Discover Sustainability

Review

Repairable electronic products for the circular economy: a review of design for repair features, practices and measures to contrast obsolescence

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Abstract
The current linear economy, with its "take-make-dispose" approach, has led to an unprecedented level of waste generation related to the end-of-life of electronics products, entailing huge impacts on climate change, pollution and resource depletion. Against this trend, product repairability is a preferred Circular Economy strategy to extend product lifespan and contrast obsolescence. It is strongly advocated by consumer movements ("Right to Repair") and supported by environmental policies, such as the European Union Circular Economy Action Plan. To be effective, a repairability strategy has to be defined at the product design stage. However, many electronics products are still designed with built-in obsolescence. In literature, Design for Repair (DfR) strategies are presented in a fragmented way, with their role in fighting obsolescence and enabling a Circular Economy being under-investigated. Through a systematic literature review, this article aims to identify the product design elements (DfR features) and detailed practical actions (DfR practices) that facilitate the repairability of products, preventing different types of product obsolescence as well as finding the indicators (DfR measures) to quantify DfR features to assess the level of product repairability. The systematic analysis revealed that, while DfR features (and the relative practices and measures) that contrast mechanical, technological and service obsolescence have been frequently investigated by the literature, lower attention has been dedicated to DfR features preventing relative obsolescence. These practices deserve more theoretical and practice-oriented research. The identified DfR features, practices and measures are then organized into a comprehensive framework, which sheds light on the operationalization of repair as a CE strategy and support designers and R&D engineers in designing products to be repaired. The framework provides guidelines to product designers and engineers to operationalize the 'Plan-Do-Check-Act' cycle of product development for repairability to increase product circularity. The framework also supports policymakers in the benchmarking and fine-tuning of currently policy adopted methods for assessing repairability at the product level.

Keywords Design for repair · Right to repair · Circular economy · Electronics

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1 Introduction

The linear economy model links economic growth to an unsustainable escalation in the production of goods and resource consumption [28, 36]. In this setting, the consumer market consistently encourages individuals to purchase new products, promoting a culture of technological advancement and excessive production [86]. For example, the number of smartphones produced has grown almost exponentially over the last 15 years [54], while their lifespan decreased from 4.7 years in 2014 to 2.7 years in 2020 [110], since users are encouraged to unnecessarily replace their products [56, 91]. This phenomenon leads to the so-called throwaway society [63], in which the product lifetime becomes unsustainably shorter. Consequently, manufacturers use more resources to sell more products, leading to unsustainable environmental and often geopolitical impacts [57]: for instance, e-waste has grown by 82% from 2010 to 2022 and is expected to grow by another 32% to 82 million tons in 2030 [10]. To address these issues, companies should consider implementing Circular Economy (CE) principles and strategies in the design of their products [22]. Moreover, other actors, for example, retailers may try to slow material and value loops by assessing products' repairability and durability and informing customers, as well as adapt their supplier selection processes and product purchasing policies to embrace circular economy [15].

Governmental institutions issued policies and directives to foster product repairability, also pushed by the Right to Repair movement, which aims to leverage repair to minimize waste. These policies are in line with the Sustainable Development Goals (SDG) of the United Nations, following the 2030 Agenda, in particular, with four SDGs. Firstly, as repair has been identified as one of the most effective CE practices to extend a product lifespan [17, 83], encouraging users to repair may contribute to SDG 12 (sustainable consumption and production), being often the least costly and least environmental impactful strategy to slow down resource usage [13, 49]. By using products as long as possible, the demand for new products (that require significant energy consumption and raw materials usage) decreases [23, 97, 102]. However, many products are purposefully designed with built-in obsolescence [58, 63, 79], which challenges repairability. Moreover, since repair is mostly a local activity, it fosters repair generates local jobs, especially in SMEs [90, 93], including young people, silver workers, and persons with disabilities, in line with the SDG 9 focusing on the access of small-scale industrial and other enterprises and SDG 8 "Promote sustained, inclusive and sustainable economic growth" [13, 49]. In addition, besides being a convenient practice to extend product lifecycle, repair is valued as a social practice. The do-it-yourself approach has proven to be a social activity that positively impacts people well-being, by developing repair skills, similarly to craft or art [112]. Motivated not only by costs but by ethical and environmental concerns, voluntary participation to repair initiatives organized by repair associations or repair cafes enables a sense of community and makes a positive impact on our planet and society, which is in line with SDG3 "promote well-being for all at all ages". Several contributions we analyzed promote a "community repair" as a way to build social relations among citizens and practice non-consumeristic and low-impact living [20].

Therefore, repair could make a remarkable contribution towards meeting the sustainable goals of Agenda 2030, and the first step to make it feasible is to adapt products' architecture to guarantee its repairability since product design. Although academic and business studies on CE, product design and repairability have spread over the years, a comprehensive systematization of Design for Repair (DfR) practices to contrast product obsolescence is still missing. Therefore, the aim of this paper is to identify and systematize the design features that facilitate product repairability for the Circular Economy, preventing different types of product obsolescence, which was historically widely accepted to preserve high volume of sales [59], however, currently represents a dangerous issue for the sustainable future of our planet. Moreover, we detail the practices to deploy DfR features and metrics to assess (and improve) the level of product repairability. To achieve this aim, a systematic literature review has been carried out, and a conceptual framework has been developed to structure DfR features, practices and measures around the different type of obsolescence they address, based on a combination of academic and grey literature on repairability. Thus, this article contributes to previous literature by suggesting a detailed and comprehensive systematization of DfR features, practices, and measures to prevent product obsolescence and enable CE, considering manufacturers', repairers' and consumers' perspectives, helpful for product designers, R&D engineers and policymakers to establish specific directives to promote the Right to Repair and enable CE. Besides, this paper strengthens the importance of product repairability for non-consumeristic sustainable future.

The remainder of this paper is structured as follows. Section 2 provides the background for the study, and Sect. 3 illustrates the methodology. Section 4 presents the results of the systematic literature review on DfR features, practices, and measures. Section 5 proposes the framework as a supporting tool for practitioners to develop repairable products and measure the level of their repairability. Lastly, Sect. 6 highlights the contributions, limitations, and perspectives for future research.

2 Background

2.1 Repair as a CE strategy contrasting obsolescence

Repair extends the life cycle of a product, letting consumers use the product longer [92]. It is a way of co-creating and redefining value, creating attachment, social innovation, and resistance to consumerism [52, 63]. It is also an economically convenient option, especially if it can be self-performed by the user [88], as in *Repair Cafes* encouraging individuals to repair their products by approaching local experts [82], in line with SDG 8 and 9. Besides, repair is widely available in low-income areas, where it is not only environmentally and socially sustainable, but also a vital necessity [51].

Repair is a product value recovery strategy that aims at correcting specific faults of a product [105] and restoring it to good working conditions after its damage [17, 33]. Product repair is a crucial part of the CE to reduce or slowing down the resource usage pace, as it extends the product lifespan [53, 100]. Compared to other recovery activities such as remanufacturing or recycling, repair is a more environmentally friendly option because it does not require complex reverse logistics and reverse manufacturing processes and infrastructures [46, 49]. As the first step in product recovery management, product repair is simpler and cheaper, according to the "inertia principle" [93], requiring fewer resources, time, and energy to bring the product back into the system [13, 44]. So, repair is a CE strategy able to contrast planned obsolescence and promotion of "wastefulness" culture with "buy new buy often" mentality [59], thus achieving longer life for goods, and reducing waste, pollution and resource consumption, in line with SDG 12.

