Advancing Repairability in Consumer Electronics
Design Guidelines and Evaluation Methods

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DOI
10.4233/uuid:33b078a4-8dc9-4144-a455-a6e2c265c11c

Publication date
2025

Document Version
Final published version

Citation (APA)
Dangal, S. (2025). *Advancing Repairability in Consumer Electronics: Design Guidelines and Evaluation Methods*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:33b078a4-8dc9-4144-a455-a6e2c265c11c

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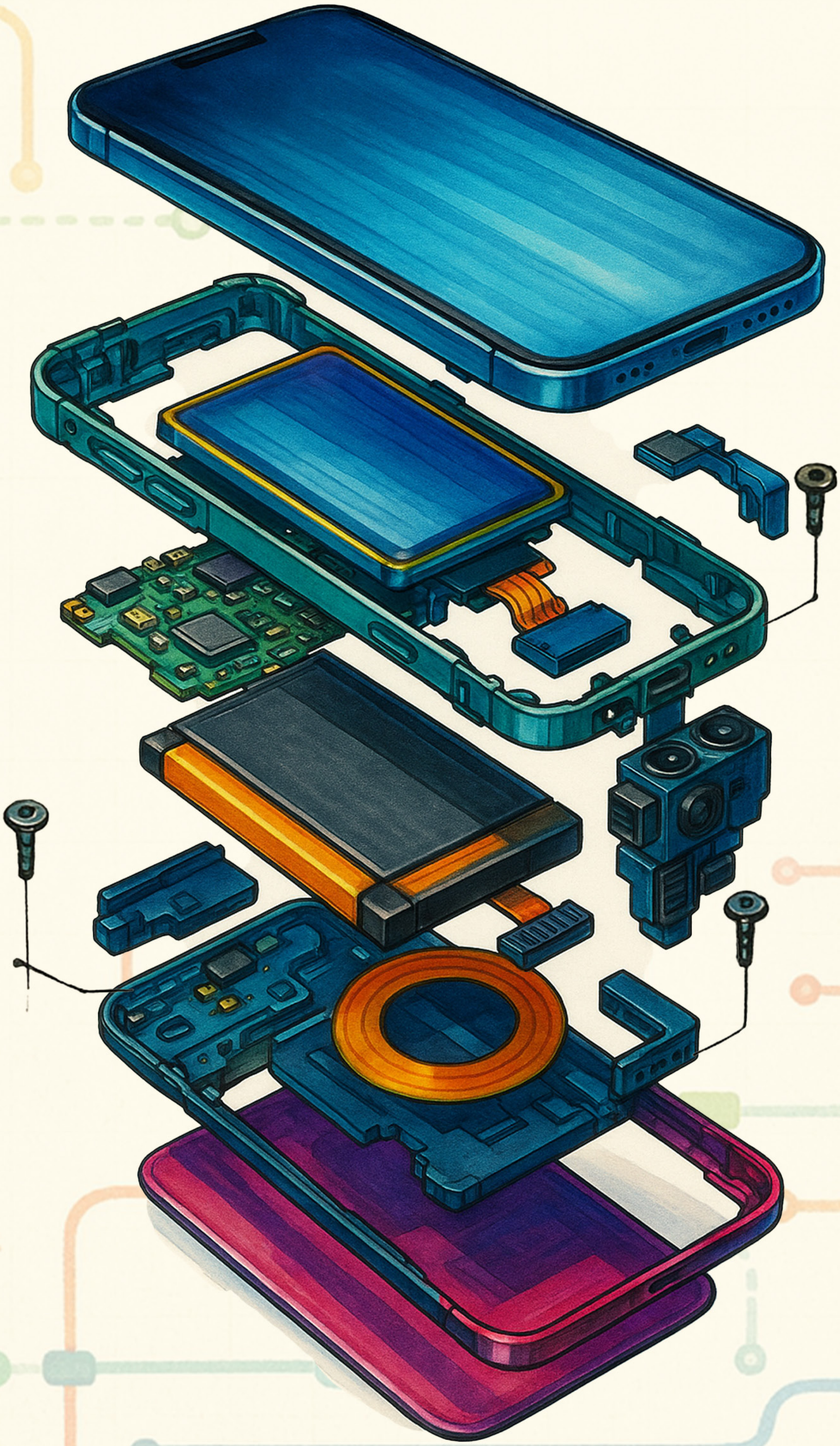

