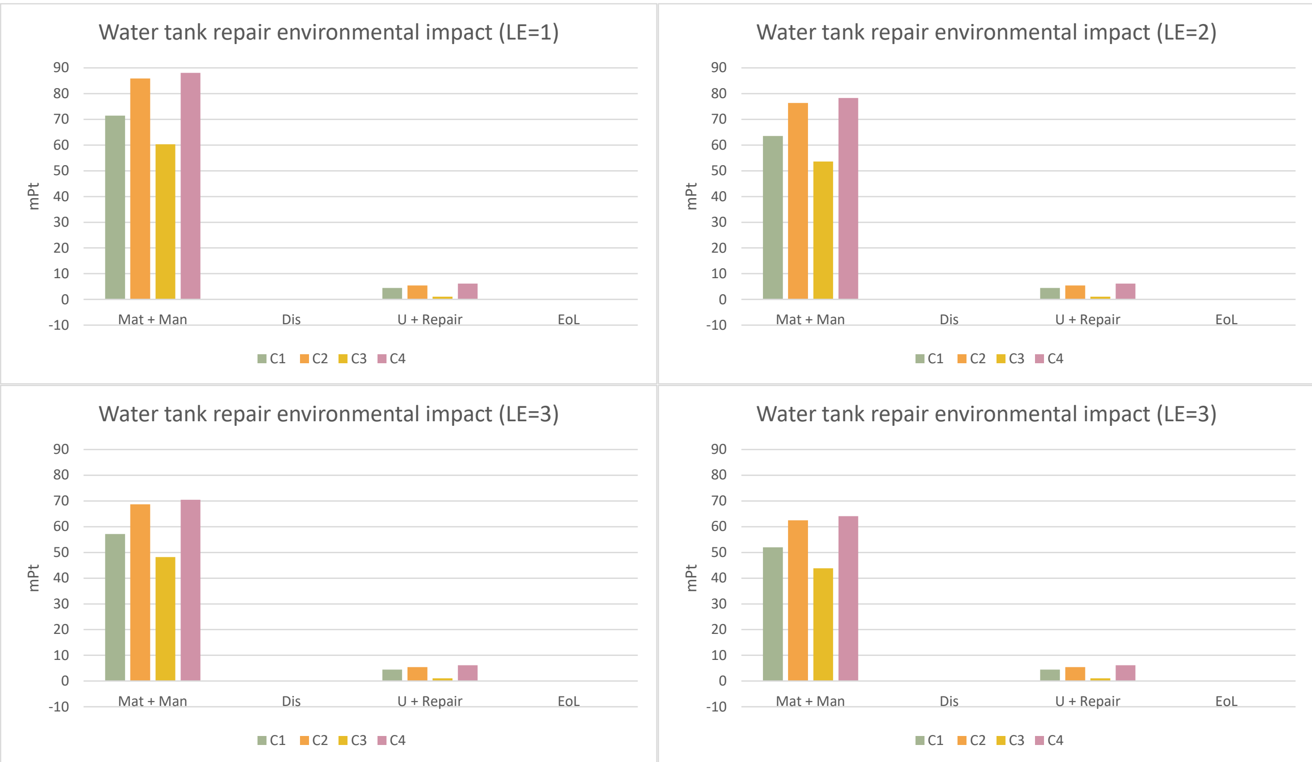

FIGURE SIII.4 WATER TANK REPAIR ENVIRONMENTAL IMPACT.

FIGURE SIII.5 BOILER REPAIR ENVIRONMENTAL IMPACT.

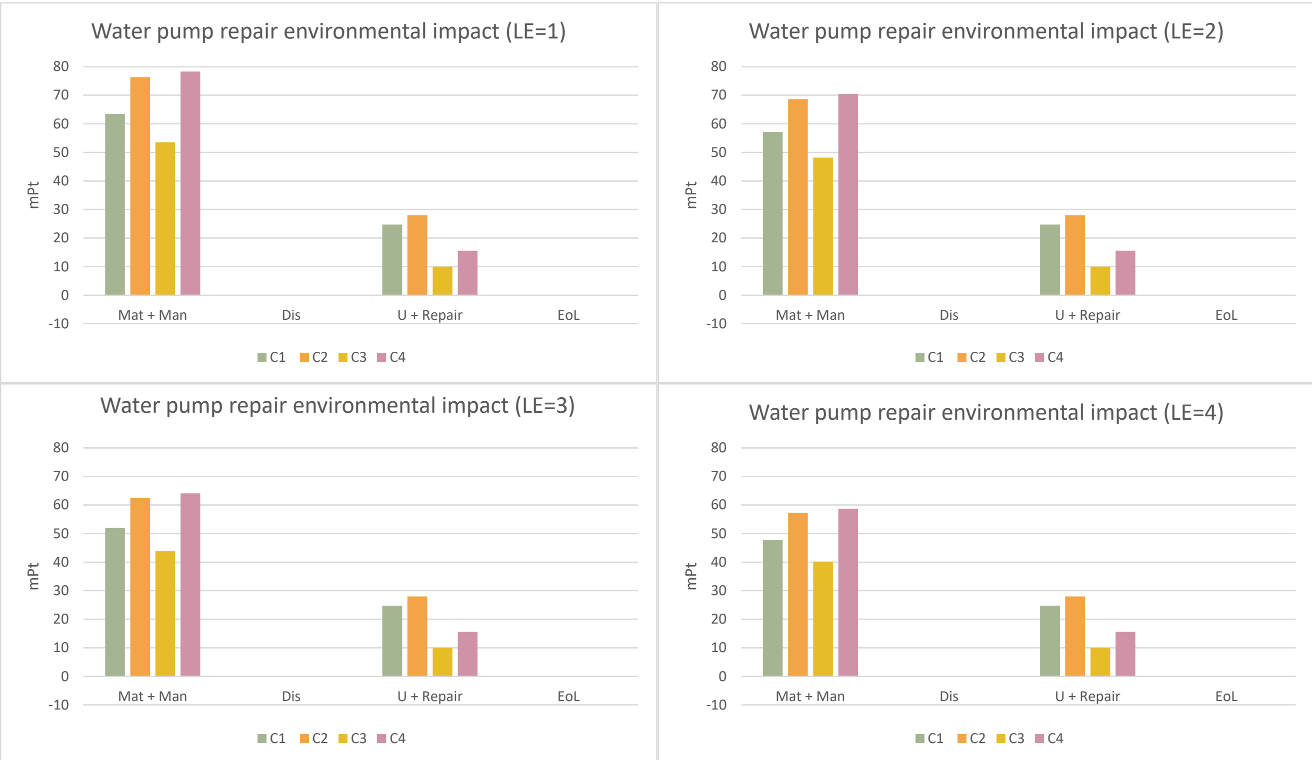

FIGURE SIII.6 WATER PUMP REPAIR ENVIRONMENTAL IMPACT.

FIGURE SIII.7 SWITCH REPAIR ENVIRONMENTAL IMPACT.