2.2 Institutional and societal efforts towards repairability and contrasting obsolescence

In Europe, environmental policies and norms, such as the European Green Deal, the EU Circular Economy Action Plan, the EU Ecodesign Directive, and the New Consumer Agenda consider product repair as an objective to fight product obsolescence and support the transition to CE [23, 76, 91, 97, 102]. Stricter control has been applied in recent years against commercial behaviors promoting planned obsolescence and preventing lifecycle extension of products. For instance, in 2022, Apple was fined in France and Italy, accused of deliberately slowing older phone models with operating system updates to sell newer models; Samsung was also fined in Italy for planned obsolescence [16]. In addition, Directive 2019/771 introduces the presumption of the existence of a conformity defect for a duration of legal guarantee (2 years) which increase incentivize producers to offer commercial guarantee of durability longer than two years [77]. However, some contributions argue that current EU measures are not sufficient to solve the planned obsolescence issue [59, 83]. Several repair institutions, such as Repair Association, HOP club (https://www.stopobsolescence.org/), Service Industry Association, Electronic Frontier Foundation, and iFixit.org, advocate for repair-friendly policies, regulations, statutes, and standards on the state and local levels. Mainly thanks to iFixit, a global community committed to making repair easier and accessible [8, 47], repair became a worldwide movement of sustainability-oriented society, aware of its impact and ready to learn and share their knowledge and competencies, as well as tools and materials [82, 111].

A product becomes obsolete when a user no longer wants it [11]. So the obsolescence may occur due to the intrinsic property of the product, user individual behavior and mindset, as well as to economic factors [26, 42, 74]. A study by the EEA (2020) classified the previous literature and distinguished between absolute and relative obsolescence [90]. Building on that study, we state that *absolute obsolescence* is associated with objective reasons. In particular, we distinguish mechanical failure (mechanical or functional obsolescence), incompatibility of software (technological obsolescence), and unavailable spare parts or tools, making it impossible to service a product (service obsolescence). *Relative obsolescence* refers to the consumer perception of inadequate product condition due to psychological, style, cosmetic, or aesthetic reasons, as well as economic aspects and perceived functionalities. Manufacturers can purposely design obsolescence of both types in their products when they intentionally adopt design practices that limit product longevity. This practice is known as *planned obsolescence*, and it is driven by the aim to increase the sales of new products [9, 42].

2.3 Product design for repairability

Product design is a critical activity to enable repair, as most of the environmental impacts of a product are locked in at the design phase [35, 40, 110]. Thus, product design should be carried out with clear repairability objectives and in compliance with current and envisaged repairability legislation. The literature on the "Design for X" (DfX) concept presents different practices for designing a product to optimize different performances, including its environmental footprint. DfX indicates a set of methods, techniques and tools that can be applied to enhance the (re-)design of a physical product. Bocken et al. [17] suggests classifying DfX practices into those that close, narrow, or slow the loop of resource usage. Considering repair as an activity that extends a product life cycle, *Design for Repair* (DfR) is defined as a "promising solution to extend the lifespan of products by making the repair process economic and reasonably time-consuming" [94]. Thus, DfR belongs to the "slowing the loop" design strategy [17].

DfR deserves more investigation within the CE context as a key enabler of the CE paradigm by extending the product lifetime and postponing the need for resources for new production. Little attention has also been devoted to investigating how DfR practices can contrast different types of product obsolescence [16, 81], in particular, the role of product design practices to influence user's attitude to the product. A detailed and comprehensive systematization of DfR practices may contribute to the operationalization of repair as a CE strategy and support designers and R&D engineers in designing products to be repaired.

3 Methods

3.1 Research framework

Focusing on DfR as the main object of the study, this research aims to explore the first stage of product lifecycle (product design phase) and identify the product design elements (DfR features) and detailed practical actions (DfR practices) that facilitate the repairability of products, preventing different types of product obsolescence as well as finding the indicators (DfR measures) to quantify DfR features to assess the level of product repairability. The research framework is illustrated in Fig. 1. In this research setting, *DfR features* are first defined as product design characteristics for an easier and quicker repair. Then, *DfR practices* are defined as practical solutions adopted to implement the different DfR features in product design. Lastly, *DfR measures* are defined as indicators to quantify the effective implementation of DfR practices. Figure 1 is depicted as a cycle to reinforce the concept that the definition of DfR features, practices and measures is not a one-step process, but it is iterative and can enable continuous improvement processes in companies where DfR features are identified, implemented through practices, measured through metrics, and then re-evaluated in subsequent improvement cycles. DfR features, practices and metrics are identified through a content-based analysis of the scientific literature and contextualized with additional grey literature (reports, policies, news articles, etc.). DfR features, in particular, were extracted from the analyzed papers, and classified according to the type of obsolescence they tackle: *absolute* obsolescence and its subcategories (*mechanical; technological* or *service*), or *relative* obsolescence. Then, DfR practices to implement DfR features and DfR measures to evaluate the effective application of DfR practices to achieve DfR features were extracted and systematized accordingly.

3.2 Literature selection

The systematization is based on the analysis of scientific literature, enriched by grey literature that has been scrutinized as well. The selection of the scientific literature was carried out through the PRISMA method [67]. The PRISMA methodology ensures clarity and transparency when reporting systematic literature reviews, reducing bias and enhancing the legitimacy of the data analysis. The literature search was performed on March 2024 on Scopus, one of the most consulted databases among researchers of engineering field, by using the following code for papers search: TITLE-ABS-KEY ((("design to repair" OR "design for repair" OR "design for durability" OR "design for product life extension" OR " Design

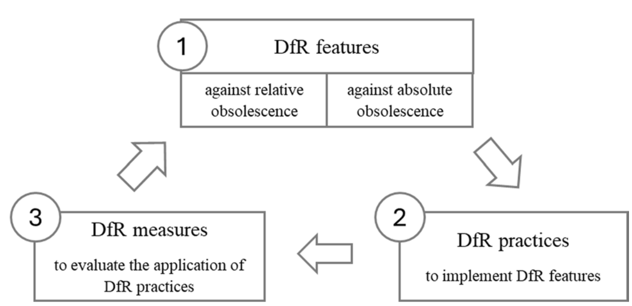

Fig. 1 Research Framework for DfR systematization

for Long-life products" OR "design for longevity" OR "design for ease of repair" OR "right to repair" OR ("design repair" W/5 ("for" OR "to" OR "eas*" OR "quick*")))) OR ("Design for attachment and trust" OR "Design for Circular Economy" OR "Design for Disassembly" OR "Design for Environment" OR "Design for Failure modes" OR "Design for Flexibility" OR "Design for LifeCycle" OR "Design for Maintenance" OR "Design for Maintainability" OR "Design for Modularity" OR "Design for Quality" OR "Design for Reassembly" OR "Design for Reliability" OR "Design for Reuse" OR "Design for Robustness" OR "Design for Reverse Logistics" OR "Design for Safety" OR "Design for Serviceability" OR "Design for standardization" OR "Design for Sustainability " OR "Design for upgradability" OR "Design for updateability" OR "Design for adaptability") AND ("Sustainab*" OR "Green" OR "Circular") AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "ECON") OR LIMIT-TO (SUBJAREA, "ENVI")). For the keywords, design strategies that aim at product repairability and longevity were selected using a snowball sampling approach performed before the systematic search. As suggested by some relevant contributions, some of them (such as Design for Attachment, Design for Adaptability and Upgradability) are important to make consumers arrive at the point when repair is needed (thus preventing relative obsolescence) and others (such as Design for Maintenance, Design for Serviceability, Design for Disassembly, Design for Safety) directly impact the repair process, making it easier and quicker (thus preventing absolute obsolescence). Instead, our review does not include design strategies to close the loop between post-use waste and production, such as Design for Recycling, Design for a biological cycle or Design for End of Life. The same holds for design strategies to narrow resource flows, such as Design for Material or Energy Conservation, Design for Miniaturization, or Design to reduce life cycle costs [14, 17]. The combined use of keywords brought to the total number of 980 papers that were then filtered by relevance based on journals, titles and abstracts, according to the steps proposed by the PRISMA method. A process chart for the systematic literature review carried out in this study is shown in Fig. 2, and hereafter illustrated.