Sagar Dangal

Propositions

accompanying the dissertation

Advancing Repairability in Consumer Electronics:
Design Guidelines and Evaluation Methods

by

Sagar Dangal

1. Product design significantly outweighs the user repair expertise in influencing the effectiveness of fault diagnosis. *(This proposition pertains to this dissertation.)*
2. In the absence of fault indicators, the complexity of product disassembly is the primary barrier to successful fault diagnosis by users. *(This proposition pertains to this dissertation.)*
3. Time based disassembly assessment models (such as DaRT) provide a more accurate representation of ease of disassembly compared to methods counting disassembly steps. *(This proposition pertains to this dissertation.)*
4. Certain key reparability criteria (disassembly, spare part price, and availability) must exceed specific thresholds for repair to become practically feasible—this critical threshold is currently neglected in existing scoring systems. *(This proposition pertains to this dissertation.)*
5. It is possible to increase reparability of a product without significant trade-offs in manufacturing costs or other circular strategies.
6. Repairability and durability should be evaluated together, as they both contribute to the shared objective of extending product lifespan.
7. While most sustainable design strategies are best implemented during the early design phase, design for repair is most effective when applied in the embodiment stage.
8. Legislation represents one of the strongest incentives driving companies towards greater circularity.
9. Over-reliance on statistical analyses can obscure practical relevance and meaningful interpretations.
10. Research produces numerous exciting findings, but eventually you must perform academic Darwinism.

These propositions are regarded as opposable and defendable, and have been approved as such by the (co)promotors Prof. dr. A. R. Balkenende and dr. J. Faludi.

Advancing Repairability in Consumer Electronics: Design Guidelines and Evaluation Methods

Dissertation

for the purpose of obtaining the degree of Doctor

at Delft University of Technology

by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen,

Chair of the Board for Doctorates

to be defended publicly on

22nd September 2025 at 10:00 o'clock

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This research was conducted as part of the Horizon 2020 project named Premature Obsolescence Multi stakeholder Product Testing Program (PROMPT) under Grant Agreement number 820331.

Cover and Layout: Sagar Dangal
ISBN/EAN: 978-94-6518-126-4
Published by: TU Delft

Contents

Summary

This dissertation sets out to strengthen the role of repair within the circular economy by filling critical knowledge gaps in the design and assessment of consumer electronic products. Its overarching aim is to develop design guidelines and evaluation methods that improve fault diagnosis, disassembly assessment and repairability scoring, thereby enabling longer product lifetimes and supporting right to repair policies.

To fulfill this aim, this dissertation combines three complementary research activities. First, an in-depth observational study followed 24 participants, with and without prior repair experience, while they diagnosed faults in four common appliances and verbalized their reasoning. This qualitative data was supported by video analysis and post-task interviews. Second, more than ten thousand timed repair actions carried out by professional technicians on fifty-two appliances fed a quantitative model that links specific disassembly and reassembly operations to realistic proxy times, yielding the DaRT model (Disassembly and Reassembly Timing). Third, two successive studies compared six widely used repairability scoring systems against state-of-the-art design literature and then tested three of them empirically on sixteen products, comparing proxy-time and step-count approaches and probing best- and worst-case interpretations for each scoring systems.

Findings show that product architecture shapes user success in fault diagnosis more strongly than prior repair expertise. Clear visual or auditory feedback, component visibility, and unobstructed access prompt a direct or "pinpointed" search strategy, whereas hidden fasteners and recessed modules push users toward trial-and-error and early abandonment. Disassembly difficulty emerged as one of the main barriers that makes most people give up the diagnostic task. These insights were translated into a set of design guidelines that extend conventional principles of modularity and accessibility with new emphases on facilitating testing and providing component-level fault cues.

The DaRT model was able to predict real disassembly times for vacuum cleaners, washing machines and televisions with high accuracy while remaining easier to apply than complex methods such as eDiM. By explicitly including reassembly, DaRT provides a fuller picture of ease of a complete repair cycle. Validation against independent product assessment confirms accuracy.

Analysis of existing scoring systems revealed that most scoring systems weigh ease of disassembly appropriately but treat other decisive criteria such as spare-part price, diagnostic information and safety too sparsely or with ambiguous wording. In scenarios where repair is deemed infeasible or too expensive, the research demonstrated that the current scoring systems do not accurately represent the actual repairability of products. To address this issue, the study proposed the implementation of a limiting factor approach for criteria that determine the feasibility of repair. Proxy-time metrics like DaRT correlated more closely with measured effort than simple step counts, recommending a shift toward time-based assessment in future scoring systems with more weight on physical repairability of products.