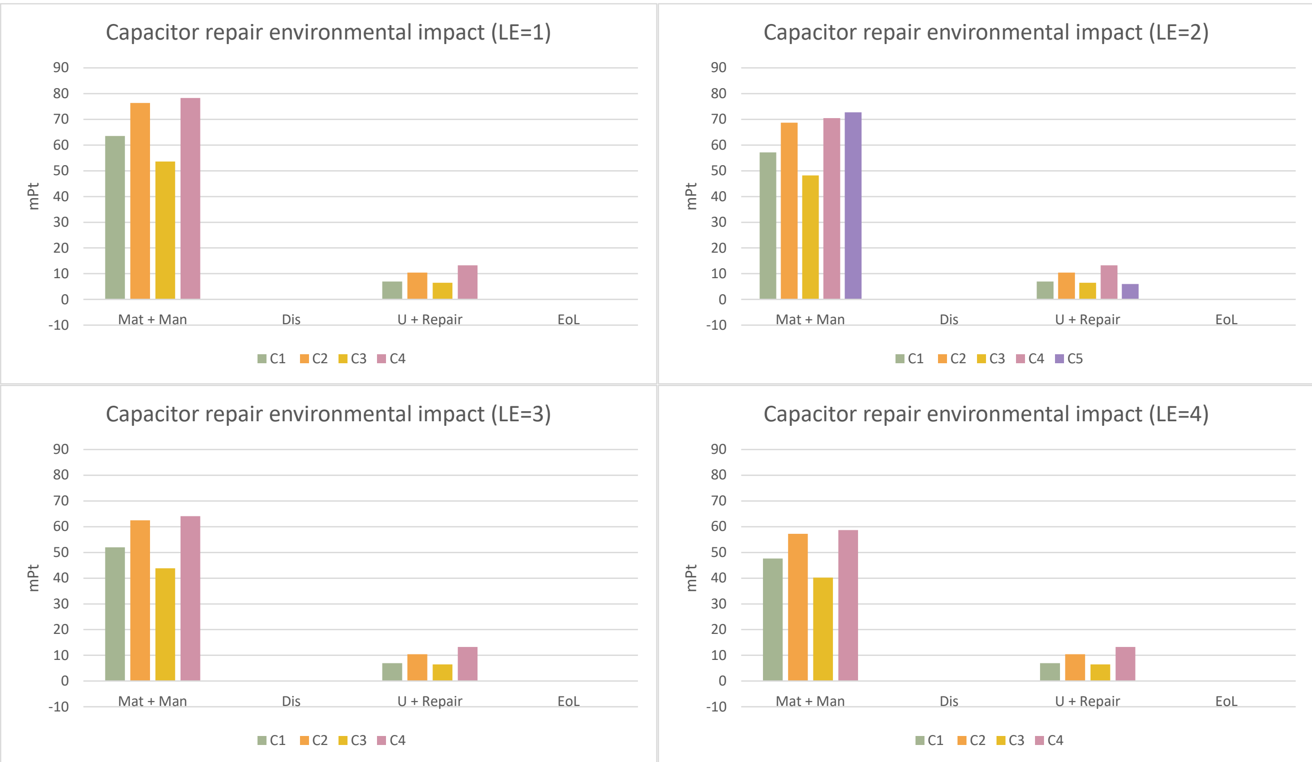

FIGURE SIII.8 CAPACITOR REPAIR ENVIRONMENTAL IMPACT.

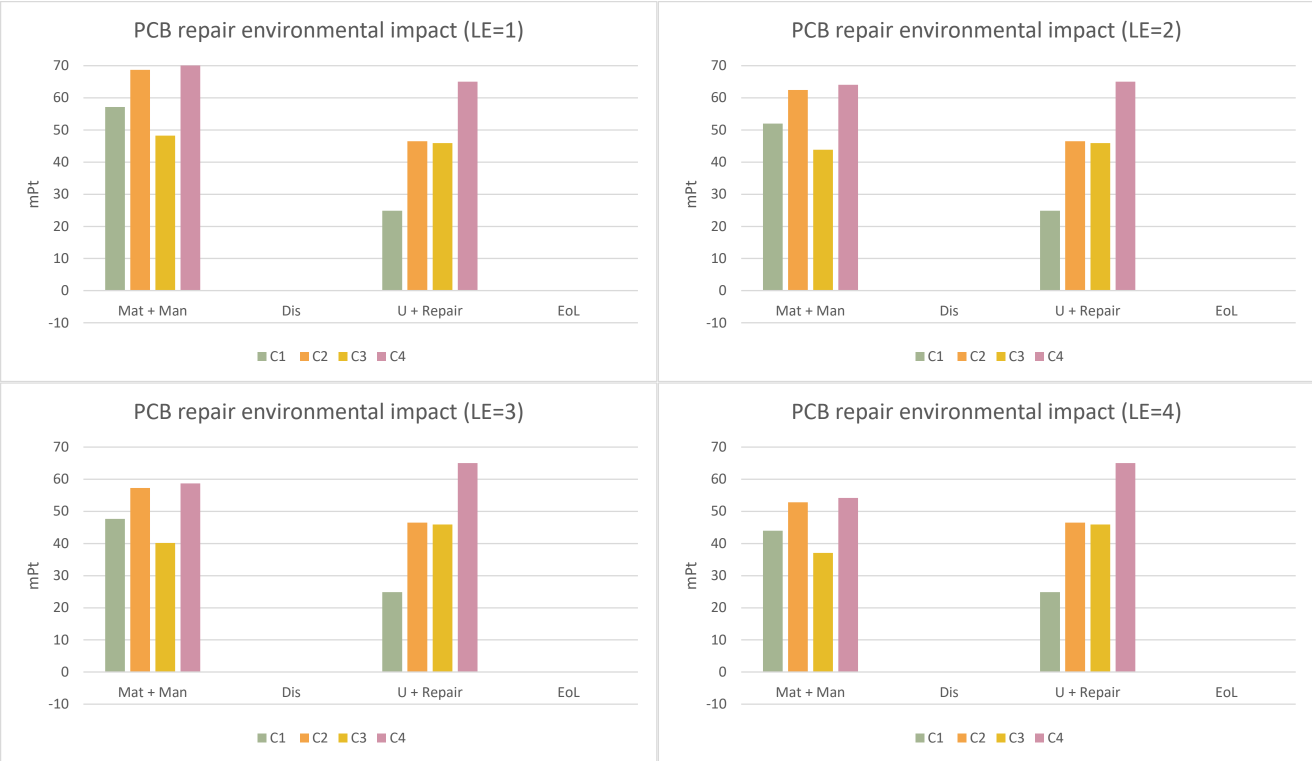

FIGURE SIII.9 PCB REPAIR ENVIRONMENTAL IMPACT.

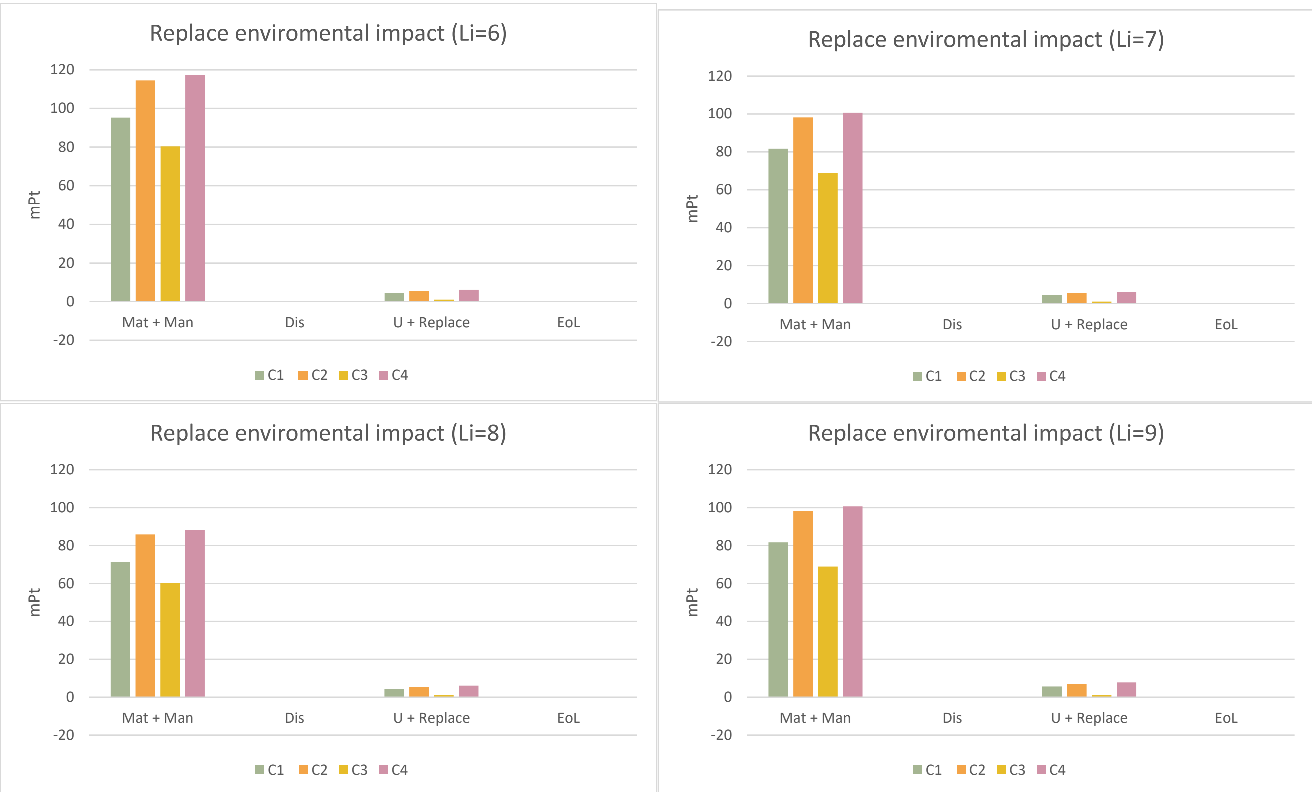

FIGURE SIII.10 REPLACE ENVIRONMENTAL IMPACT.

FIGURE SIII.11 FILTER REPAIR ECONOMIC IMPACT.

FIGURE SIII.12 O-RING REPAIR ECONOMIC IMPACT.

FIGURE SIII.13 HOSES REPAIR ECONOMIC IMPACT.