In the screening phase, four main exclusion criteria were applied for practical screening. The first one is related to the research area: the papers on civil engineering, built environment, marine science, medicine, sociology, history, agriculture, materials and energy management and design creativity were excluded. The second one is related to the focus of the study: papers focused on recycling, materials selection and the assessment of the environmental impact or the lifecycle of such activities were excluded. The third exclusion criterion is related to the unit of analysis: included papers should focus on the product design and not on process design or business model conceptualization. The literature on product lifecycle that provides only lifecycle assessment methods but no design practices to enrich the collection of this study was first carefully examined and then excluded at the eligibility phase. Other papers describing material selection or software solutions for sustainable product development were also discarded, as they focus more on earlier stages of product development than the ones discussed in the paper. The fourth and last criteria is related to the time bounding. The interval between two earliest from the selected publications is around 50 years (1946 and 1996), which might not include other papers in the meanwhile. Therefore, we have decided to limit the publication period of the analysis to the last 25 years, starting to explore papers published since 2000.

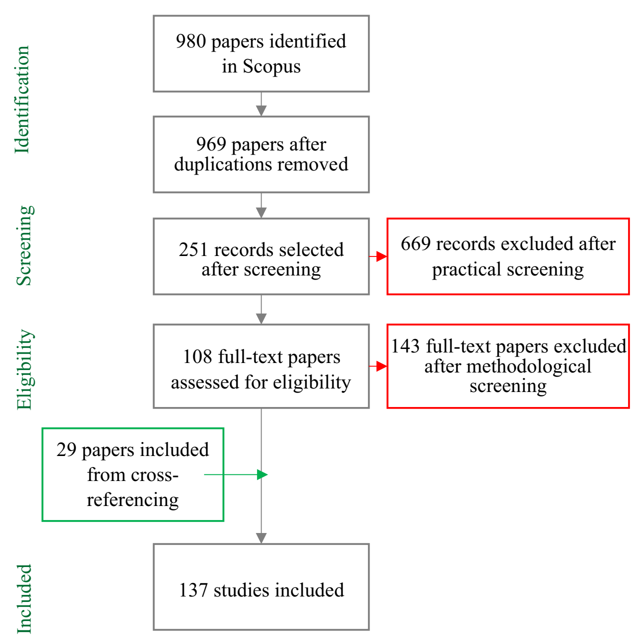

Fig. 2 Process chart for the systematic literature review

During the methodological screening (eligibility phase), the following criteria were applied: exclusion of technical documents that contain a detailed description of repair services, which are hardly generalizable; exclusion of papers in which repair is just mentioned, but it is not a focus of study. After the keywords-based search, a backward approach was adopted to include the relevant studies cited in the articles and other relevant papers recommended by the reviewers, which led to 29 additional papers. Therefore, the detailed content-based literature review was carried out on a set of 137 papers.

4 Results: design for repair systematization

4.1 Descriptive analysis

All selected publications have been categorized according to the year of publication, document type and journal. Quite a few publications were found before the years 2010s, and the years 2020s show a remarkable rise in the number of publications (Fig. 3). One of the possible reasons for the recent growth could be the greater attention paid by the European Commission to the issues related to eco-design and the implementation of French repairability index in 2020. Indeed, 46 out of 114 papers published after 2012 discuss the "Right to Repair" directive, European Green Deal, EU Ecodesign directive and other regulations.

As shown in Fig. 4, the Journal of Cleaner Production is the main publication outlet on this topic, covering 22% of the sample papers. Only three other journals (Sustainable Production and Consumption, Business Strategy and the Environment, and Resources, Conservation and Recycling) have published more than three papers. The rest of the sample is dispersed across 76 other journals and conference sources.

Geographical distribution of selected papers (Fig. 5) demonstrates that most of the literature comes from the USA or developed European countries. It might be explained by the spread of the Right to Repair and iFixit initiatives in the USA, active social movements in the Netherlands, Sweden, the UK and recent regulations of the European Commission about sustainable product design, including repair or the presence of funding opportunities (e.g. Horizon calls).

4.2 Classification of design for repair features

The analysis of the literature allowed pointing out 17 different DfR features, and their links with obsolescence types. Thirteen DfR features address absolute obsolescence, while four contrast relative obsolescence. The features addressing absolute obsolescence have been grouped according to their action domain (mechanical, service, or technological), as described in Sect. 2.1. They are described in the following subsections.