This dissertation advances scientific understanding of repairability by emphasizing the critical yet underexplored role of fault diagnosis within product design and user interaction, presenting a holistic perspective that bridges technical elements with user cognition and behavior. It refines existing repairability assessment frameworks by highlighting gaps such as inadequate coverage of diagnostic aids and inconsistent weighting criteria, proposing improvements that enhance assessment validity and reliability. Moreover, this research introduces the DaRT proxy time model as a practical, accurate alternative to complex existing metrics, beneficial across diverse product categories. Societally and environmentally, this work supports the right to repair movement by empowering users to confidently diagnose and repair devices, thereby reducing electronic waste, informing purchasing decisions, and enabling manufacturers and policymakers to create genuinely repairable, sustainable products aligned with broader climate and circular economy goals.

Samenvatting

Het doel van dit proefschrift is het versterken van de rol van reparatie binnen de circulaire economie, door cruciale kennishiaten in het ontwerp en de beoordeling van consumentenelektronica te dichten. Het overkoepelende doel is het ontwikkelen van ontwerprichtlijnen en evaluatiemethoden die storingsdiagnose, demontagebeoordeling en repareerbaarheidsscores verbeteren, waardoor de levensduur van producten wordt verlengd en beleid rond het recht op reparatie wordt ondersteund.

Om dit doel te bereiken, combineert dit proefschrift drie complementaire onderzoeksactiviteiten. Ten eerste werden in een diepgaand observationeel onderzoek 24 deelnemers, met en zonder eerdere reparatie-ervaring, gevolgd terwijl zij storingen in vier gangbare huishoudelijke apparaten diagnosticeerden en hierbij hun redenering hardop uitspraken. Deze kwalitatieve data werd ondersteund met videoanalyse en nagesprekken. Ten tweede werd een kwantitatief model dat specifieke demontage- en hermontagehandelingen koppelt aan realistische proxytijden, gevoed met meer dan tienduizend getimede reparatiehandelingen, uitgevoerd door professionele monteurs op 52 apparaten, resulterend in het DaRT model (Disassembly and Reassembly Timing). Ten derde vergeleken twee opeenvolgende studies zes veelgebruikte repareerbaarheid-scoresystemen met toonaangevende ontwerpliteratuur, en werden drie daarvan empirisch getoetst op 16 producten, waarbij proxytijdbenaderingen zijn vergeleken met staptellingen en best- en worst-case interpretaties per systeem zijn onderzocht.

De bevindingen laten zien dat productarchitectuur belangrijker is voor het succes van gebruikers bij storingsdiagnose dan eerdere reparatie-ervaring. Duidelijke visuele of auditieve feedback, zichtbaarheid van componenten en onbelemmerde toegang stimuleren een directe of precies gerichte (‘pinpointed’) zoekstrategie, terwijl verborgen bevestigingsmiddelen en verzonken modules gebruikers richting trial and error en vroegtijdig afhaken duwen. De moeilijkheid van de demontage bleek een van de belangrijkste barrières die ertoe leidde dat de meeste mensen de diagnose taak opgaven. Deze inzichten zijn vertaald naar een set ontwerprichtlijnen die conventionele principes van modulariteit en toegankelijkheid uitbreiden met nieuwe accenten op het faciliteren van testen en het bieden van foutsignalen op componentniveau.

Het DaRT model kon werkelijke demontagetijden voor stofzuigers, wasmachines en televisies met hoge nauwkeurigheid voorspellen, terwijl het eenvoudiger toe te passen blijft dan complexe methoden zoals eDiM. Door hermontage expliciet mee te nemen, geeft DaRT een completer beeld van de uitvoerbaarheid van de volledige reparatiecyclus. Validatie aan de hand van onafhankelijke productbeoordelingen bevestigt de nauwkeurigheid.

Analyse van bestaande scoresystemen toont dat demontagevriendelijkheid meestal adequaat wordt meegewogen, maar dat andere beslissende criteria, zoals prijs van reserveonderdelen, diagnostische informatie en veiligheid, te summier of met onduidelijke formuleringen worden behandeld. In scenario’s waarin reparatie onhaalbaar of te kostbaar wordt geacht, laat het onderzoek zien dat huidige scoresystemen de feitelijke repareerbaarheid van producten niet accuraat weergeven. Om dit te verhelpen wordt een limiterende factorbenadering voorgesteld voor criteria die de haalbaarheid van reparatie bepalen. Proxytijdmaten zoals DaRT correleren sterker met gemeten inspanning dan eenvoudige staptellingen, wat pleit voor een verschuiving

naar tijdgebaseerde beoordeling in toekomstige scoresystemen, met meer gewicht voor de fysieke repareerbaarheid van producten.