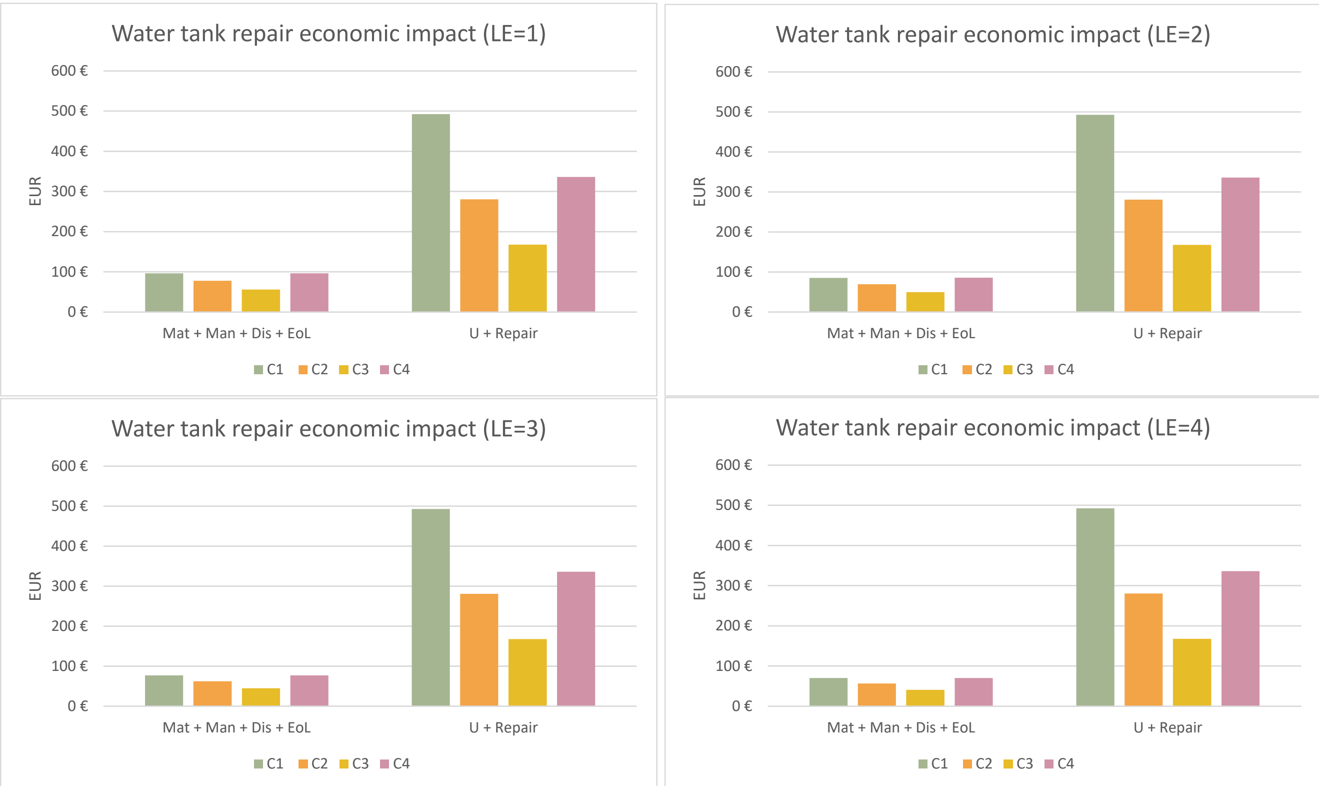

FIGURE SIII.14 WATER TANK REPAIR ECONOMIC IMPACT.

FIGURE SIII.15 BOILER REPAIR ECONOMIC IMPACT.

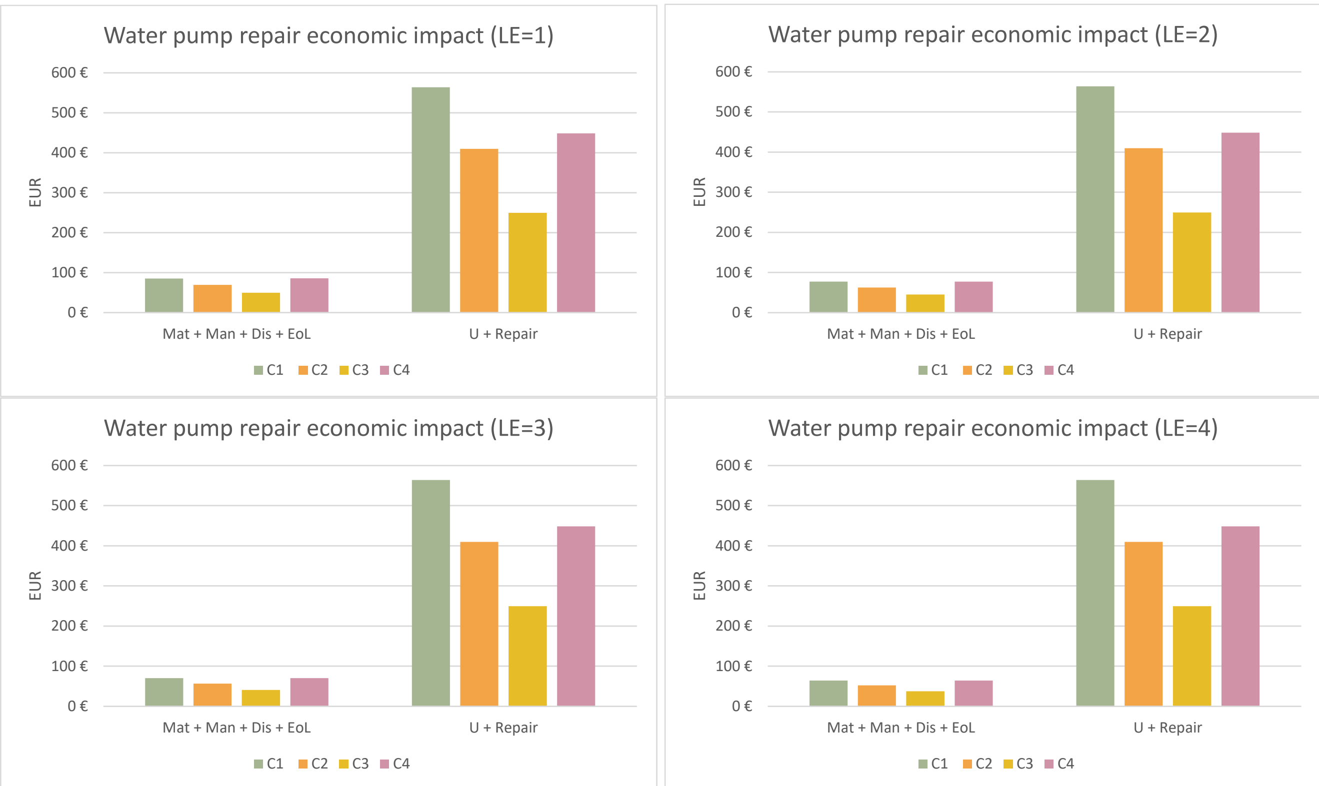

FIGURE SIII.16 WATER PUMP REPAIR ECONOMIC IMPACT.