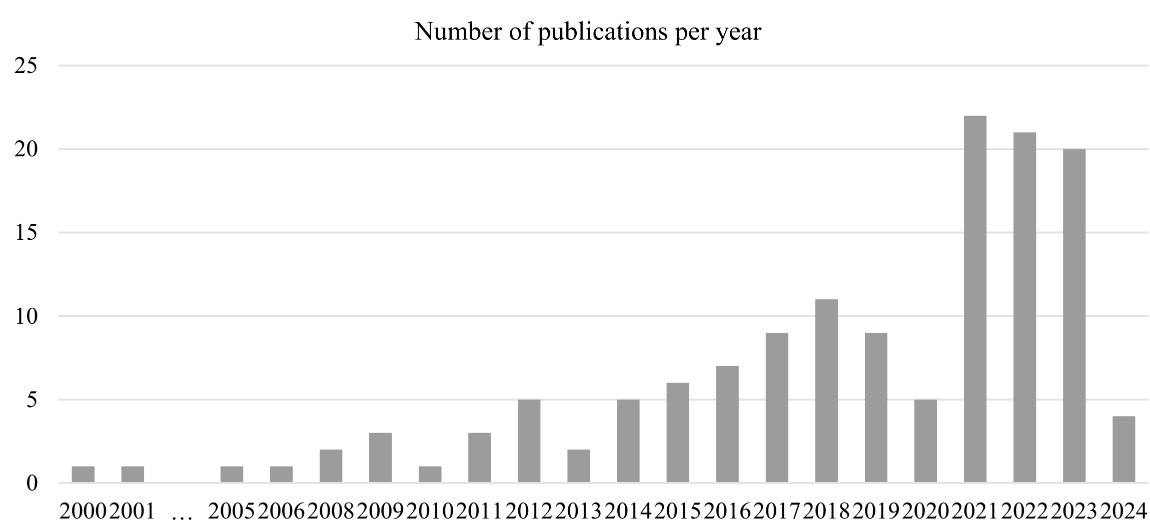

Fig. 3 Time distribution of the literature sample

Fig. 4 Number of publications per outlet

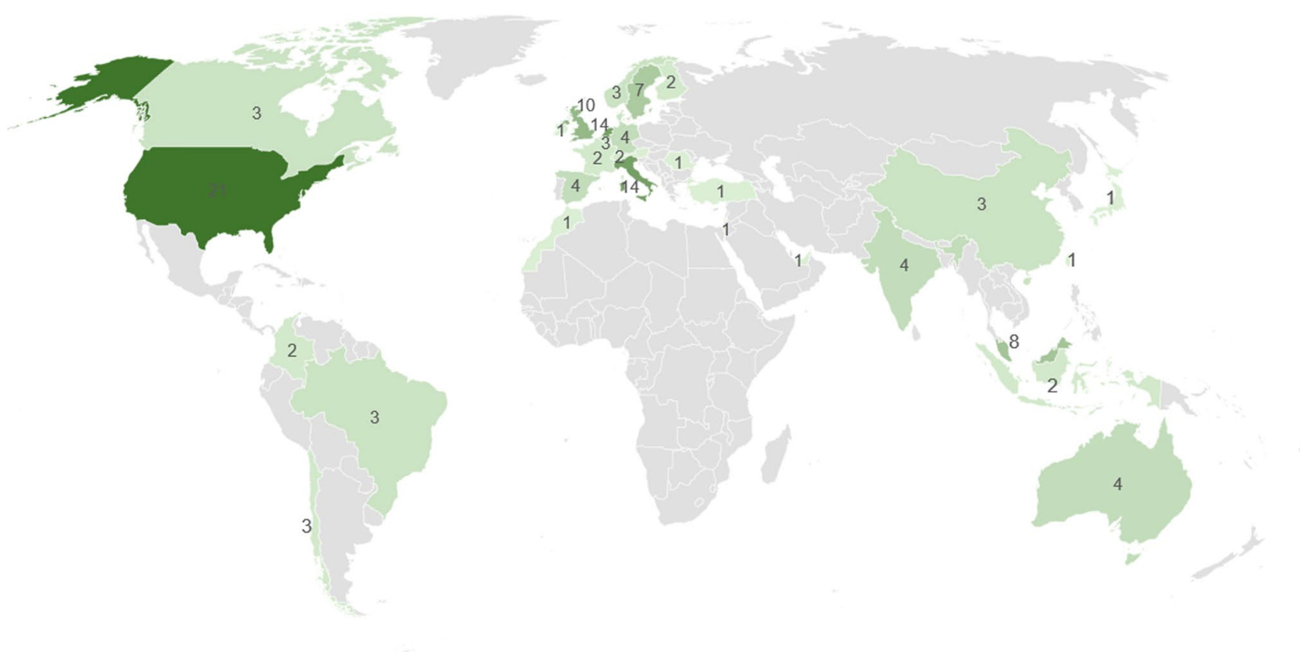

Fig. 5 Number of publications per country of the corresponding authors

4.2.1 DfR features preventing absolute obsolescence

DfR features related to absolute obsolescence are divided into three subgroups according to the specific subtype of obsolescence addressed: mechanical (Table 1), service (Table 2) and technological (Table 3). Since absolute obsolescence heavily depends on product functionalities, the first set of features is to guarantee that the product will work correctly through its lifetime to overcome mechanical obsolescence. These features are related to choices at the product architecture level that favor repair in case of failure. The identified features are modularity, easy and quick disassembly and

Table 1 DfR features to prevent mechanical obsolescence

Nr	DfR feature	Representative example	References
1	*Modularity*—product functions are delivered using individually distinct functional units instead of an integrated, monolithic structure	Framework laptop is deeply customizable, allowing disassembly, upgrades and replacing almost all components [29]	[38, 44, 79]
2	*Easy and quick disassembly and reassembly*—possibility to perform a straightforward, intuitive disassembly process and uncomplicated reassembly process	Fairphone is an easy-to-disassemble and -repair phone [17]	[14, 45, 73, 86, 106, 107]
3	*Openability/accessibility*—the ability to open a product and be able to access its architecture with standard tools and equipment, including product arrangement, allowing access to components without the complete removal of a part	iPad has an adhesive and glue-based design, that requires special tools to open or disassemble it [46]	[2, 55]
4	*Safety*—the ability to perform safe repair in terms of injuries, avoiding using sharp tools or other risks (electrical, chemical, thermal, mechanical)	Lack of safety notifications on a product or in its repair manuals [89]	[14, 30, 41, 79]
5	*Material durability*—the use of robust materials compatible with a long product lifespan that could withstand the stress of product opening and repair	Product components are robust enough to be reused without replacement [38], like smartphones that can survive accidental drops [13] or create protective layers to avoid surface scratches due to shipping [34]	[13, 34, 38]
6	*Repairable appearance*—a product looks repairable (e.g. it has an interface for feedback and diagnostics, including intuitive signals/interaction interfaces about the functioning and failure of a product)	Electronic displays on the products [90, 101] that indicate the error code, different coloring for blinking lights[79], robust product look [57]	[57, 78, 80]

Table 2 DfR features to prevent service obsolescence

Nr	DfR feature	Representative example	References
7	*Standardization and reuse of components*—use of non-custom components across the product range and product generations within the same product category	EU Parliament approved common charging cable since 2024: all smartphones and tablets must be adapted for the USB-C charger	[17, 18, 30, 38, 55, 58, 80, 81, 106]
8	*Commonality or compatibility of components*—use of common parts across product lines	Apple's repair software does not allow independent repairers to 'replace a broken part with one taken from another Apple device' [60]	[14, 19, 46, 58, 108]
9	*Spare parts and tools availability and affordability*—the presence of spare parts and repair tools on the market at a competitive price in relation to the total product price	The main fail-to-repair reasons for iPads was the absence of appropriate repair tools [46]. In 2020, Apple declared to make available spare parts, tools and training to their authorized service providers [95]	[7, 17, 85, 86, 102]
10	*(Convenience in) after-sales servicing*—establishing the infrastructure for returns and services, warranties	Dutch company Bundles, in partnership with Miele and Siemens, offers white goods and kitchen appliances via a subscription fee service, including repair and maintenance costs [21, 60, 71]	[5, 71, 108, 111]
11	*Documentation*—providing manuals and guidelines containing information on how to service a product, illustrations and diagrams for better understanding	Motorola and Lenovo supply a wide range of product manuals and guides, warranty information, DIY instructions, and multiple repair service options and solutions directly from their corporate websites [95]	[66, 86, 95, 102]

Table 3 DfR features to prevent technological obsolescence

Nr	DfR feature	Representative example	References
12	*Updateability*—the ability of a product to keep its performance as it was initially designed	Miele washing machine is equipped with upgradeable software, an intelligent system and dynamic washing program management based on the availability of new cleaning products [108]	DeWinter et al. [30] Eckersall et al. [32] Persson [75] Vanegas et al. [106]
13	*Upgradability*—the ability of a product to continue being useful under changing conditions by improving its quality, value, and effectiveness or performance in line with the technological evolution	Computer software updates to assist products in adapting to technological change [40]	Hernandez, [44] Carlsson, [24] Sabbaghi, [86]

reassembly, openability/accessibility, safety, material durability, and repairable appearance. First, modularity means optimally designing product families in order to allow effective repair and upgrading [6, 41, 87, 107]. Easy and quick disassembly and reassembly enable to perform a straightforward, intuitive disassembly process and uncomplicated reassembly process after repair, reducing waste. The same holds for openability and accessibility features to ease access to components and materials for repair purposes [24, 73]. Often, manufacturers create additional protection to prevent non-authorization or any kind of repair. Being able to open a product creates a feeling of "control and mastery" over the possessed object, and it leads to psychological well-being [48]. Safety helps reduce risks of injury and to integrate hazards and risks of humans, materials, etc., while repairing products [14]. Durability allows users to achieve enduring satisfaction with the product rather than only meeting momentary desires, stimulating longer product use [104]. Lastly, repairable appearance supports consumers in understanding when and how a product should be repaired [79]. Table 1 lists these features, provides definitions formulated by the authors based on the examined literature, and some representative examples for each feature.

When the product architecture allows repairability in case of a failure, the repair service infrastructure is the next to consider. Standardization and commonality of components, spare parts and tools availability, and the access to documentation such as repair manuals are vital for product through-life servicing. For example, to support independent repairers and individuals to self-repair products, Motorola has officially partnered with repair organizations (iFixit, Cell Phone Repair) to distribute DIY information and tools and to connect users with a national network of independent repairers to enable walk-in repair options [95]. Also, Apple's 'Independent Repair Provider Program' will provide independent repairers not part of the Apple Authorized Service Provider network with parts, tools, and training limited to certain approved repairs. Table 2 summarizes DfR features that prevent service obsolescence and representative examples for each of them.

Due to continuous technological evolution, prolonging the product life cycle through repair may not be the best choice for the user when more technologically advanced solutions come to the market. Consumers often desire to use technologically updated products [86], requiring the market to move along with their changing needs and future uncertainties [50, 113]. Thus, to prevent customers from simply abandoning their old products and buying more technologically advanced substitutions, product developers must consider so-called "evolvability", considering two elements. Firstly, updateability will allow consumers to keep using the product, guaranteeing safety updates to preserve products' performance. Secondly, product upgrades will provide consumers with improved product performance [6, 57]. Table 3 summarizes DfR features that prevent technological obsolescence and representative examples for each.