Dit proefschrift verdiept het wetenschappelijk begrip van repareerbaarheid door de cruciale maar onderbelichte rol van storingsdiagnose binnen productontwerp en gebruikersinteractie te benadrukken en presenteert een integrale benadering die technische elementen verbindt met gebruikers-cognitie en -gedrag. Het verfijnt bestaande kaders voor repareerbaarheids beoordeling door hiaten te signaleren, zoals onvoldoende aandacht voor diagnostische hulpmiddelen en inconsistente wegingscriteria, en doet voorstellen die de validiteit en betrouwbaarheid van beoordelingen vergroten. Daarnaast introduceert dit onderzoek het DaRT proxytijdmodel als een praktische en nauwkeurige alternatieve maatstaf voor complexe bestaande methoden, bruikbaar voor uiteenlopende productcategorieën. Op maatschappelijk en ecologisch gebied ondersteunt dit werk de beweging voor het recht op reparatie, door gebruikers in staat te stellen om met vertrouwen storingen te diagnosticeren en apparaten te repareren, waardoor elektronisch afval afneemt, aankoopbeslissingen worden ondersteund en fabrikanten en beleidsmakers worden geholpen daadwerkelijk repareerbare, duurzame producten te ontwikkelen, in lijn met bredere klimaatdoelstellingen en de doelstellingen van de circulaire economie.

1. Introduction

Repairing a product is a multi-step process that includes fault diagnosis, disassembly, the correction or replacement of faulty components, reassembly, and functionality testing [1], [2]. Historically, repair has been integral to human practices, serving to extend the usability of tools, products, and infrastructure. In pre-industrial societies, repair was both an economic necessity and a social norm, driven by resource scarcity and performed by skilled craftsmen who reused available materials to restore broken items [3].

While repair was once a foundation of resource conservation and craftsmanship, its role has been reshaped by a shift toward mass production and consumerism [3], [4]. Advances in technology have introduced integrated designs and proprietary tools that complicate disassembly and repair processes, often requiring specialized skills and equipment [2]. Coupled with practices such as planned and premature obsolescence [5], [6], these changes have fundamentally altered the economic, technological, and cultural frameworks surrounding repair, transforming it from a necessary and routine activity into a less accessible and often impractical option. This transition reflects a broader societal move away from practices that prioritize longevity and reuse [2], [4].

This decline has led to far-reaching consequences, particularly for the environment, economy, and society. Environmentally, the reliance on replacement accelerates resource depletion and contributes to growing electronic waste, which is increasing at a rate of 2–5% annually [7]. Economically, it undermines opportunities for the repair sector to generate local jobs and build economic resilience [8]. Socially, it erodes the culture of resourcefulness and repair skills that once empowered individuals to maintain their possessions. Furthermore, this also adds financial burden to consumers, having to replace whole products [9]. As repair becomes less prevalent, it also impacts global sustainability goals [10].

The circular economy offers a transformative framework for addressing the sustainability challenges posed by the traditional linear "take-make-use-dispose" model. By prioritizing lifetime extension strategies such as reuse, remanufacturing, and repair, circular economy aims to decouple economic growth from resource consumption and waste generation [11]. Among these strategies, repair plays a pivotal role by enabling products to remain in use for longer periods, thereby reducing the demand for virgin materials and help mitigate the environmental impacts of production and disposal [4], [12].

There is a growing momentum to revive repair as a critical component of sustainable practices. Grassroots repair initiatives, like the Right to Repair movement [13], [14] and Repair Cafes [15] demonstrate the societal interest [16]. Legislative initiatives such as the European Union's Circular Economy Action Plan aim to dismantle systemic barriers by promoting repairability standards, ensuring access to repair information and spare parts, and empowering consumers to make sustainable choices [17]. The repair initiatives, advances in repair-friendly design, and evolving legislative efforts reflect the renewed focus on the value of repair.

