A review on Design for Repair practices and product information management

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Abstract. Repair is a product value recovery strategy that slows down the use of new resources, allowing more time for resource recreation. Although it is one of the cheapest and easier to adopt circular economy strategies, the repair is still poorly applied in practice and less investigated in the literature compared to other strategies, especially in terms of product information management. This paper aims to shed light on Design for Repair practices for circular economy and sustainability, as well as on their data needs, requirements and ownership, which are vital for establishing proper product information management systems across its circular supply chain. A systematic literature review is carried out to collect and classify Design for Repair practices and their data needs. Results show that seven classes of data are needed to enable the adoption of Design for Repair practices in the supply chain of durable products: materials specifications; manufacturing and engineering Bill of Materials; routing lines such as product assembly/disassembly/testing sequences; product specifications; network and service infrastructure data; users' data reflecting personas; usage data such as use frequency, failures and alerts. The identified practices and their data needs may help practitioners redesign their products in line with current and future Right to Repair regulations.

Keywords: Product Design, Repair, Sustainability, Circular Economy, Extended Producer Responsibility.

1 Introduction

The topic of responsible manufacturing and extended producer responsibility has been paramount for the last few decades [1], and it has become an urgent issue, considering recent challenges related to climate change and the geopolitical context. Indeed, scientific articles on sustainable production and consumption have been increasing over the last few years [2, 3]. As a response to these challenges, academic society develops theoretical and practical frameworks for circular economy business models and sustainable product design implementation [4, 5], as well as establishing sustainable behaviour culture [6]. Governmental institutions also react by issuing policies to regulate energy consumption, material efficiency, and green product development [7, 8].

However, most products are designed to be substituted quickly [3], ignoring the responsibility for the entire product lifecycle. For instance, the number of smartphones produced per year has grown almost exponentially over the last 15 years [9], but the treatment of smartphone disposal and their redesign to meet the requirements of environmental policies do not follow the same pace. On the other hand, Extended Producer Responsibility policies expect the entrepreneurs to be in charge of the product lifecycle treatment, not only to the production and disposal stage but to proper servicing throughout the lifecycle [1], guaranteeing its longevity.

Product repair is one of the most frequent practices to extend a product lifecycle [10]. Repair contributes to the sustainability of our planet, recovering product value after a failure and making products last longer. It slows down the use of new resources needed for new product manufacturing by postponing a moment when a new item is bought. Attention to repair has been raised after emerging the Right to Repair in the USA and the recent new opening of repair cafes all around the world [11]. To follow the Extended Producer Responsibility policy, changes must be introduced in the design phase of product development, and a proper product information management system must be set. The literature highlights the significant role of digitalisation in facilitating product design and managing its lifecycle [12]. For example, virtual reality and additive manufacturing may enable the prototyping of easily repairable products [13]; simulation of product performances can be enhanced with digital twins and the application of Artificial Intelligence algorithms [14]; monitoring and improvements recommendations can be given thanks to IoT sensing systems and Industrial Analytics dashboards. Even if repair is one of the cheapest and easier to adopt strategies of the circular economy [15], paradoxically, it is less investigated in the literature compared to other circular economy strategies, especially in terms of product information management.

Therefore, this paper aims to shed light on Design for Repair (DfR) practices for circular economy and sustainability, as well as on their data requirements and ownership, which are vital for establishing proper product information management systems across its circular supply chain. To achieve this objective, a systematic literature review is performed with a content-based analysis of the selected articles. Section 2 presents the methodology adopted for this research. In Section 3, DfR practices are identified from the literature and systematised according to different perspectives of interested stakeholders and data ownership. In addition, data requirements are provided for each DfR practice. Then, Section 4 discusses the findings of the research in terms of DfR practices, types of product obsolescence and product information management. Lastly, the conclusions of the research are reported in Section 5.

2 Research Methodology

Scientific articles on design strategies contributing to an easy and quick repair were reviewed in the context of sustainability and circular economy. Thus, two groups of keywords were used: (i) related to repair and design strategies to slow the loop, such as "design for repair", "design for long life products", "design for longevity", etc.; and (ii) related to sustainability, such as "sustainab*", "circular", "green". The "AND" operator was used to compose different search fields with two keyword groups from different sets. Scopus was the selected database, as it is a renowned source for engineering studies. Articles, books, conference papers and editorials were included, and three subject areas were selected: "Engineering", "Business Management and Accounting", and "Econometrics and Finance", as they appear to be the most related to the field of study. The language of contributions was set for English only. The combined use of keywords brought to the total number of 828 papers that were then filtered by relevance based on journals, titles and abstracts (see Fig. 1).