4.2.2 DfR features preventing relative obsolescence

Some products are highly function-oriented and the emotional, and aesthetic and economic consequences of design decisions are hardly considered [9, 33]. In these cases, when users perceive it as obsolete or outdated, they will be willing to replace it despite of its repairability [2, 12]. Huang et al. [46], Carlsson et al. [24], Van Den Berge et al. [93] highlight the importance of considering the user's perspective and strengthening consumers' emotional attachment when designing products because the repair-replace decision depends mainly on the user's preferences. Thus, product designers have an essential role in enhancing positive product experience by adopting emotional design [56] and considering users' preferences to recall their emotional attachment to the product and encourage them to take care of their products [81, 104]. Table 4 summarizes design features preventing relative obsolescence. Guaranteeing ergonomics in use and aesthetic product design over time is essential to let consumers enjoy using the product. If the customer associates the product with a significant value or feeling, it can increase the consciousness of responsibility and obligation to take care of the product [24]. Therefore, product customization and personalization play an important role in making consumers want to keep the product longer.

4.2.3 Analysis of DfR features in the literature

Figure 6 shows the number of publications in the literature sample discussing each DfR features. The figure emphasizes that the more frequently discussed DfR features are mainly related to product architecture to contrast mechanical obsolescence, such design for disassembly, modularity and material durability probably due to the main focus on the engineering perspective, demonstrating the technical opportunities of repairable designs [101]. Openability is the least mentioned among them, but it has become more popular since the Right to Repair promotion. The least attention is dedicated to repairable appearance, even if it is fundamental for the first evaluation of repair feasibility and directly affects the repair-replace decision of users [12, 79]. DfR features preventing relative obsolescence received much less

Table 4 DfR features to prevent relative obsolescence

Nr	DfR feature	Representative example	References
14	*Ergonomics in use*—product design to ensure suitable and intuitive functioning and comfort in use	Intelligent assistant for the troubleshooting and testing processes [69, 89, 103]	[69, 86, 103]
15	*Attachment*—product design recalling a feeling of emotional closeness, commitment or loyalty to the product for products with a particular value for a user. (vs. Detachment—product design recalling a neutral attitude from users)	Product with a special meaning for the user, derived from collaborative design, purchasing or user experience [70, 81]. Acceptance of imperfect products after their long use helps avoid their substitution [33]	[33, 70, 81, 109]
16	*Aesthetic and timeless design*—applying classic and "never old" design techniques to make product appearance pleasant over time	Simple, symmetric products with neutral colors [57] which is less likely to annoy a consumer soon	[57, 81]
17	*Personalization/customization*—allowing a user to personalize its products and enhance a feeling of uniqueness	Product adapted to the consumer's specific needs or preferences [1] or simply a product with personalized writing on it [31]. Garments are sewn using individual body measures [81]	[1, 31, 66, 81]

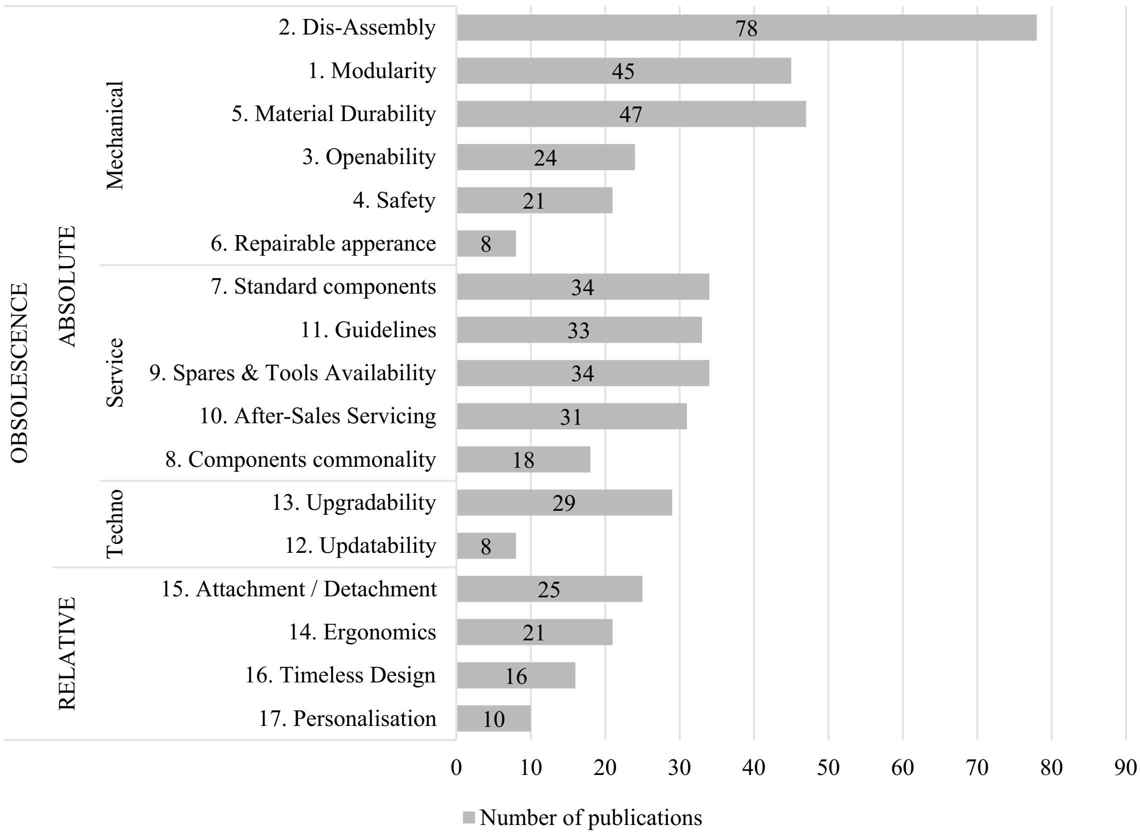

Fig. 6 Number of publications discussing one or more DfR feature

attention from academicians. However, user-centricity is vital for sustainable product redesign [50, 62, 84] as users are key decision-makers in product repair or disposal. If the customer associates the product with some personal value or feeling, the inclination to take care of the product will increase [24, 104]. Ackermann et al. [2, 3] confirm that product attachment increases the likelihood of care activities towards the product and postponed replacement. Indeed, DfR features to contrast relative obsolescence were mainly discussed after 2020.

The analysis also showed that DfR features are sparsely mentioned in the literature, without a detailed DfR conceptualization. Figure 7 shows that most papers discuss up to 5 features and few publications have a broader coverage, with three features being addressed jointly by 30% of the papers.

4.3 DfR practices

This section provides a list of recommended DfR practices stemming from the systematic literature review and complemented with a grey literature analysis, also illustrating the actions suggested to enable DfR features, and pitfalls to be avoided.

To address mechanical obsolescence, modularity may be achieved using a clear separation among the physical components, developing product architectures as a joint union of physically detachable modules [79, 92], where each module is responsible for a separate function [38] to determine the root-cause failure [30]. Disassembly requires straightforward methods that do not damage (reusable) components [45, 73, 86, 107], short disassembly time [85], appropriate materials for products that would not require additional painting after reassembly [24, 61]. A useful method for making disassembly and reassembly easier is keying or poke-yoke. This approach involves using matching geometric features, such as holes and pins that have the same size and shape. This ensures that connectors, components, and parts are correctly positioned [31]. Minimizing the number of fasteners used in an assembly may reduce the number of manufacturing operations, which favors quick and easy disassembly as well as product openability and accessibility to product's parts. Table 5 summarizes the identified DfR practices for the DfR features addressing mechanical obsolescence.