The European Union’s Circular Economy Action Plan, first introduced in 2015 and updated in 2020, is a policy framework designed to foster sustainable consumption and production practices. At its core, the CEAP emphasizes repair as a key strategy to “close the loop” of product lifecycles, ensuring that materials and resources remain in use for as long as possible [17] . Building on this foundation, two major legislative instruments were adopted in 2024: the Right to Repair Directive [18] and the Ecodesign for Sustainable Products Regulation [19]. The Right to Repair Directive establishes a harmonized legal framework to facilitate the repair of goods, including obligations for manufacturers to provide spare parts, tools, and repair-related information, and to offer repair services beyond the legal guarantee period across the EU [18]. The ESPR replaces the 2009 Ecodesign Directive, expanding its scope beyond energy-related products to all physical goods. It sets out binding requirements on product durability, reusability, upgradability, and repairability, as well as provisions on ease of disassembly, availability of spare parts, and digital product passports [19]. These instruments reinforce the Circular Economy Action Plan’s vision by embedding repairability into product design and market practices.

These repair initiatives and directives related to repair not only highlight the importance of repair in fostering a circular economy but also stress the need for clear frameworks to operationalize these goals. To make repair a practical and scalable strategy, it is essential to address the design and evaluation of products systematically. This is where design guidelines and scoring systems become indispensable, as they provide structured methodologies to enhance repairability and ensure accountability across stakeholders [20], [21]. Guidelines could facilitate repairability considerations being integrated into the design phase, making repair processes more user-friendly and cost-effective. Scoring systems offer standardized metrics to evaluate and communicate the repairability of products [21]. Additionally, these systems provide a basis for policymakers to enforce repairability standards and promote sustainable production practices [17]. By linking design practices with measurable repair outcomes, these tools lay the foundation for achieving the broader objectives of the CEAP and a sustainable circular economy.

This dissertation focuses on domestic appliances as they are one of the largest contributors to global e-waste [7]. Furthermore, this category offers abundant opportunities for design improvements, particularly in enhancing repairability and extending product lifespans, which align with the principles of a circular economy [22]. Additionally, addressing domestic appliances carries substantial environmental and societal impacts, as these products are integral to daily life and their sustainable management can promote more responsible consumption patterns [23], [24].

The research described in this dissertation was part of the PROMPT (Premature Obsolescence Multi-stakeholder Product Testing program) project [25]. This project aligns with the goal of Circular Economy Action Plan and is funded under the European Union's Horizon 2020 framework. The PROMPT project developed methodologies and tools for assessing the repairability and durability of consumer products to support policy recommendations and fostering transparency and informed decision-making for consumers. Consequently, the scope of this research is framed within the European context, however these results still give insights into wider context.

1.1. State of the art and gaps

Design guidelines for improving repairability have become one of the focal points in circular economy research, emphasizing the need to extend product lifespans by making repair processes more accessible and efficient. Central to this body of knowledge are principles such as modularity, ease of disassembly, accessibility, and standardization, which contribute to creating products that are easier to disassemble and repair [26], [27].

Ample research on design guidelines for repairability has been presented over the years, reflecting a growing recognition of the critical role repairability plays in advancing the circular economy [20], [26], [28]. These guidelines have evolved to address various aspects, including modularity in product design to enable easier disassembly, the use of standardized and easily replaceable components, and the integration of repair-friendly interfaces and tools. Furthermore, studies have emphasized the importance of providing clear documentation and user instructions to empower consumers and technicians to conduct repairs independently [29]. However, a number of gaps still exist. Here we will focus on three specific topics of interest: fault diagnosis, ease of disassembly, and repairability scoring systems.

Fault diagnosis

Fault diagnosis, the process of identifying which component has failed, is a critical step in repair. Improving diagnosis not only reduces the time and effort required for diagnosis but also improves users' confidence in undertaking repairs [30], [31]. Moreover, studies emphasize that simplifying the diagnosis process can significantly lower the intangible costs associated with repairs, such as frustration and uncertainty, making repairs a more attractive option for consumers [32], [33]. This could make the difference between users repairing the product versus throwing it away.

In academic research, fault diagnosis has primarily been explored from a technical perspective. Design guidelines for diagnosis processes largely focus on technicians and complex industrial products [2], [34]. Furthermore, research includes improving product-specific algorithms and methods for fault detection in home appliances [35], [36], [37]. Other studies explore the integration of home appliances into smart networks using technologies such as the Internet of Things (IoT), cloud computing, and machine learning to enhance monitoring and diagnosis capabilities [38], [39], [40].