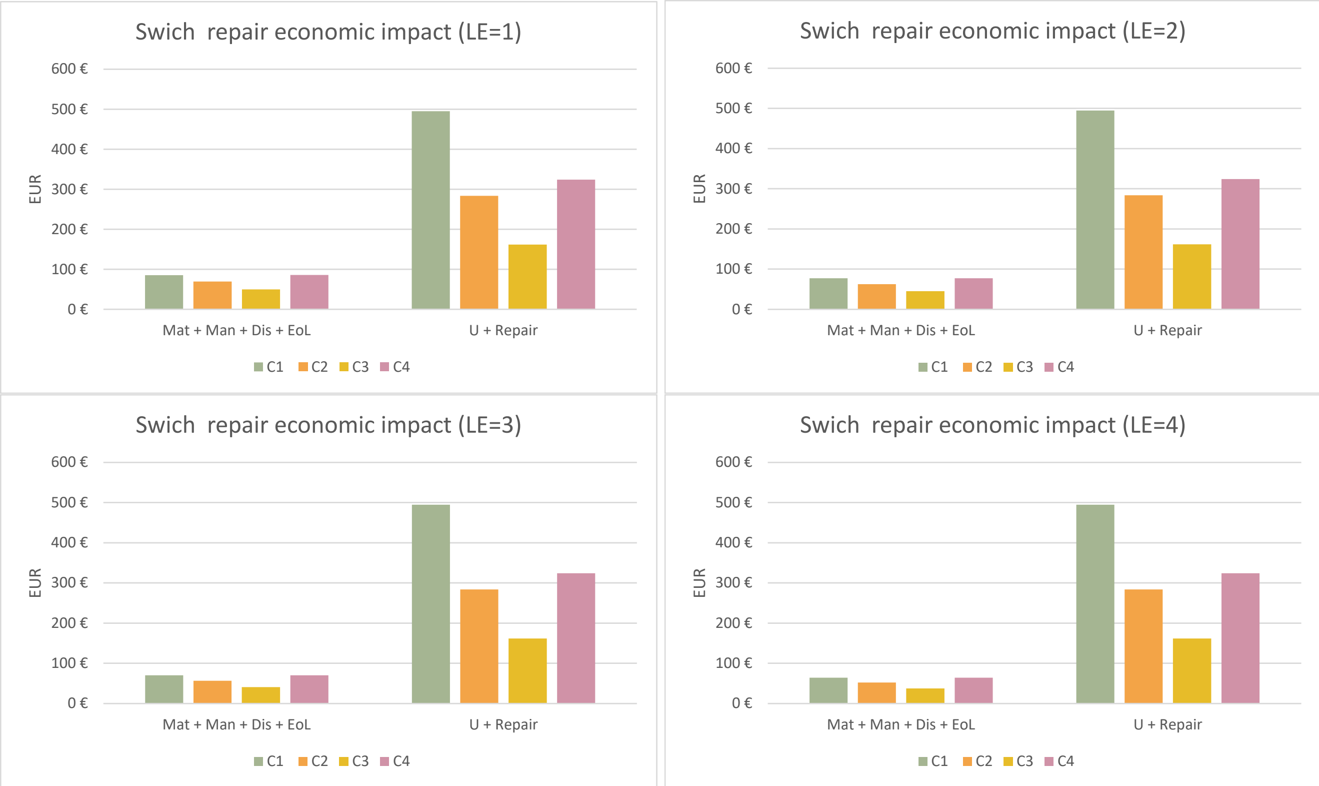

FIGURE SIII.17 SWICH REPAIR ECONOMIC IMPACT.

FIGURE SIII.18 CAPACITOR REPAIR ECONOMIC IMPACT.

FIGURE SIII.19 PCB REPAIR ECONOMIC IMPACT.

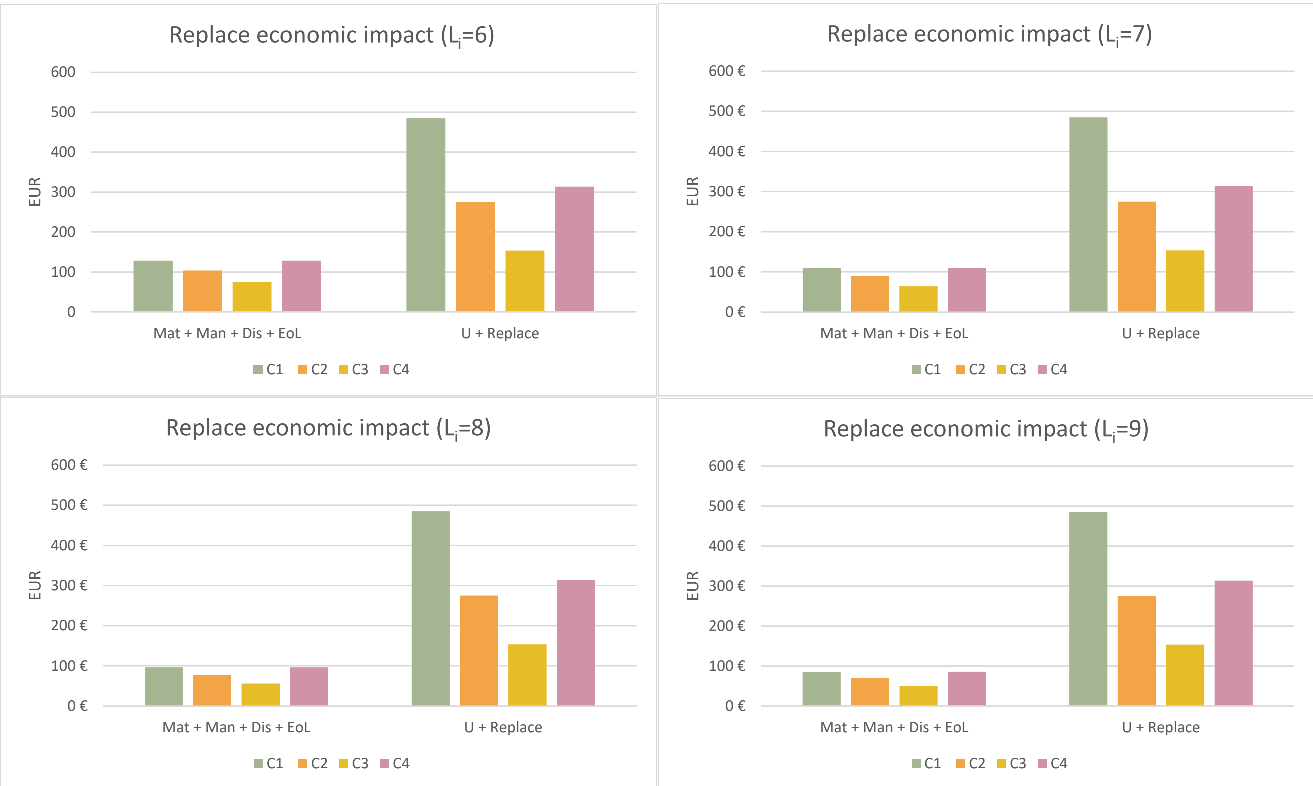

FIGURE SIII.20 REPLACE ECONOMIC IMPACT.

3 GENERAL DISCUSSION OF THE RESULTS

The discussion is structured according to the research questions formulated for the thesis. For each question, the main findings are examined and positioned within the context of existing scientific literature. A summary of the discussion is provided in Table 3.1.

RQ1 WHAT ARE THE LIMITATIONS AND ADVANTAGES OF CURRENT METHODS FOR EVALUATING THE REPAIRABILITY OF ELECTRICAL AND ELECTRONIC EQUIPMENT?

Regarding **RQ1**, several limitations have been identified in existing repairability assessment methods. First, some methods as the iFixit score (Flipsen et al., 2019) and the AsMeR method (Bracquené et al., 2018) rely on semi-quantitative evaluations. While these approaches may offer a simplified analysis, they introduce a degree of subjectivity that can compromise both the transparency and reproducibility of results. According to Boix Rodríguez et al. (2023), the evaluation of certain criteria, as well as components, is often subject to interpretation, and most methods do not provide support for identifying measures that enhance product repairability during the design phase (Boix Rodríguez and Favi, 2022).

Second, there is a lack of harmonisation in the selection, weighting, and aggregation of parameters, leading to inconsistencies across different repairability assessments. For example, when comparing the relative importance given to specific repairability aspects, substantial variation emerges. Regarding the Information parameter, RSS led with 30%, in contrast to iFixit, which only reached 10%. In terms of Design, iFixit showed a clear dominance with 80%, whereas AsMeR obtained 38%. For the Service parameter, FRI and AsMeR shared the lead with 34%, while iFixit again lagged behind with just 10%. This variability makes it difficult to compare outcomes across methods and reduces the potential for standardised assessments. In addition, some of them do not evaluate repairability at the priority parts level , such as AsMeR or iFixit, limiting their usefulness for product-specific improvement strategies.

Third, although some tools are intended to be general frameworks (EN 45554 or RSS) they still require adaptation to the specific characteristics of each product category in order to be effectively applied.

Fourth, the application of current methods tends to be mainly to ICT categories (19% of the studies are to mobiles phones). In contrast, Small EEE, which are also a priority which in policy and environmental impact, remain largely unexplored.

In summary, although several methods have contributed to the advancement of repairability assessment, the field still lacks a harmonised, reproducible, and product-specific approach. There is a clear need for a method that addresses these gaps by providing a structured, quantitative, and adaptable framework, especially for underrepresented product categories.

RQ2 HOW CAN EN 45554 BE ADAPTED TO BUILD A RELIABLE ASSESSMENT FRAMEWORK FOR EVALUATING THE REPAIRABILITY OF SMALL ELECTRICAL AND ELECTRONIC EQUIPMENT?

Regarding **RQ2**, to address the need for a more structured and reproducible repairability assessment method, EN 45554 was interpreted and operationalised into a matrix-based framework, referred to as the Repair Matrix (RM), a quantifiable framework, incorporating product-specific priority parts, weighting parameters and priority parts. The RM enables the calculation of a Repairability Index (RI) applicable to real products. Its application to capsule coffee machines allowed identifying design weaknesses and proposing targeted improvements, demonstrating the method's capacity to support product-oriented analysis.