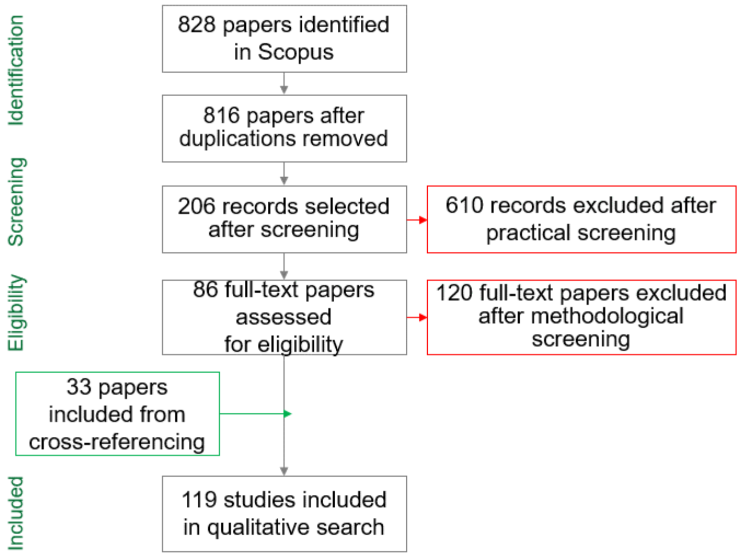

Fig. 1. Process chart for the systematic literature review (Moher et al., 2009)

There were two main exclusion criteria 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.

During the methodological screening phase, the following criteria were applied: exclusion of technical documents that contain a detailed description of repair services which are hardly generalisable; and exclusion of papers in which repair is just mentioned but is not a focus of study. After the keywords-based search, a backward approach was adopted to include the relevant studies cited in the found contributions: this led to additional 33 papers being included in the review. So, in total, this literature review considers 119 available papers.

The papers have been scrutinized, looking for the practices of different design strategies that could facilitate product repairability. Thus, examining design for disassembly, design for modularity, design for durability and other design strategies, the comprehensive list of practices was collected to conceptualize Design for Repair. The representative examples found in the literature were provided for a better illustration of each DfR practice, and the relevant data required were stated to support the adoption of product DfR.

3 Literature review

3.1 Descriptive analysis

In the current section, the descriptive findings are reported. Firstly, the distribution over time of the 119 articles is presented on the intersection between DfR and circular economy and sustainability (see Fig. 2). Single contributions were published before 2000, focusing on repair in general or some product characteristics that extend the product lifecycle. Since then, there has been an overall increasing trend, with around 50% of papers published in the last five years. This trend also confirms the general claim that the number of published papers about circular economy and sustainability has grown considerably due to the increasing interest of researchers, practitioners and governments in this topic and emerged Right to Repair regulation [16].

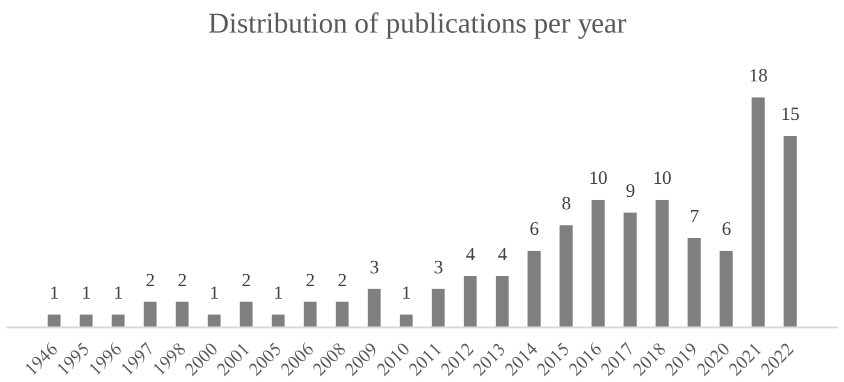

Fig. 2. Distribution of publications per year

Secondly, the distribution of the 119 papers across the journals where they have been published was analysed (see Fig. 3). The majority of articles (44 papers out of 119) have been published in the Journal of Cleaner Production, Sustainability, Resource, Conservation and Recycling, Proceedings of the ASME Design Engineering Technical Conference, International Journal of Advanced Manufacturing Technology. The Journal of Cleaner Production is the dominant source of articles in this literature review, accounting for 27 of the 119 articles. It confirms that research focusing on DfR is strongly connected to sustainability aspects. The 119 contributions scrutinised in the present review appeared in 71 different journals. There are also 4 book chapters and one dissertation among them. Consequently, it can be stated that the topic applies to many different research areas besides those related to sustainability.