From a consumer perspective, initial models of fault diagnosis have been proposed, emphasizing the role of product design features in reducing the time and expertise required for diagnosing faults [41]. These models highlight how user-centric design can support non-expert users in identifying and addressing product issues more effectively. However, studies exploring diagnosis processes in consumer electronics do not typically integrate design guidelines that would make this stage simpler and more intuitive for non-experts [41]. Instead, much attention has been directed towards technological solutions, like embedded diagnostics, fault detection algorithms, and networked appliances communicating with centralized systems [36], [37], rather than guidelines that inform how products should be designed to facilitate diagnosis by users. A noticeable gap thus remains in addressing the integration of user-focused, design-oriented approaches that facilitate fault diagnosis.

Ease of disassembly

Disassembly processes have received significant attention in research on repairability, given their direct influence on the time and effort required to complete a repair. Studies have shown that the ease of disassembly strongly impacts consumer decisions to repair or replace faulty products [30], [42]. Design features that facilitate disassembly include the use of reversible fasteners, reduced reliance on adhesives, and intuitive layouts that guide users through disassembly steps [43]. Further, research also points to the relevance of standardizing fasteners and interfaces, which allows for more straightforward repair procedures and compatibility with existing tools [44], [45], [46].

Because of this, ease of disassembly is also a key criterion within most scoring frameworks [43], [47]. Established methods for evaluating disassembly include the "step method," which counts the number of disassembly operations needed [48], and "proxy time methods," such as eDiM [43] and iFixit proxy time [49], which estimate the labor and complexity involved. While step methods are widely used, eDiM provides a more accurate representation of real-world repair scenarios by emphasizing time as a critical factor [50]. However, the eDiM method is limited to ICT products, and its application seems to be hampered by its usability and computation complexity [43]. These limitations highlight the need for improved models that balance accuracy with practicality, considering both disassembly and reassembly, and can be applied across a broader range of products, making repairability assessments more robust and widely implementable.

Repairability scoring systems

As the focus on repairability within the circular economy has intensified, numerous evaluation methods have emerged to assess how readily products can be repaired. Among these, repairability scoring systems - such as AsMeR (Assessment Matrix for ease of Repair) [51], the Joint Research Centre Repair Scoring System (RSS) [21], iFixit's repairability indexes [49], the French Repairability Index (FRI) [52], the ONR:192012 standard [53], and EN45554 [48] - have received growing attention. These systems provide criteria for comparing the repairability of different products and identifying aspects of their design that hinder or enhance the ease of repair.

For these scoring systems to be effective in policymaking and for assessment by consumer organizations, market surveillance authorities, and other stakeholders, they must be objective, complete, valid and reliable. Validity means that the scoring system accurately measures what it is intended to measure in a complete manner, while reliability means consistency and objectivity of the scores [54], [55], avoiding variations caused by subjective interpretations.

Multiple studies have compared scoring systems [47], [50], [51]. These analyses have helped identify variances in repairability scores for identical products across different systems. These studies suggest that, within their contexts, scoring systems tend to provide similar scores. However, several studies [56], [57] have identified reliability issues in scoring systems, particularly due to varying interpretations of criteria, such as handling spare part bundles (i.e., integrated multifunctional modules) during disassembly and the provision of repair information. Despite these insights, existing studies do not holistically assess how well these systems capture the complexities of repairability across diverse products and use cases.

1.2. Dissertation Aim

The aim of this dissertation is to address the forementioned gaps and provide directions to enhance the repairability of consumer products by developing design guidelines and evaluation methods that improve fault diagnosis, disassembly evaluation, and repairability scoring systems. It advances the scientific understanding of repairability by exploring dimensions of product design, user interaction, and evaluative criteria that have previously received limited attention. These advancements intend to provide actionable insights for designers to create more repairable products, inform policymakers in shaping effective regulations, and empower consumers to make informed choices.

The first two chapters of this dissertation focus on specific steps within the repair process: diagnosis and disassembly. The following aims are addressed in these chapters:

> Chapter 2: Investigate how users with different repair skills carry out the process of fault diagnosis on consumer products and how this is affected by the product's design and the end-user's repair skills.
>
> Chapter 3: Explore opportunities for a disassembly and reassembly assessment model that is accurate, easy to use and applicable towards a broader range of products.

The next two chapters deal with repairability scoring systems and address the following aims:

> Chapter 4: Investigate objectivity and completeness of scorings systems based on literature on design aspects related to repairability.
>
> Chapter 5: Investigate the validity and reliability of the current scoring systems.