The accuracy of the RM has been enhanced by aligning its structure with the policy recommendations. Specifically, the integration of a parameter related to the price of spare parts responds to previous calls for a more comprehensive evaluation of economic factors influencing repair decisions. This addition reflects similar approaches the adopted by methods such as the FRI (Ministère de la Transition écologique, 2021) and AsMeR (Bracquené et al., 2018) and fulfils the recommendation issued by BEUC (2022) to consider spare part affordability within repairability assessments. Thus, the incorporation of this parameter strengthens the RM's ability to capture user-relevant decision-making criteria, in line with the objectives of Directive 2009/125/EC (European Parliament, 2009).

The RM was further refined by introducing disassembly times (replacing disassembly depth), enhancing the method's accuracy and robustness. The substitution of disassembly depth with theoretical times aligns the RM with AsMeR, with the aim of reducing the subjectivity or interpretation involved in the evaluation of disassembly sequences.

When comparing the outcomes of different methods, it was observed that AsMeR tends to produce higher repair scores than the RM. This discrepancy can be attributed to its global product-level evaluation, in contrast to the part-level focus adopted by the RM. Despite these methodological differences, the relative ranking of products according to their repairability remains largely consistent across methods, supporting the robustness of the proposed.

RQ3 IN WHAT WAY CAN A GRAPH-BASED MODEL REPRESENT AND QUANTIFY THE REPAIRABILITY OF PRODUCTS?

Regarding **RQ3**, graph-based modelling techniques have increasingly been explored to visualise product disassembly and structural relationships, as seen in the development of AND/OR graphs (De Mello and Sanderson, 1986; Cao and Sanderson, 1998), matrix-based disposition modelling (Agrawal et al., 2016) and visual tools like the Disassembly Map (De Fazio et al., 2021) or Peony Diagram (Huang et al., 2025). On the one hand, while these tools provide valuable visual insights, graph-based modelling have not yet been applied to repairability assessment. On the other hand, visual tools that do incorporate repairability aspects, such as the Disassembly Map or Peony Diagram, facilitate interpretation and component localisation but do not offer automated outputs or calculated metrics. They often lack standardised metrics and fail to incorporate critical repairability parameters such as failure probability, joint complexity, or spare part availability.

This thesis addresses those limitations by proposing a graph-based model that encodes repairability-related parameters derived from EN 45554 into a product graph in which nodes represent components and edges represent physical or functional connections. The application of network analysis metrics (such as degree, betweenness centrality, eccentricity and modularity are then used to identify critical components and structural bottlenecks) enables the identification of critical components and structural bottlenecks that may hinder repairability. Additionally, a novel graph-based RI metric is introduced, enabling a visual and quantitative assessment of product repairability. This approach bridges the current gap between structural visualisation and analytical evaluation, providing a more complete and scalable data-driven tool for assessing and designing for repairability.

RQ4 WHAT ENVIRONMENTAL AND ECONOMIC BENEFITS ARISE FROM PRIORITISING COMPONENT REPAIR OVER REPLACEMENT IN SMALL ELECTRICAL AND ELECTRONIC EQUIPMENT?

Regarding **RQ4**, the reviewed literature consistently supports the environmental benefits of repair and reuse over replacement in most scenarios involving sEEE, particularly when energy efficiency and extended product lifetime are considered (Bovea et al., 2020; Sandez et al., 2024; Kouloumpis et al., 2023). However, studies also highlight exceptions depending on the type of component (e.g., PCBs or electric motors) (Bovea et al., 2020). These findings underline the importance of product-specific and component-level assessments to ensure accurate evaluation of environmental trade-offs.

Despite the broad agreement on the environmental advantages of repair, economic aspects are less frequently addressed in depth. Only a limited number of studies integrate LCC, suggesting that repair and refurbishing scenarios are often more economically attractive than purchasing new products (Cordella et al., 2021; Rizan et al., 2022), though potential rebound effects must be considered (Zink and Geyer, 2017).

Nonetheless, a major gap identified in the literature is the lack of integration between environmental and economic assessments and repairability levels at the component scale.

The thesis results address this gap by applying an integrated framework combining life cycle assessment (LCA), life cycle cost (LCC), and the Repairability Index (RI) derived from the proposed Repair Matrix (RM) to a product category that has received limited attention in previous research: capsule coffee machines. The findings show that repair scenarios consistently outperform full replacement in both environmental impact and cost impact. These advantages are particularly pronounced when high-failure, high-impact parts such as the pump, boiler or PCB are targeted.

The results obtained confirm the usefulness of integrating repairability metrics with LCA and LCC to compare repair and replacement scenarios. However, it should be noted that the proposed framework is not limited to these options. Its structure allows adaptation to other circular strategies, such as durability enhancement, refurbishment, remanufacturing or reuse, by modifying lifespan parameters and scenario boundaries. This flexibility highlights the potential of the methodology to support a broader evaluation of circular economy strategies and to capture additional environmental and economic benefits beyond those strictly derived from repair.

RQ5 HOW DOES THE JOINT PRESENTATION OF REPAIRABILITY, ENVIRONMENTAL IMPACT AND REPAIR COST INDICATORS INFLUENCE A CONSUMER’S DECISION TO BUY OR REPAIR PRODUCTS?

Regarding **RQ5**, recent European policy developments stress the importance of transparent and accessible information to empower consumers in their purchasing and repair decisions. Regulation (EU) 2024/1781 (European Union, 2024) and Directive (EU) 2024/825 (European Parliament, 2024b) highlight the need for repairability scores to be presented in clear and consumer-friendly formats, using clear language or pictograms, and recommend including repair cost information alongside these scores. These provisions reflect a growing recognition that informed consumers are more likely to choose sustainable options.

Empirical evidence supports this policy direction. Studies by the European Commission (2012, 2018) indicate that information on product durability and repairability positively influences consumer choices, especially when it is presented using intuitive and easily interpretable formats. Key findings include consumer preference for global indicators, colour-coded systems, and letter-based classifications, which are more readily understood than technical metrics. Moreover, the integration of this information into familiar formats, such as the EU energy label, can enhance visibility and trust, an essential factor considering that 93% of EU citizens recognise the energy label and 79% consult it when purchasing appliances (European Commission, 2019b).

In line with these insights, this thesis contributes to bridging the gap between technical repairability assessments and effective consumer communication , The results show that the joint presentation of repairability, environmental and economic indicators can significantly enhance the consumer's ability to make informed and sustainable decisions. Moreover, the visual representation of product architecture and component complexity, through graph-based models, supports designers in understanding and improving repairability. By integrating this technical information into clear, accessible formats, barriers to interpretation are reduced, enabling a shift in consumer behaviour toward products that are not only more efficient and affordable to repair, but also aligned with sustainability goals.

Beyond the methodological contribution, the practical applicability of the framework is a critical factor to ensure its impact. The use of EN 45554 as a reference standard facilitates its potential integration into industrial and regulatory contexts. Likewise, the Repair Matrix offers a structured and replicable tool for product designers, enabling the identification of design improvements that enhance repairability. The graph-based modelling approach provides intuitive visualisations that practitioners can easily interpret, supporting product development and repair strategies. Furthermore, by combining repairability outcomes with LCA and LCC results, the framework offers researchers quantitative evidence linking product design choices with environmental and economic performance. These features underline the usability of the methodology while highlighting the need for further validation in collaboration with industry and policy makers.

TABLE 3.1 DISCUSSION OF THE THESIS RESULTS BY RESEARCH QUESTIONS.

RESEARCH QUESTION 1	
What are the limitations and advantages of current methods for evaluating the repairability of electrical and electronic equipment?	Some methods rely on semi-quantitative evaluations and lack harmonisation in how parameters are selected and weighted, which can affect consistency and reproducibility. Some offer general frameworks (e.g. EN 45554, RSS) and they require adaptation for specific products. Some do not assess repairability at the priority parts level and are mainly applied to ICT products, with limited use in other relevant categories such as sEEE.
RESEARCH QUESTION 2	
How can EN 45554 be adapted to build a reliable assessment framework for evaluating the repairability of small electrical and electronic equipment?	Building on EN 45554, the RM translates its qualitative guidance into a quantifiable framework, as suggested by recent literature advocating more standardised and detailed tools (Bracquené et al., 2018; Ministère de la Transition écologique, 2021). By integrating parameters such as spare part cost and disassembly time, the RM improves accuracy and aligns with policy recommendations (BEUC, 2022), enabling part-level evaluation of sEEE.
RESEARCH QUESTION 3	
In what way can a graph-based model represent and quantify the repairability of products?	While previous approaches such as AND/OR graphs (De Mello and Sanderson, 1986; Cao and Sanderson, 1998), matrix-based models (Agrawal et al., 2016), and visual tools like the Disassembly Map (De Fazio et al., 2021) offer structural insights, they often omit key repairability factors. This thesis builds on these foundations by encoding EN 45554 parameters into graph models, using metrics like centrality and modularity to identify design weaknesses, and introducing a new RI metric to enable scalable, quantitative repairability assessment.
RESEARCH QUESTION 4	
What environmental and economic benefits arise from prioritising component repair over replacement in small electrical and electronic equipment?	Literature confirms that repair and reuse generally reduce environmental impacts compared to replacement, especially when extending product life (Bovea et al., 2020; Sandez et al., 2024). However, exceptions exist for parts, like PCBs. Economic benefits are also noted (Cordella et al., 2021), although they remain less explored. Moreover, there is a lack of integration between LCA and LCC methodologies and repairability metrics. This thesis fills that gap by combining LCA, LCC, and RM, showing that priority parts with high failure rates and favourable repairability, results in significant environmental and economic benefits.
RESEARCH QUESTION 5	
How does the joint presentation of repairability, environmental impact, and repair cost indicators influence a consumer's decision to buy or repair products?	Literature and policy highlight that consumers prefer clear and visual formats. This thesis confirms that presenting integrated indicators through visual tools, combining repairability, cost, and environmental data, supports more sustainable purchasing and repair decisions, in line with Right to Repair goals.