Fig. 3. Distribution of publications per journal

3.2 Conceptualisation of Design for Repair practices and their data needs, requirements and ownership

As a sustainable product design strategy, DfR requires practices not only to facilitate repair when a failure occurs but to extend the product lifecycle until repair may be needed. Design practices for easier and quicker repair are mostly related to product architecture and functioning [17]. Relative design choices of Original Equipment Manufacturers (OEMs) become visible to repairers in the moment of product servicing. Instead, design practices to prolong product longevity have to consider how consumers use the product. For instance, [12, 18, 19] highlight the importance of including the consumer perspective when designing a product for a specific lifetime because, in the end, a consumer is the one who decides whether repair or replace a product. Thus, it is fundamental that product design recalls consumer attachment to the product, so he is willing to take care of it as long as possible. Therefore, DfR is supposed to be shaped considering several perspectives: the one about product functioning that mostly depends on OEMs choices, the one about product servicing that considers repairing services infrastructure and the one about product longevity that mostly depends on consumer preferences. The following sections report a collection of DfR practices from the systematic literature review, providing the definition formulated by the authors for each practice, giving representative examples and some indications of data required to manage the product lifecycle. Following the French repairability index requirements, the DfR practices provided in the following section were considered for consumer electronics.

Design for Repair practices: OEM perspective. When a failure occurs, OEM’s choices about product architecture during the product design phase will guide the repair-replace decision. The complexity of repairing activities is tied up with the physical characteristics of products: materials choices, product fixing, disassembly sequences, etc. These product characteristics depend indeed on OEMs, manufacturers and suppliers. Table 1 summarises DfR practices which depend entirely on the abovementioned actors.

Table 1. Design for Repair practices: OEM perspective.

#	DfR practice and definition	Representative example	Data requirements and ownership
1	**Modularity** – product feature that ensures its construction using individually distinct functional units instead of a solid monolithic structure	Framework laptop that is deeply customisable, allowing disassembly, upgrades and replacement of almost all components [20]	For redesigning products architectures as a joint union of physically detachable modules, an **engineering Bill of Materials (BOM)** and **material information** is needed [21], where each module is responsible for separate function [22]. These data are pertinent to manufacturers and suppliers
2	**Easy and quick disassembly and reassembly** – possibility to perform a straight-forward intuitive disassembly process and uncomplicated reassembly process	Fairphone is a representative example of an easy-to-disassemble and -repair phone [10]	To allow disassembly without damage to (reusable) components [2, 23–26] in a way to ensure short disassembly time, **Products assembly/disassembly routing and sequences** should be designed considering the ease of servicing and be reported in repair documentation
3	**Openability and Accessibility** – the ability to open a product and access its architecture and components with standard tools and equipment [21]	iPad has an adhesive and glue-based design that requires special tools to open or disassemble it [17].	Manufacturers should avoid narrow slits and holes for easier cleaning [27], adhesives and soldering components [28], or proprietary screws. **Manufacturing BOM** and **disassembly routing lines** should be reported in repair documentation and shared with repair technicians
4	**Safety –** product design allowing safe repair	In terms of health injuries during use and repair because of the required use of small sharp tools	Besides avoiding toxic materials or unprotected sharp elements [2, 29], product tests of electrical items like voltage, frequency, load, and brownout should be made in security conditions [30]. In that regard, technical manuals with product specifications and **testing routing lines** according to ISO standards should be made

			available to repair technicians [21]
5	**Material Durability –** use of robust materials according to the product performance	Being able to replace parts without breaking them	To ensure that components are robust and durable in line with product lifespan [22], **materials information** and **technical specifications** should be provided to repair technicians
6	**Upgradability –** keeping product performance by improving product functioning to prevent technological obsolescence	Miele washing machine is equipped with upgradeable software, an intelligent system and dynamic washing program management, according to the new cleaning products availability [1]	To communicate available upgrades to consumers and provide them with the right to decide whether accept or decline new upgrades**, product version and characteristics** should be made available [31], as well as **usage data** in order to understand consumers' needs
7	**Updateability –** keeping product performance as it was originally designed to adapt to a temporally deteriorated product value	Computer software updates to assist products in adapting to technological change or adaptable highchair for children [32]	Constant updates release to maintain the competition and ensure the product's effectiveness in changing environment [31]. **Product version and characteristics** should be available [33, 34], as well as **usage data,** in order to understand consumers' needs