Each objective is linked to at least one research chapter. The overview of the chapters and their objectives is presented in Figure 1.

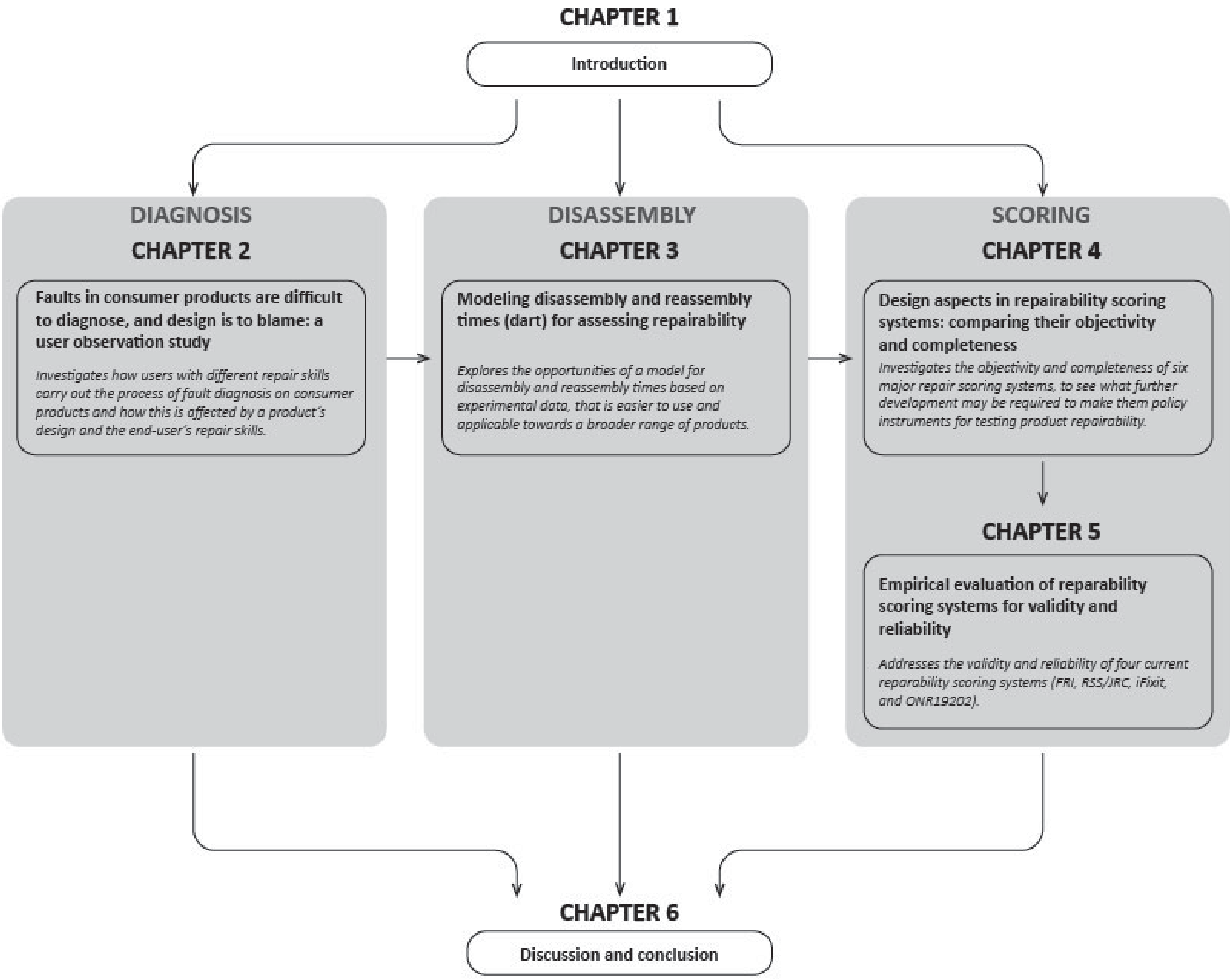

Figure 1: Overview of the dissertation.

1.3. Research approach and chapter overview

This dissertation examines repairability through three key dimensions. First, it explores how product design affects users' ability to diagnose faults (Chapter 2). Second, it presents a model for predicting disassembly and reassembly times (Chapter 3). Third, it evaluates repairability scoring systems, assessing their objectivity and completeness (Chapter 4) as well as their validity and reliability (Chapter 5). The findings are synthesized in Chapter 6, offering insights for design improvements, policy development, and assessment methodologies. This section briefly introduces each chapter's focus, approach, and type of result.