4 CONCLUSIONS AND FUTURE DEVELOPMENT

4.1 CONCLUSIONS

The conclusions are structured with a general overview of the thesis, followed by specific conclusions organised according to the five main topics: existing repairability evaluation methods, assessment framework based on EN 45554, graph-based modelling for product repairability assessment, environmental and economic benefits of prioritising repair over replacement and new tools for visualising repairability. For each topic, the main contributions are summarised. In addition, Table 4.1 presents a synthesis of these contributions in relation to stakeholders: researchers, product designers, consumers and policy makers

Novelty in this thesis lies in the design of a general matrix for evaluating repairability based on the EN 45554 standard. The work further advances the state of the art through the analysis and visualisation of repairability using graph-based modelling, including the development of a graph-based Repair Index metric to quantify product repairability in a comprehensive and interpretable manner. Additional originality is found in the integrated approach, combining Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methodologies to deliver a holistic evaluation of repairability. Finally, the study contributes by applying a component-level perspective to a widely used yet under-analysed product category: capsule coffee machines.

Regarding the **general conclusions**, in response to the "Right to Repair" directive (European Parliament, 2024) and Regulation (EU) 2024/1781 (European Union, 2024), this thesis has contributed to the advancement of repairability research by developing and integrating tools that combine structural analysis, policy alignment, environmental and economic evaluation and user-centred visualisation. The work addresses key challenges in analysing and visualising repairability, particularly at the part level, and offers practical solutions applicable to both design and policymaking. By focusing on capsule coffee machines, a previously understudied but environmentally relevant category, the thesis not only demonstrates the utility of the proposed methods but also highlights their potential for broader application across product types. Overall, the findings reinforce the strategic role of repair in circular economy transitions and underline the importance of harmonised, transparent tools to support informed decision-making by researchers, designers , consumers and policy makers . Although the proposed methods have been developed in alignment with the European regulatory framework, they are also applicable beyond the EU in contexts where similar legislation and policy instruments are being introduced or are under consideration.

TOPIC 1 EXISTING REPAIRABILITY EVALUATION METHODS.

Regarding **Topic 1**, a new repairability assessment method has been developed to address current methodological gaps in standardisation, objectivity and applicability. The proposed approach, based on the EN 45554 standard, introduces a Repair Matrix (RM) that allows quantifying repairability both at the product and priority part level. This method is adaptable to different product categories and provides a clear structure for parameter selection, weighting and scoring. In doing so, it responds to the lack of harmonised and detailed tools for assessing repairability, particularly in small electrical and electronic equipment (sEEE).

TOPIC 2 ASSESSMENT FRAMEWORK BASED ON EN 45554.

Regarding **Topic 2**, building on the findings of Stage 1, the RM was developed to operationalise EN 45554 into a quantifiable framework tailored to sEEE. Its application to capsule coffee machines enabled the identification of weak points in design and repair accessibility. The inclusion of new parameters, such as spare part cost and disassembly time, aligned the tool with recent policy recommendations and increased its robustness.

TOPIC 3 GRAPH-BASED MODELLING FOR PRODUCT REPAIRABILITY ASSESSMENT.

Regarding **Topic 3**, graph-based modelling was used to represent the product architecture of capsule coffee machines. By integrating EN 45554-derived repairability parameters into network structures, it was possible to analyse part connectivity, accessibility and complexity using graph metrics like degree, betweenness, eccentricity and modularity. A novel graph-based Repair Index metric was also proposed, bridging the gap between visualisation and analytical assessment.

TOPIC 4 ENVIRONMENTAL AND ECONOMIC BENEFITS OF PRIORITISING REPAIR OVER REPLACEMENT.

Regarding **Topic 4**, this thesis evaluated the environmental and economic impacts of repairing versus replacing capsule coffee machines. The integrated LCA-LCC analysis demonstrated that repair scenarios, particularly those involving high-failure and high-impact components like pumps and boilers, result in significant reductions in both environmental impact and cumulative cost. Nonetheless, components such as the boiler, water pump, and PCB still present considerable barriers to repair due to their low repair success rates. Improving the design of these parts remains essential. Promoting the right to repair therefore requires a careful balance between technical feasibility, repair affordability, and the associated environmental benefits. This approach addressed the literature's lack of component-level analysis and integrated impact modelling.

TOPIC 5 NEW TOOLS FOR VISUALISING REPAIRABILITY.

Regarding **Topic 5,** in response to European policy directives and consumer preferences identified in previous studies, this thesis explored the joint presentation of repairability, environmental and cost indicators in accessible formats. On the one hand, with regard to designers, the integration of visual tools, such as architecture graphs, supports designers comprehension and informed decision-making. On the other hand, in relation to consumers, the design of tools that aggregate and visualise environmental and economic impacts and repairability information can effectively empower consumers, promoting sustainable behaviours aligned with the Right to Repair agenda.

In addition to the methodological advances achieved, the thesis provides tools with clear potential for practical application. For product designers and repair professionals, the Repair Matrix and graph-based visualisations can serve as decision-support instruments to improve product architectures and facilitate disassembly processes. For policy makers, the integration of repairability with LCA and LCC provides evidence-based indicators that can be incorporated into regulatory frameworks and eco-design policies. Therefore, the proposed methodology not only contributes to academic research but also offers actionable insights for the effective implementation of the Right to Repair in practice.

TABLE 4.1 CONCLUSIONS OF THE THESIS BY STAGES AND STAKEHOLDERS.

Topic	Researchers	Product designers	Consumers	Policy makers
TOPIC 1 Existing repairability evaluation methods.	Key gaps in standardisation, quantification and product-specific adaptation in repairability methods were identified up to the present day.	Provided a critical synthesis to support method selection and refinement for product developers and policymakers.	Limitations of current methods were identified, supporting the development of policies that empower consumers to make more informed and sustainable choices.	Support the development of policies aligned with the objectives of the Right to Repair addressing standardisation gaps and ensuring coherence across frameworks.
TOPIC 2 Assessment framework based on EN 45554.	Transformed EN 45554 into a quantifiable framework through the Repair Matrix, integrating new parameters (disassembly time and spare parts cost).	Delivered a validated tool (RM) for practitioners to assess and improve repairability of sEEE at the component level.	Empowering consumers through improved assessment frameworks that also support ecodesign regulations and right to repair initiatives.	Provided a scalable methodology adaptable to any product category and transferable to countries with similar legislation, integrating both technical and economic parameters to inform coherent policy indicators.
TOPIC 3 Graph-based modelling for product repairability assessment.	Adaptation of existing metrics to repairability assessment and development of a new repair specific metric.	Offered a scalable method using Gephi to visualise and evaluate repairability during product development.	Graph-based models can be adapted to enhance consumer understanding, offering an intuitive visual representation of product repairability.	The visual and quantitative nature of graph-based modelling provides a parametric system that enhances transparency and enables global comparability, supporting evidence-based policy design.
TOPIC 4 Environmental and economic benefits of prioritising repair over replacement.	Demonstrated how integrating RI with LCA and LCC enables accurate evaluation of environmental and economic trade-offs.	Enabled design teams to identify improvement opportunities in low-repairability parts to help reverse associated environmental and economic impacts.	At the point of decision-making to repair or replace a product, providing information on repairability, environmental and cost impact enables consumers to choose the option with the lowest overall impact.	Provided evidence-based insights showing how integrating repairability assessment with environmental (LCA) and economic (LCC) analysis supports the development of policies that prioritise repair over replacement.
TOPIC 5 New tools for visualising repairability.	Introducing novel visualisation tools that enable the analysis of product repairability supporting future research in design optimisation.	Created visual and interpretable tools to guide designers decisions and inform product labelling schemes.	Empowered consumers to make informed decisions.	Support the development of labelling schemes and policies aligned with Sustainability Goals and EU policies.