Fig. 7 Number of publications discussing DfR features jointly

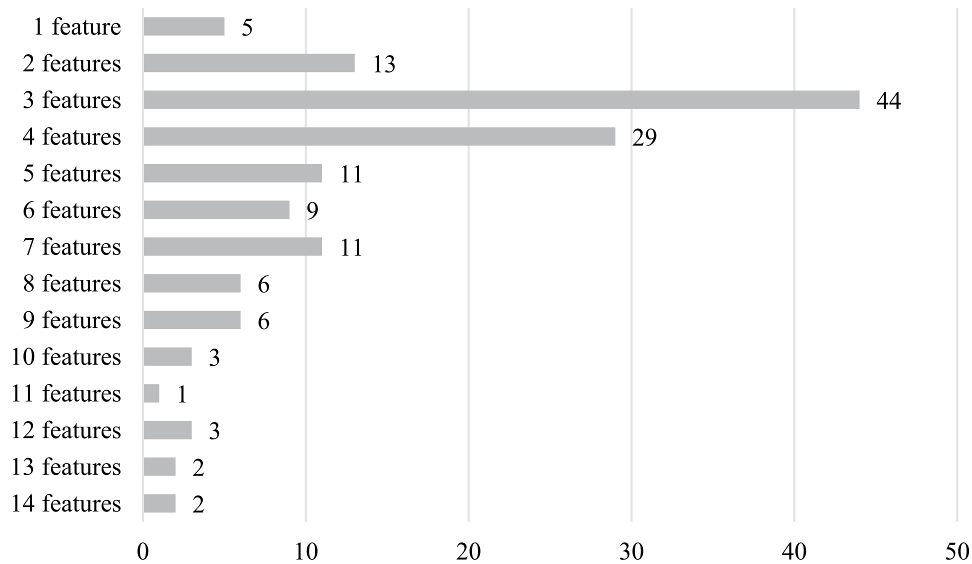

Table 6 summarizes the identified DfR practices for the DfR features addressing service obsolescence. Determining the standard of product components, especially fixing ones, may be implemented through the redesign of entire product lines or product families that would allow manufacturers and repairers to substitute easier failed or missing components, if they become common across different brands within the same industry. Establishing an authorized network of after-sales services with proper supply chain partners and collaborative measures to provide original spare parts will enhance the product use experience to address service obsolescence Hernandez et al. [44]; Tischner and Stasiuk, [100]. Setting up multi-channel spare parts delivery through different platforms will allow professional and self-repairs [94, 99], especially if the required parts are standard and common across different products of the same category. Open-access, online repair manuals and documentation are vital to enable repair. For instance, the French government developed detailed requirements related to the clarity and completeness of repair guidelines [65].

Table 7 summarizes the identified DfR practices for the DfR features addressing technological obsolescence. For example, for electronic equipment it is fundamental to guarantee the adequate, safe, and up-to-date use of functionalities in line with current technological trends. Granting the user the right to accept or decline new updates and upgrades is also of utmost importance, especially when software elements are involved [83, 98]. Updateability and updateability can be achieved by releasing updates and upgrades and making them available to users who may decide whether to install them or not.

Finally, Table 8 summarizes the identified DfR practices for the DfR features addressing relative obsolescence. Considering the primary role of users in a "repair or replace" decision, it is crucial to involve them in product design development to grasp fashion and social trends. Users desire to differentiate themselves from others and express their identity, as this gives a sense of uniqueness, which may be achieved through the personalization of the product. At the same time, some products with a focus on functionality do not require strong temporal identities, for which a neutral design will be appropriate [41]. Clear and visible communication of green design and repairing benefits, replying to environmental concerns of customers [99]: for example, the percentage of recycled materials used to produce and repair an item the sustainable sources of materials may recall or reinforce user's attachment to the product.

4.4 DfR measures

Practitioners use several qualitative, semi-quantitative and quantitative indicators to measure repairability, as described in the academic and grey literature [23, 27].

Academic contributions in the selected sample rarely discuss comprehensive methods to measure repairability. For example, Barros and Dimla [13] investigate smartphone repairability indexes based on iFixit criteria; Bracquené et al. [18] explore washing machine's repairability using the criteria of French repairability index, which proved to have limitations. The academic literature is rather focused on single dimensions, such as, for example, measuring disassembly ease [34, 106] or material and energy use [43, 75]. This section provides a collection of metrics (Table 9) to measure DfR features

Table 5 DfR practices addressing mechanical obsolescence

Nr	DfR feature	Practices to implement	Pitfalls to avoid
1	Modularity	Clearly separate replaceable components according to their function Create replaceable modules of two or more components typically replaced together in case of difficulty in determining the root-cause component Label modules Ensure module detachment Place together components with similar lifetimes	Develop inseparable monolithic products Combine parts with different physical life or maintenance intervals
2	Disassembly and reassembly	Use straightforward methods and minimize disassembly sequences for short disassembly time; report disassembly maps and liaisons diagrams using standard icons Choose appropriate materials, tools, and compatible fasteners with the base material Prefer fasteners that do not require tools to join components, such as snap fits, force fits, and complaints Standardize the size, shape, and interface locations Keep the visible relationship between components and colored wires Apply keying (poka-yoke), a technique to prevent errors in product reassembly. For example, making specific shapes for cables and appropriate holes to re-insert them, so it is impossible to switch the cables	Damage reusable components Use many (5 +) screws and fasteners Use coating, painting or plated components to prevent discoloring Welding, gluing and putting adhesive between sub-assemblies Use security (proprietary tool) fasteners, sacrificial snap-fits, and hidden fixings, fragile ribbon cables
3	Openability/accessibility	*DfR practices for disassembly and reassembly* + Position the parts that correspond to the same function close to each other (e.g. make all electronics accessible from the same angle) Apply loose fits for internal components Use non-isolated electrical measuring points that are valid for testing	Apply hidden fixings and snaps, deeply recessed fasteners, and unnecessarily long cables Apply narrow slits and holes that prevent or limit servicing
4	Safety	Ensure the product performs well and it is safe to use Recommend the use of PPE (personal protective equipment) for safe and efficient repair, for example, gloves, glasses, masks Clearly identify and describe component load limits, tolerances, and adjustments Test electrical items like voltage, frequency, load, and brownout, along with environmental items like heat, humidity, shock, and vibration	Use toxic materials and unprotected sharp elements in product design
5	Material durability	Use non-corrosion, resistant materials in moist environments that are easy to clean and sterilize Use materials and construction are unlikely to fail or survive in case of accidental drops Consider product performance and lifespan when selecting materials Ensure the components are robust enough to reuse them without replacement	Use non-compliant coatings, such as painting, fragile or low-quality materials that lose their properties over time
6	Repairable appearance	Embed monitoring sensors and displays to signal when it's time to schedule service before a failure actually occurs Provide evident indications about product malfunctioning: design signals in the form of text, blinking or colored light, sounds, etc	Design counterintuitive product fixing

Table 6 DfR practices addressing service obsolescence

Nr	DfR feature	Practices to implement	Pitfalls to avoid
7	Standardization and reuse of components	Apply the standard parts design and interfaces Use easily replaceable standard components and materials	Use unique fasteners, connections, and components
8	Commonality or compatibility of components	Use components that are feasible to back up from one product line to another within the industry Adopt product family design rules	DfR practices for standardization and reuse of components
9	Spare parts and tools availability and affordability	Allow easy access and identification of spare parts Ensure spare parts are available throughout the product use cycle (after the last production) and have adequate delivery times	Very specific (no commonality) and/or highly expensive parts
10	After-sales servicing	Establish an authorized network of after-sales services and suggest warranties Offer multi-channel delivery possibilities for spare parts Ensure that experts have enough capacity to guarantee customer care Ensure remote assistance to facilitate the search for information to identify the breakdown cause or to carry out the repair (phone/video call line, chat, application included in the equipment, remote control of the equipment Allow easy component testing Ensure products can be stacked and safely transported	Long disassembly sequence required to effectively test components
11	Documentation	Provide understandable repair instructions, including guidelines for disassembly and assembly sequences, product technical characteristics, and troubleshooting Use standard icons and terms Store and provide data on performed inspections, faults, history repairs, replacements, etc Clearly identify and describe component load limits, tolerances, and adjustments Clearly describe each operational step (e.g. changing a tool or spare part) in the language of the selling market, including the list of professional repairers, instructions for self-repair, and illustrative schemes	Online product documentation (manuals) not available