Design for Repair practices: servicing perspective. For proper functioning of repairing services network and infrastructure, there are fundamental aspects, such as spare parts availability, standardisation and commonality of components, accessibility to repair manuals, and others. No matter whom repair is performed: official repairing services guaranteed by the manufacturer, or independent repairers or do-it-yourself, the absence of these DfR practices will impede repair (see Table 2).

Table 2. Design for Repair practices: servicing perspective.

#	DfR practice and definition	Representative example	Data requirements and ownership
8	**Standardisation or adaptability of components** – use of non-custom components through product generations within	Apple's repair software does not allow independent repairers to 'replace a broken part with one taken from another Apple device' [35]	Apply the standard parts design and interfaces to make replacements feasible and economically viable; product **manufacturing BOM** should be made available in this regard [17, 23], as well

	the same product category		as **usage data** to standardise the most critical components
9	**Commonality or compatibility of components** – use of common parts across product lines	EU Parliament approves common charging cable from 2024: all smartphones and tablets will have to be adapted for USB-C charger	Use of components that are feasible to back up from one product line to another within the industry (sector agreements); **manufacturing BOM** should be made available in this regard [2], as well as **usage data** to identify the critical components
10	**Spare parts and tools availability and affordability** – the existence of spare parts and repair tools on the market at a competitive price that does not exceed 30% of the product price	The highest percentage of fail-to-repair reasons for iPad is the absence of appropriate repair tools [17]. However, in 2020 Apple declared to provide their authorised service providers with parts, tools and training [36]	To allow easy access and identification of the spare parts [23, 37] as well as to ensure spare parts availability throughout the product use-cycle (after last production) and fair price, delivery condition, **manufacturing BOM** and **network and infrastructure data** should be made available, as well as **usage data** to identify critical components.
11	**After-sales servicing –** establishing infrastructure for returns and services, warranties	Paying a fee for full servicing needed along with use [38]	To establish an authorised network of after-sales services to enhance the experience of the product use [12], **network and infrastructure data** should be made available (location of after-sales technicians, their characteristics, etc.), as well as **usage data** to understand which services are needed
12	**Documentation** – providing manuals and documentation containing information on how to service product	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 [36]	Providing understandable repair instructions with guidelines for **disassembly and assembly routing lines** [17, 36], clear illustrations, diagrams [39], as well as **product information** in terms of technical specification and points of product return for servicing and repair

Design for Repair practices: a consumer perspective. No matter how well the product may be serviced, if a consumer perceives it obsolete, it will become an excuse for replacement [18]. Thus, to prolong product longevity, it is fundamental to consider consumers' way of product use and their preferences on its look, as they are key decision makers upon repairing or replacement. Table 3 summarises DfR practices that make consumers keep products longer.

Table 3. Design for Repair practices: consumer perspective.

#	DfR practice and definition	Representative example	Data requirements and ownership
13	**Attachment** for products that contain a particular value for a consumer **Detachment:** consumer neutral attitude toward products	Users are likely to take care of a product that has a special meaning for them (e.g. being gifted by someone special)	To communicate the potential value of a product to its users, underline the meaning it bears [37], **customer data and preferences** should be made available [7]
14	**Timeless design –** applying classic and "never old" design techniques	Traditional white washing machine, which is less likely to annoy a consumer soon	To prevent "fashion obsolescence" in design, there is the need to consider the various time and ecological dimensions of the materials that exist within the product lifetime [29]; **customer data and preferences** should be taken into account in this regard
15	**Personalisation / Customisation –** allowing a user to personalise its products and enhance a feeling of uniqueness	A product with personalised writing on it	To allow customisable product architecture so that the users may personalise their products in a way it matches their personality, being an additional reason to keep it longer [34], **customer data and preferences** should be considered in this regard
16	**Ergonomics in use –** product design to ensure suitable and intuitive functioning	Comfort in use [40] Intelligent assistant for the trouble-shooting and testing processes [41]	To provide easily understandable and reliable information about how to inspect [22], use and service product, advice on product care, describe signals of product malfunctioning [21], **usage data** such as diagnostics, alert/error codes should be made available. In addition, **customers' data** should be included in