4.2 LIMITATIONS AND FUTURE DEVELOPMENTS

This section summarises the main limitations identified throughout the thesis and the corresponding directions for future developments. While the thesis has contributed to the development of novel methodologies, is required to expand their applicability to a broader range of product categories, incorporate social dimensions of sustainability, advance the automation of data collection and processing and conduct empirical validation of the proposed consumer information tools to support their effective implementation. The identified limitations and future lines of research for each research block are presented in Table 4.2.

Although the methodology has been conceived with applicability in mind, the thesis did not include a direct validation phase with practitioners or policy researchers. This represents a limitation, as usability testing in real-world contexts is essential to ensure that the proposed tools respond to stakeholder needs. Future developments should therefore prioritise engagement with designers, repair professionals and regulatory bodies, enabling the co-validation and refinement of the method. Such interaction would ensure that the framework not only advances academic knowledge but also becomes a practical instrument to guide design practices and inform policy-making on repairability.

TOPIC 1 EXISTING REPAIRABILITY EVALUATION METHODS.

Regarding **Topic 1**, the literature review was limited to studies published in English and indexed in selected academic databases, overlooking grey literature and industry practices. Future research should expand the scope of the review to include grey literature, industry white papers, corporate sustainability reports, and policy-related documentation. This broader perspective will allow for a more comprehensive understanding of how repairability is being addressed in other contexts and may reveal innovative tools or criteria that are not yet reflected in academic publications.

TOPIC 2 ASSESSMENT FRAMEWORK BASED ON EN 45554.

Regarding **Topic 2**, the RM adaptation process requires expert input for weighting factors and priority part selection. To enhance objectivity and replicability, future work could focus on automating the RM adaptation by integrating AI-driven tools. These tools could analyse large repair databases (e.g., Open Repair Alliance) to dynamically update failure probabilities and identify priority components based on real-world data. Furthermore, embedding this system into CAD environments would allow designers to calculate repairability scores in real time during the early stages of product development.

The framework was applied only to capsule coffee machines, limiting generalisability to other product categories. In parallel, the framework should be applied and validated across a broader range of product categories to assess its scalability and robustness.

TOPIC 3 GRAPH-BASED MODELLING FOR PRODUCT REPAIRABILITY ASSESSMENT.

Regarding **Topic 3**, the manual nature of data entry and dependence on accurate modelling of product structure can be time-consuming and prone to human error. Future work should integrate the graph-based repairability modelling into CAD environments to enable real-time, parametric evaluations during early design phases, increasing applicability and efficiency and facilitating systematic implementation of design-for-repair principles.

Another limitation is the limited number of case studies conducted. Future research should aim to expand the application of the proposed methodology to a broader range of coffee machine models and diverse product categories. This would strengthen the robustness of the approach and demonstrate its adaptability across different product architectures.

TOPIC 4 ENVIRONMENTAL AND ECONOMIC BENEFITS OF PRIORITISING REPAIR OVER REPLACEMENT.

Regarding **Topic 4**, consumer behaviour variables, such as willingness to repair, frequency of repair, and awareness, were not fully integrated into the analysis. Future developments should model consumer behaviour more dynamically by integrating those variables.

Parameters such as energy consumption, product lifespan, and usage patterns were treated as fixed rather than dynamic. However, future work should focus on developing dynamic models that capture their variability over time, taking into account differences in usage intensity, degradation rates and user behaviour to provide a more realistic and comprehensive repairability assessment.

Although this thesis has primarily focused on the comparison between repair and replacement scenarios, the proposed methodological framework is adaptable to other circular strategies. In particular, durability improvements can be represented in LCA and LCC by adjusting lifespan parameters, allowing the quantification of avoided environmental and economic impacts associated with extended product use. Likewise, scenarios such as refurbishment, remanufacturing or reuse could be integrated by redefining system boundaries, functional units and assumptions related to product life extension. Incorporating these additional circular scenarios would broaden the scope of the analysis, enable the comparison of multiple circular strategies within the same product category and provide more comprehensive insights into their environmental and economic trade-offs. Therefore, the extension of the framework to these strategies represents a promising line of future research.

The social impacts of repair practices were not addressed in this study. To provide a more comprehensive view of sustainability, future work could extend the approach into a full Life Cycle Sustainability Assessment (LCSA) by integrating Social Life Cycle Assessment (S-LCA) methods, allowing for the evaluation of social, environmental, and economic dimensions of repairability.

TOPIC 5 NEW TOOLS FOR VISUALISING REPAIRABILITY.

Regarding **Topic 5**, the development of visual tools to communicate repairability indicators remains at a conceptual stage and their effectiveness has not yet been validated through real-life consumer testing. As a result, the impact of these information formats on consumer understanding and behaviour is still unknown. Future research should incorporate user-centred evaluations of the proposed visual tools, assessing aspects such as comprehension, perceived usefulness, and their influence on purchasing or repair decisions. Controlled experiments, surveys, or living lab approaches could be employed to test different formats (e.g., pictograms, colour-coded labels, composite indices) and assess their effectiveness across diverse user profiles.

TABLE 4.2 LIMITATIONS AND FUTURE DEVELOPMENTS OF THE THESIS BY TOPICS.

TOPIC 1	Limitations	Future developments
Existing repairability evaluation methods.	Limited to studies indexed in English and overlooking grey literature and industry practices	Extend the review to include grey literature, technical reports, and industry-led initiatives.
TOPIC 2	**Limitations**	**Future developments**
Assessment framework based on EN 45554.	The adaptation process requires expert inputs.	Automating the RM adaptation by integrating AI-driven tools and embedding this system into CAD environments.
	Limiting generalisability to other product categories.	Apply and validate across a broader range of product categories.
TOPIC 3	**Limitations**	**Future developments**
Graph-based modelling for product repairability assessment.	Manual data entry and reliance on accurate product modelling can be time-consuming and error-prone.	Conduct additional case studies across the different models of coffee machines and product categories.
	Limited number of case studies performed.	Integrate CAD tools to enable real-time, parametric evaluations and support design-for-repair implementation.
TOPIC 4	**Limitations**	**Future developments**
Environmental and economic benefits of prioritising repair over replacement.	Consumer behaviour variables were not fully integrated into the analysis.	Model consumer behaviour more dynamically by integrating variables like repair frequency, willingness, and awareness into environmental and economic assessments.
	Parameters such as energy consumption, product lifespan, and usage patterns were treated as fixed rather than dynamic.	Develop dynamic models that account for variability in usage intensity, lifespan, and energy consumption over time.
	Social impacts of repair practices were not evaluated.	Extend the approach into a full Life Cycle Sustainability Assessment (LCSA).
TOPIC 5	**Limitations**	**Future developments**
New tools for visualising repairability.	Initial conceptual development, no real-life consumer testing performed.	Consumer testing to evaluate understanding, usability and impact of proposed information tools.

4.3 CONTRIBUTION TO THE SUSTAINABLE DEVELOPMENT GOALS

The thesis contributes to various of the United Nations Sustainable Development Goals (SDGs), addressing aspects related to product repairability, sustainable design, consumer information and the development of tools supporting circular economy strategies. Table 4.3 summarises the main SDGs covered by this work and the specific contributions associated with each.

TABLE 4.3 CONTRIBUTION OF THE THESIS TO THE SUSTAINABLE DEVELOPMENT GOALS.

SUSTAINABLE DEVELOPMENT GOAL		
SUSTAINABLE DEVELOPMENT GOAL 9	Industry, Innovation and Infrastructure	Development of methodologies and tools (Repair Matrix, graph-based modelling) to support design for repairability, promote innovation in product development processes, and assist designers in identifying improvements.
SUSTAINABLE DEVELOPMENT GOAL 12	Responsible Consumption and Production	Promotion of product repair as a strategy to extend product lifespan, reduce resource consumption, and minimise waste generation. Empowerment of consumers through clear and accessible repairability, environmental and economic information to support more sustainable consumption decisions.
SUSTAINABLE DEVELOPMENT GOAL 13	Climate Action	Quantification of the environmental benefits of repair over replacement through Life Cycle Assessment (LCA), contributing to the reduction of climate-related impacts associated with product lifecycles.
SUSTAINABLE DEVELOPMENT GOAL 4	Quality Education	Generation of knowledge, methodologies and tools that can be transferred to academia, research, professional training, and educational programmes in the fields of sustainable product design and circular economy.