Table 7 DfR practices addressing technological obsolescence

Nr	DfR feature	Practices to implement	Practices to avoid
12	Updateability	Constantly release updates and ensure an optimal updating time	Avoid software locks preventing diagnostics and updates
13	Upgradability	Communicate available upgrades to users Provide users with the right to decide whether to accept or decline new upgrades Ensure an optimal upgrade time	Avoid materials and assembly methods that prevent the upgrade and rebuilding of the product

Table 8 DfR practices addressing relative obsolescence

Nr	DfR feature	Practices to implement	Practices to avoid
14	Ergonomics in use	Provide easily understandable and reliable information about how to use and service products and suggest product care routines	Limited consideration of user preferences regarding product use
15	Attachment/detachment	Communicate the product value and its possible meaning, green design, and repair benefits and reply to customers' environmental concerns/Develop a neutral design	Limited consideration of user values regarding product use
16	Aesthetic and timeless design	Use eco-appropriate and product adapted materials with coatings that does not wear out rapidly with age or "age gracefully"	Radical design that is likely to annoy a user soon
17	Personalization/customization	Allow customizable product architecture Design inspired by unique handcrafted objects Create opportunities so the user can redesign and reconfigure the product during its use and involve users in the product engineering phase	Intentionally limit possibility of product personalization

Table 9 Quantitative indicators to measure repairability level

Obsolescence type		Nr	DfR feature	Quantitative indicators
Absolute	Mechanical obsolescence	1	Modularity	Number of independent modules [46]; Number of functions per module [38, 64]; Number of components that can be replaced independently [25]
		2	Easy and quick dis-reassembly	Number of steps required to disassemble the spare part [30]; Number of wires to be disconnected, fasteners to be removed [30]; Time/Number of different tools required for disassembly [65]
		3	Openability/accessibility	Binary criteria: use of glues and welding; need for proprietary tools; holes longer than tools, other difficulties to access [46] Number of steps/tools required to access the product [65]
		4	Safety	Score: A score is assigned based on the risk level associated (electrical, chemical, thermal, mechanical), considering likelihood and severity [4, 30] Binary criteria: Presence of safety warnings and recommendations on a product or in the relative documentation
		5	Materials durability	Material intensity metrics [43]; material resistance level, a measure of fatigue strength, temperature stability, fracture toughness, etc., [72]
		6	Repairable appearance	Score based on the type of interface: intuitive, coded, or proprietary [4, 79]; calculated score based on openability and accessibility
	Service obsolescence	7	Standardization or adaptability of components	Number of components that require proprietary tools to repair [65, 68]
		8	Commonality or compatibility of components	% of fastener commonality within the product system; % of potentially reusable fasteners [37]
		9	Availability (and affordability) of spare parts and tools to repair	Spare parts and tools cost; Spare parts delivery conditions: time, order lot [65]; Number of distributors ready to supply tools and spare parts [65]
		10	After sales servicing (infrastructure for returns and services, warranties)	Binary criteria: presence of authorized service providers recognized by OEMs (original equipment manufacturer that creates its own products) Number of steps and checks required for the removal and replacement of the component [30]
		11	Documentation (guidelines)	Binary criteria: Documents availability (free of charge, in the local language); repair manuals including schematic diagrams and technical information about the product [65]
	Technological obsolescence	12	Upgradability	Binary criteria: compatibility of hardware and software with programmed upgrades; Time required to perform upgrade [113]
		13	Updateability	Binary criteria: compatibility of hardware and software with programmed updates [4]
Relative		14	Ergonomics in use	Binary criteria: use of intuitive product architecture; the presence of a user-friendly interface [4]; specific criteria by certification bodies (e.g. ErgoCert)
		15	Attachment/detachment	Based on user's preferences and product performances
		16	Timeless design	
		17	Personalization	

preventing obsolescence, as emerged from the literature sample analyzed. For instance, the indicators include the number of independent modules, the number of steps to open or disassemble a product, the number of components that require proprietary tools to measure absolute obsolescence, and the results of the users' test on ergonomics or consumer survey to test attachment, personalization or design aesthetic for relative obsolescence, which is generally assessed following the consumer perspective and subjectivity.

5 Discussion: towards a comprehensive DfR framework

This paper highlights the importance of repairability as a product value recovery strategy and conceptualizes DfR features, practices, and measures to prevent product obsolescence and enable CE. The results are summarized within a comprehensive framework that systematizes academic and grey literature and facilitates the development of easily repairable products (Fig. 8), following a 'Plan-Do-Check-Act' (PDCA) cycle of continuous improvement in product design [96]. In quality management, the PDCA cycle (also known as the Deming Cycle) is a four-step iterative process used for the continuous improvement of business and operation processes. Traditionally applied for the quality improvement of manufacturing and production processes, the proposed comprehensive framework shows how the PDCA cycle can be effectively applied to product design process to continuously enhance repairability to contrast obsolescence. In particular, the first step ('Plan') refers to the identification of specific repairability goals, which are operationalized in the Framework through the list of the 17 DfR features [3, 19, 44, 46, 86]. The selection of features can be driven by the intent of designers to contrast absolute or relative obsolescence. At this step, designers should also design a proper strategy, which includes the definition of DfR practices to be applied, and the selection of appropriate metrics to measure repairability. The second step ('Do'), refers to the implementation of a subset of DfR practices [73, 78, 79]. The framework links DfR practices to DfR features based on their ability to contrast different types of product obsolescence (mechanical, service, technological, and psychological). Therefore, at this stage, the comprehensive framework helps designers in the selection of a limited but effective number of DfR practices. Designers are encouraged to implement these practices to design product prototypes considering repairability from the very first design stages [40, 110]. Subsequently, designers should also consider several testing steps, and appropriate documentation by developing repair manuals and guidelines [73, 78]. The third step ('Check') refers to the evaluation of the repairability of the product [4, 65, 79]. At this stage, the selected metrics should be fueled by proper data collected during the implementation of DfR practices. Since the comprehensive framework provides a list of DfR metrics and links them to DfR practices, it helps designers in metrics selection. This step is also relevant for identifying any issues or shortcomings in the design of products that hinder repairability. According to the selected measures, examples could include parts that are difficult to access, non-standard fasteners, or the need for specialized tools [73, 86, 87]. Lastly, the fourth step ('Act') refers to the implementation of improvements, based on the findings of the check phase, to make the necessary design adjustments. This can be operationalized through the framework by the selection of new or adjusted DfR features, in a continuous improvement loop, where the insights gained from this cycle are used to continuously refine the product design process, applying the lessons learned to subsequent products or iterations. By iterating through the PDCA cycle and thanks to the operationalization of DfR features, practices and measures provided by this comprehensive framework, product designers can systematically improve the repairability of their products.