			order to meet consumers' preferences and expectations
17	**Repairability look and feedback interface** – including intuitive interaction signals about product functioning and failure	Electronic displays on the products that may indicate the error code, different colouring for blinking lights [21]	Embed **alert, error codes** in monitoring sensors and display to signal when it's time to schedule service before a failure actually occurs [42]

4 Discussion: towards product information management for Design for Repair practices in sustainable supply chains

Sustainability-aware society starts forcing manufacturers to take on their extended producer responsibility, for example, by claiming their Right to Repair [31, 43]. To comply with the current Extended Producer Responsibility policy, changes must be introduced in the design phase of product development. However, paradoxically, repair is less investigated in the literature compared to other circular economy strategies.

DfR practices, collected through the systematic literature review, reflect the perspectives of OEMs, suppliers and manufacturers, repairers, and consumers. Figure 4 shows the number of publications that addressed each specific DfR practice.

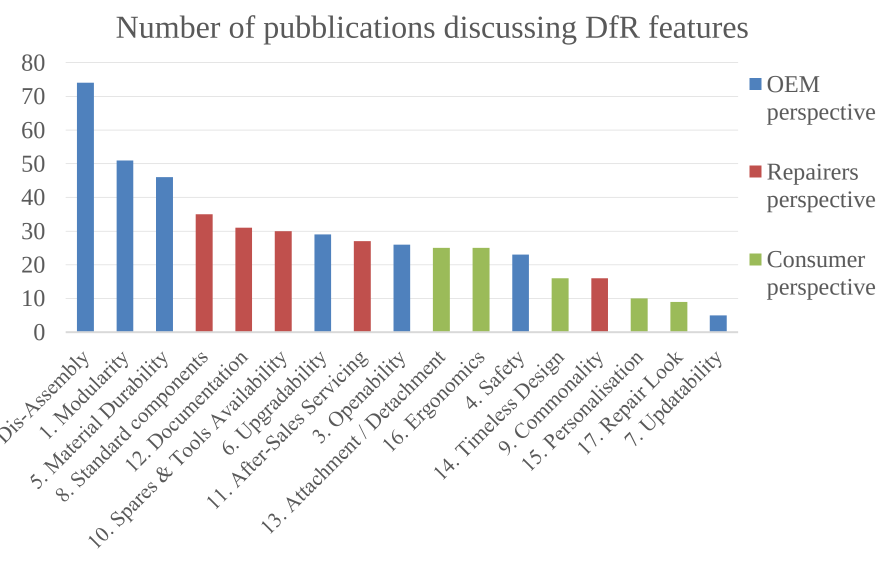

Fig. 4. Number of publications of DfR practices

Overall, this systematic literature review demonstrated that design practices discussed more often are those related to product physical functionality and servicing, such as disassembly, modularity, and spare parts availability. Instead, design practices crucial to making consumers keep products longer are less discussed. To meet consumer preferences and ensure product longevity, it is essential to analyse the product usage data. It is the responsibility of the producer to establish related product information management processes to enable product design accordingly.

The analysed literature provides considerations on data requirements and ownership for establishing a sustainable and circular supply management system based on repair. In particular, Table 4 summarises the data needed for each DfR practice to be shared among the supply chain actors. Data have been grouped into seven classes: (i.) materials specifications such as their composition and characteristics, usually owned by suppliers; (ii.) Bill of Materials, usually owned by the manufacturer; (iii.) routing lines, such as product assembly/disassembly/testing sequences, usually owned by the manufacturer; (iv.) product specifications, such as its technical characteristics and versions, usually owned by the manufacturer; (v.) network and service infrastructure data and information such as actors of the circular supply chain, their characteristics and geographic location, usually owned by the manufacturer and distributors; (vi.) users' data reflecting personas with their preferences and willingness to pay, owned by customers; (vii.) usage data such as use frequency, failures, alerts, owned by customers, or in some cases by manufacturers. Even though currently, tracking and tracing usage data by manufacturers is challenging due to privacy issues.