5 SCHEMATIC SUMMARY OF THE THESIS

SUPPORTING THE IMPLEMENTATION OF THE RIGHT TO REPAIR: TOOLS FOR REPAIRABILITY ANALYSIS AND VISUALISATION

						CONCLUSIONS					
RESEARCH GAPS	RESEARCH QUESTIONS	OBJECTIVES	STAGES	PUBLICATIONS	DISCUSSION	Researchers	Product designers	Consumers	Policy makers	LIMITATIONS	FUTURE DEVELOPMENTS
RG1 Although existing repairability frameworks are in use, they could be further developed into implementation-oriented formats suitable for a broader range of product categories.	**RQ1** What are the limitations and advantages of current methods for evaluating the repairability of EEE?	**O1** To identify and critically analyse existing methods for evaluating the repairability of electrical and electronic equipment.	**S1** Critical review of existing repairability evaluation methods.	All articles Conference I	Some methods rely on semi-quantitative evaluations and lack harmonisation in how parameters are selected and weighted, which can affect consistency and reproducibility. Some offer general frameworks (e.g. EN 45554, RSS) and they require adaptation for specific products. Some do not assess repairability at the priority parts level and are mainly applied to ICT products, with limited use in other relevant categories such as sEEE.	Key gaps in standardisation, quantification and product-specific adaptation in repairability methods were identified up to the present day.	Provided a critical synthesis to support method selection and refinement for product developers and policymakers.	Limitations of current methods were identified, supporting the development of policies that empower consumers to make more informed and sustainable choices.	Support the development of policies aligned with the objectives of the Right to Repair addressing standardisation gaps and ensuring coherence across frameworks.	Limited to studies indexed in English and overlooking grey literature and industry practices	Extend the review to include grey literature, technical reports, and industry-led initiatives.
RG2 Although existing repairability frameworks have been implemented, policy makers still lack coherent and reliable indicators to support effective regulation.	**RQ2** How can EN 45554 be adapted to build a reliable assessment framework for evaluating the repairability of small electrical and electronic equipment?	**O2** To design and validate an assessment framework, based on EN 45554 criteria.	**S2** Design and validation of an assessment framework based on EN 45554.	Article I Conference IV	Building on EN 45554, the RM translates its qualitative guidance into a quantifiable framework, as suggested by recent literature advocating more standardised and detailed tools (Bracquené et al., 2018; Ministère de la Transition écologique, 2021). By integrating parameters such as spare part cost and disassembly time, the RM improves accuracy and aligns with policy recommendations (BEUC, 2022), enabling part-level evaluation of sEEE.	Transformed EN 45554 into a quantifiable framework through the Repair Matrix, integrating new parameters (disassembly time and spare parts cost).	Delivered a validated tool (RM) for practitioners to assess and improve repairability of sEEE at the component level.	Empowering consumers through improved assessment frameworks that also support ecodesign regulations and right to repair initiatives.	Provided a scalable methodology adaptable to any product category and transferable to countries with similar legislation, integrating both technical and economic parameters to inform coherent policy indicators.	The RM adaptation process requires The adaptation process requires expert inputs. Limiting generalisability to other product categories.	Automating the RM adaptation by integrating AI-driven tools and embedding this system into CAD environments. Apply and validate across a broader range of product categories.
RG3 Existing repairability assessment methods are not sufficiently oriented towards guiding design decisions.	**RQ3** In what way can a graph-based model represent and quantify the repairability of products?	**O3** To propose and implement a repairability assessment approach based on graph theory, capable of assessing and visualising product repairability.	**S3** Assessment and visualisation of repairability through graph-based modelling.	Article I Article II Conference III	While previous approaches such as AND/OR graphs (De Mello and Sanderson, 1986; Cao and Sanderson, 1998), matrix-based models (Agrawal et al., 2016), and visual tools like the Disassembly Map (De Fazio et al., 2021) offer structural insights, they often omit key repairability factors. This thesis builds on these foundations by encoding EN 45554 parameters into graph models, using metrics like centrality and modularity to identify design weaknesses, and introducing a new RI metric to enable scalable, quantitative repairability assessment.	Adaptation of existing metrics to repairability assessment and development of a new repair specific metric.	Offered a scalable method using Gephi to visualise and evaluate repairability during product development.	Graph-based models can be adapted to enhance consumer understanding, offering an intuitive visual representation of product repairability.	The visual and quantitative nature of graph-based modelling provides a parametric system that enhances transparency and enables global comparability, supporting evidence-based policy design.	Manual data entry and reliance on accurate product modelling can be time-consuming and error-prone. Limited number of case studies performed.	Conduct additional case studies across the different models of coffee machines and product categories. Integrate CAD tools to enable real-time, parametric evaluations and support design-for-repair implementation.
	RQ4 What environmental and economic benefits arise from prioritising component repair over replacement in small electrical and electronic equipment?	**O4** To evaluate the environmental and economic benefits of prioritising repair over replacement adaptable to different categories of small electrical and electronic equipment (sEEE).	**S4** Life cycle assessment (LCA) and life cycle cost (LCC) analysis of repair and replacement scenarios of capsule coffee machines.	Article I Article III Conference V	Literature confirms that repair and reuse generally reduce environmental impacts compared to replacement, especially when extending product life (Bovea et al., 2020; Sandez et al., 2024). However, exceptions exist for parts, like PCBs. Economic benefits are also noted (Cordella et al., 2021), although they remain less explored. Moreover, there is a lack of integration between LCA and LCC methodologies and repairability metrics. This thesis fills that gap by combining LCA, LCC, and RM, showing that priority parts with high failure rates and favourable repairability, results in significant environmental and economic benefits.	Demonstrated how integrating RI with LCA and LCC enables accurate evaluation of environmental and economic trade-offs.	Enabled design teams to identify improvement opportunities in low-repairability parts to help reverse associated environmental and economic impacts.	At the point of decision-making to repair or replace a product, providing information on repairability, environmental and cost impact enables consumers to choose the option with the lowest overall impact.	Provided evidence-based insights showing how integrating repairability assessment with environmental (LCA) and economic (LCC) analysis supports the development of policies that prioritise repair over replacement.	Consumer behaviour variables were not fully integrated into the analysis. Parameters such as energy consumption, product lifespan, and usage patterns were treated as fixed rather than dynamic. Social impacts of repair practices were not evaluated.	Model consumer behaviour more dynamically by integrating variables like repair frequency, willingness, and awareness into environmental and economic assessments. Develop dynamic models that account for variability in usage intensity, lifespan, and energy consumption over time. Extend the approach into a full Life Cycle Sustainability Assessment (LCSA).
RG4 Repairability information remains insufficiently accessible and visual to effectively support consumer decision-making.	**RQ5** How does the joint presentation of repairability, environmental impact and repair cost indicators influence a consumer's decision to buy or repair products?	**O5** To design tools for analysing and visualising repairability that effectively inform the consumer and support informed decision-making. **O6** To maximise the impact of the research by disseminating results to both academic and practical contexts..	**S5** Design and validation of consumer information tools.	Article I Article II Article III Conference II Conference V	Literature and policy highlight that consumers prefer clear and visual formats. This thesis confirms that presenting integrated indicators through visual tools, combining repairability, cost, and environmental data, supports more sustainable purchasing and repair decisions, in line with Right to Repair goals.	Introducing novel visualisation tools that enable the analysis of product repairability supporting future research in design optimisation.	Created visual and interpretable tools to guide designers decisions and inform product labelling schemes.	Empowered consumers to make informed decisions.	Support the development of labelling schemes and policies aligned with Sustainability Goals and EU policies.	Initial conceptual development, no real-life consumer testing performed.	Consumer testing to evaluate understanding, usability and impact of proposed information tools.

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ABSTRACT

The increasing relevance of circular economy policies within the European regulatory framework has placed repairability at the core of sustainable product design strategies, aiming to reduce raw material consumption, minimise e-waste generation and extend product lifespan. In this context, the recent adoption of the European Right to Repair has further highlighted the need for tools capable of analysing and visualising repairability, enabling its integration into broader sustainability assessments. This study proposes an integrated methodological framework combining a Repair Matrix (RM) based on EN 45554, graph-based modelling techniques, and Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) approaches. Applied to capsule coffee machines as a representative product category, the framework enables the quantification of repairability at component level, the assessment of environmental and economic trade-offs between repair and replacement scenarios, and the generation of decision-support information for designers and consumers. The research follows a five-stage approach: (1) a review of existing repairability assessment methods, identifying current methodological gaps, (2) the development and application of a Repair Matrix tailored to the case study, (3) the implementation of a graph-based modelling approach for analysing product architecture and interdependencies, (4) the integration of LCA and LCC analyses to evaluate repair scenarios and (5) the design of consumer- and designer-oriented information tools to facilitate informed decision-making. The results demonstrate the potential of combining repair, environmental, and economic dimensions to enhance product repairability assessment and support the implementation of circular economy strategies aligned with the Right to Repair framework.

KEYWORDS

Circular Economy, Right to Repair, EN 45554, Repair Matrix, Graph-based modelling, Life Cycle Assessment (LCA), Life Cycle Cost (LCC), Visual communication.