This research provides the following scientific contributions. First, thanks to its comprehensiveness, the framework allows to systematize the vast DfX extant literature by organizing and connecting the different DfR features, practices, and measures to the different types of obsolescence. In particular, seventeen features collected from the systematic literature review facilitate the initial stages of product design to favor repairability. These features are actionable through the list of practices that characterize each feature. DfR practices provide detailed indications of what to implement or to avoid for enabling a specific feature. The practices then may be translated into measures to evaluate the level of product repairability. To the best of the authors' knowledge, literature lacked an analysis of DfR in the light of the obsolescence types addressed. The framework shed light on these relations, providing a first attempt to close this research gap. Second, the systematic analysis highlights which DfR features (and the relative practices and measures) have been less investigated by previous literature and, therefore, deserve more theoretical and practice-oriented research. The more frequently discussed DfR features are the ones related to product architecture, while lower attention has been dedicated to openability and repairable appearance, even if they are fundamental for implementing a CE. Also, DfR features preventing relative obsolescence received much less attention from academics than those preventing absolute obsolescence. Since user-centricity is vital for sustainable product redesign, more research on these topics is strongly

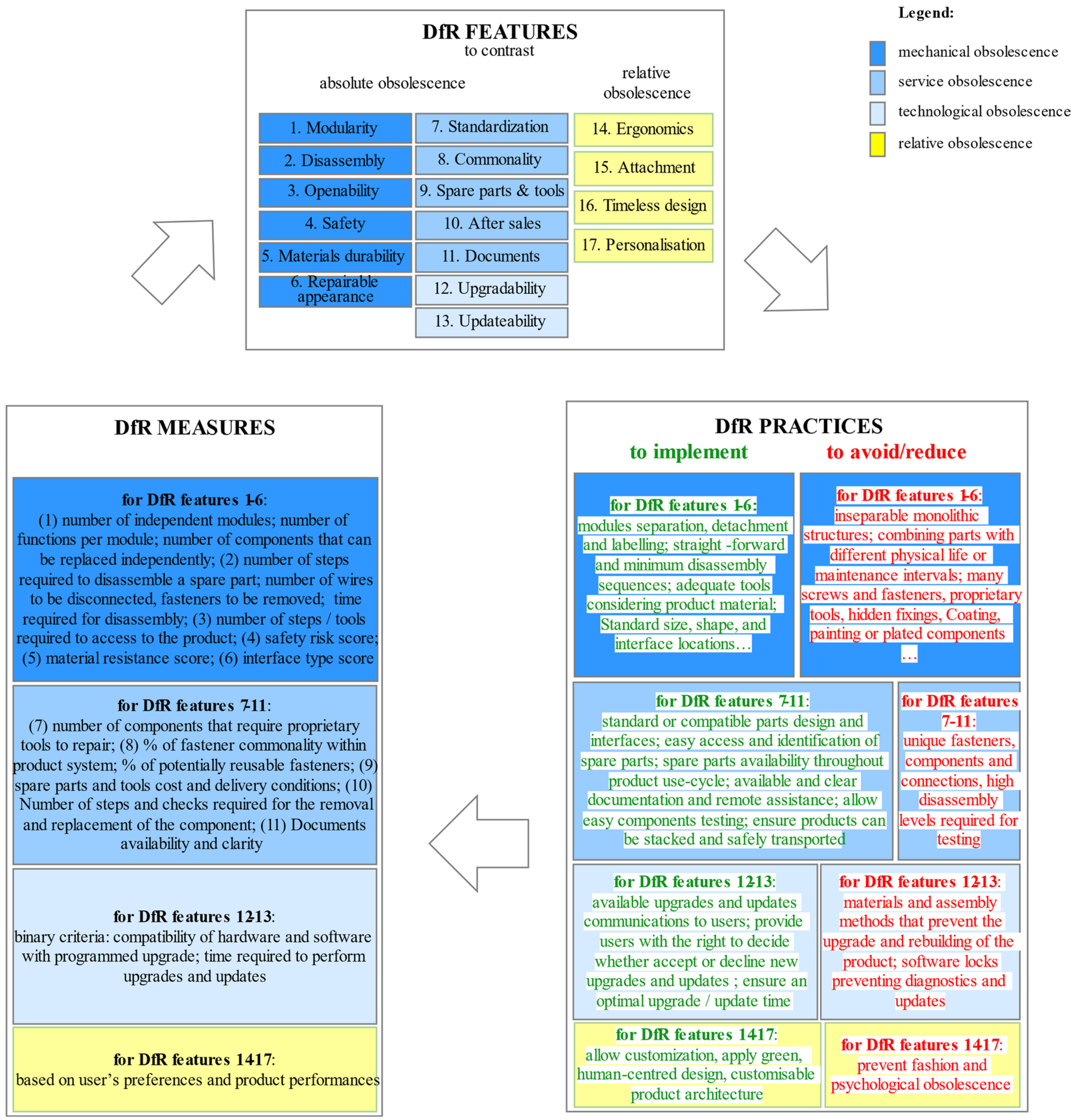

Fig. 8 Framework to design easily repairable products

envisaged. The analysis showed limited attention to users' perspectives on product design, which is crucial to prevent relative product obsolescence when users abandon their products. However, recent literature shows a changing trend towards addressing relative obsolescence.

In addition, the study and the framework provide relevant managerial and practical contributions. The framework could guide continuous DfR improvement by designers and development engineers. In fact, the framework can be used to operationalize the PDCA cycle of continuous improvement as it helps in better defining the PLAN step (which DfR features to implement among the seventeen proposed), the DO step (through an explorative initial application of the DfR practices and pitfalls to avoid), the CHECK (through the DfR measures) and the ACT (through an extensive application of the DfR practices). Finally, this paper contributes at the policymaking level, by providing elements to support the quantification of product repairability. This is fundamental for regulatory policies and organizations accredited to provide compliance certification. This framework may be a reference tool to support designers and manufacturers in developing repairable products and verifying their compliance with repairability regulations. Nevertheless, designers and companies might face several challenges in implementing the selected DFR practices, such as supply concerns and limitations to guarantee spare parts availability and product material adequacy [44], costs and convenience issue to redesign the product [35, 40], as well as lack of skills and competencies to properly implement DfR practices. Another important issue is related to the intellectual property rights, as some manufacturers intentionally prevent product opening, fearing being copied [5, 39].

6 Conclusion

This paper sheds light on the importance of repairability as a practice to prevent product obsolescence and enable a CE. Design for Repair received less attention in the literature compared to other CE strategies, such as reuse and recycling. However, it is fundamental to postpone product replacement and the use of resources for new production to enable sustainable production and consumption, and repair is a favorable approach to reach the SDG n. 12 “Responsible consumption and production” due to its increased resource efficiency potential and reduced environmental impact, but also SDG n.3 “Good health and well-being” due to its social value but also SDGs 8 and 9, for its potential to create local and inclusive jobs, favoring especially the growth of small enterprises. Thanks to the creation of local jobs also for silver and disadvantaged workers. Through a systematic review of the literature, a list of relevant design features for DfR have been provided and associated to the different categories of absolute and relative obsolescence, along with the identification of practices and measures to implement and assess them. Through the systematization of the academic literature on repair, this paper outlines a comprehensive framework based on the collection of seventeen DfR features.

Designing a product for easier and quicker repairability will prevent different types of product obsolescence, from those related to product architecture (absolute obsolescence) to those perceived by the user (relative obsolescence). The proposed framework, thus, will support both practitioners and policymakers in the process of designing more sustainable and circular products based on repairability. For instance, practitioners may exploit the list of practices and pitfalls, listing “do’s and don’ts” when implementing DfR. On the other hand, policymakers may use these metrics to set up regulations for product compliance with the Right to Repair and other environmental policies.

Lastly, this paper has some limitations. Although this paper provided a comprehensive framework for developing repairable products, it does not consider specific product or users’ or manufacturers’ characteristics that might impact design decisions. Missing contributions from the developing countries could limit the overview of their attitude to repair, however, with this contribution we hope to spread awareness of repair importance and reach out to less active countries. Therefore, future research would be essential to validate the framework’s applicability and explore the challenges that designers might face when implementing DfR practices, by conducting case studies with different companies and products in different countries, including less developed ones. It would also be interesting to investigate whether there are any relationships among identified DfR features that may impact their implementation for different products.

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Data availability No datasets were generated or analysed during the current study.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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