Table 4. Design for Repair practices data and ownership across the supply chain.

	Supplier	**Manufacturer**				**Consumer**	
DfR practice	Materials specifications	Bill of Materials	Routing lines	Product specifications	Network data	Users' data	Usage data
1. Modularity	X	X					
2. Dis-reassembly			X				
3. Openability, accessibility		X	X				
4. Safety			X	X			
5. Materials durability	X			X			
6. Upgradability				X			X
7. Updateability				X			X
8. Standardisation of components		X					X
9. Commonality of components		X					X
10. Spare parts and tools		X			X		X
11. After sales servicing					X		X

12. Documentation	X	X	X		
13. Attachment / Detachment				X	
14. Timeless design				X	X
15. Personalisation / customisation				X	
16 Ergonomics in use				X	X
17. Repairability look					X

Table 4 confirms that DfR practices 1-7 related to product architecture require data sharing from suppliers, OEMs and manufacturers, such as materials composition, bill of materials, and product specifications. When it comes to product servicing (practices 8-12), the ownership of data required shifts from suppliers to consumers, keeping involved manufacturers and distributors because to service the product effectively, the data on how the product has been used is crucial. It implies the identification of critical components with a higher probability of failure. Other essential data to service the product are product specifications to open a product safely, routing lines to disassemble and reassemble it quickly, and so forth. It is also essential to gain distributors' willingness to collaborate and share network data to establish repair services infrastructure (e.g., drop-off and pick-up points, distribution channels for spare parts and tools). Indeed, the literature confirms that easily accessible and widely available repair infrastructure nudges consumers to repair their products instead of replacing them. Lastly, DfR practices 13-17 for prolonging product lifespan require data on user preferences and their usage of products.

Digitalization can enable transparency and more accessible information sharing among circular supply chains through the interconnection of its processes. In this regard, the literature confirms the significant impact of IoT, Big Data and Analytics, Blockchain and other digital technologies on product lifecycle management and optimisation. Profound and structured data collection may ensure more efficient decision-making when integrating sustainability considerations, particularly, DfR practices, in product design.

Overall, this is the first attempt to shed light on data requirements and ownership for DfR purposes. Following the extended producer responsibility policies, this information can be a first step in conceptualising a Digital Product Passport for long-lasting products that enable easier repair.

5 Conclusion

Circularity and eco-efficiency are gaining momentum both in the state-of-practice and the state-of-art, nudging manufacturers to respect their extended producer responsibility by redesigning the product for longevity. Repair is a product value recovery strategy that extends the product lifecycle that helps follow environmental policies. Although crucial in the journey towards sustainability, product DfR is still both poorly investigated in the context of the circular economy literature and seldomly applied in practice. This paper provides the results of a systematic literature review on DfR practices for circular economy and sustainability, as well as on their data requirements and ownership. Based on the analysis of 119 articles, design practices to enable easier repair are systematised and discussed. A definition of each practice, a representative example and the data required to implement them have been highlighted. Through this literature review, we found that practices related to product architecture and product servicing are widely discussed, probably as they are more connected with traditional manufacturing excellence practices, while others are less investigated. Future research should then investigate DfR practices adopting the consumers' perspective, which are crucial to meet consumers' preferences and make them keep products longer. A first attempt to shed light on data needs, requirements, and ownership of relevant information needed for DfR is also carried out. These data and information are vital for establishing proper product information management systems across its circular supply chain. They can be seen as a first step in creating a Digital Product Passport for long-lasting products that enable easier repair, following the extended producer responsibility policies. Nevertheless, future research is needed on this topic, encompassing theoretical and empirical investigations on designing Digital Product Passport solutions based on repair for different long-lasting product categories.

The DfR practices and their data needs may help practitioners implement sustainability and circular economy projects in the supply chain of durable products. Indeed, this paper could be taken as a starting point for practitioners who consider redesigning their product in line with current and future environmental policies and Right to Repair legislation, as well as a point of reference to draw the repairability evaluation criteria for further application and promotion of repairability index to enhance manufacturers responsibility for sustainable product development. Nevertheless, the results of this research are purely based on the scientific literature, thus lacking insights from the practice world. Therefore, the next research step would be to test the relevance of the identified DfR practices through several case studies taking different durable products.

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