Chapter 2: *Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study*

This chapter investigates how product design can facilitate fault diagnosis by end-users and provides recommendations towards design guidelines through qualitative analysis. We investigated how product users go through the process of fault diagnosis in malfunctioned consumer products, and how this process is affected by the design of the product. Data was collected in a user observational study in which participants with different self-reported repair experience performed the process of fault diagnosis in four consumer products. During the experiment, the participants were asked to think aloud to explain their actions and understandings. Afterwards, they were interviewed regarding their experience. The outcome of this chapter was a framework on the fault diagnosis process, as well as insight into the effect of design features on the diagnosis process and guidelines for improving fault diagnosis for household appliances.

Chapter 3: *Modelling Disassembly and Reassembly Times (DaRT) for assessing Repairability*

This chapter explores the opportunities of a model for disassembly and reassembly times based on experimental data that is accurate, easy to use and applicable towards a broader range of products. This research was mainly done following a quantitative approach. Median times for repair actions were determined using experimental data collected from over 10,000 disassembly and reassembly actions across 52 products in 4 different types of household appliances carried out by professional repairers. Actions were grouped into categories with comparable median times to establish proxy times, and the model was validated through external testing on vacuum cleaners, washing machines, and smart TVs. This resulted in the Disassembly and Reassembly Time (DaRT) model, a time-based tool developed to assess ease of disassembly and reassembly based on experimental data from household products.

Chapter 4: *Design Aspects in Repairability Scoring Systems: Comparing Their Objectivity and Completeness.*

This chapter assesses six major repairability scoring systems based on their objectivity and completeness. Completeness was assessed by comparing them to the latest literature on what design features and principles drive product repairability. Objectivity was determined by assessing whether the scoring levels in each criterion were clearly defined with a quantifiable and operator-independent testing method. The outcome of the chapter presented gaps in the current methods and opportunities for improvements related to completeness and objectivity for the assessed scoring system.

Chapter 5: *Empirical evaluation of repairability scoring systems for validity and reliability*

This chapter assesses the three most used objective repairability scoring systems on validity and reliability. Building on the results of chapter 4 on objectivity and completeness, this chapter evaluates the validity and reliability of the scoring systems. Furthermore, this chapter compares the DaRT method developed in chapter 3 with the step method, that is commonly used in scoring systems to assess ease of disassembly. This research was done by scoring and evaluating 10 smartphones and 6 vacuum cleaners with the FRI, JRC, and iFixit scoring systems. The reliability of the scoring system is determined by scoring the best and worst-case interpretations per criterion and identifying the cause of the interpretation differences. The validity of the scoring system is evaluated through two activities: a) by evaluating how the scoring system handles scenarios where repair is not possible or realistic, b) by examining the relationship between different assessment methods for ease of disassembly. The chapter highlighted gaps in current methods and identified opportunities to enhance the reliability and validity of the evaluated scoring system. Additionally, this chapter provides recommendations for improving the scoring systems.

Chapter 6: *Discussion and Conclusion*

The conclusion of this dissertation synthesizes findings on repairability, covering fault diagnosis, disassembly assessment, and scoring systems. It examines the impact of repairability on users, manufacturers, policymakers, and legislative support. The discussion extends to its connection with other circular strategies, as well as the tensions and trade-offs between them. Furthermore, this section highlights scientific advancements and societal relevance, particularly in empowering consumers and promoting sustainability. Finally, limitations are identified, and future research directions are proposed to improve repairability practices and policies.

Authors contribution

The dissertation consists of the following research publications.

Chapter 2: Arcos, B. P., Dangal, S., Bakker, C., Faludi, J., & Balkenende, R. (2021). Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study. *Journal of Cleaner Production*, 319, 128741.

Chapter 3: Dangal, S., Faludi, J., & Balkenende, R. (2025). Modelling Disassembly and Reassembly Times (DaRT) for assessing Repairability (In Press)

Chapter 4: Dangal, S., Faludi, J., & Balkenende, R. (2022). Design Aspects in Repairability Scoring Systems: Comparing Their Objectivity and Completeness. *Sustainability*, 14(14), 8634.

Chapter 5: Dangal, S., Martinez, S., Bolanos, J., Faludi, J., & Balkenende, R. (2024). Empirical evaluation of repairability scoring systems for validity and reliability. *Resources, Conservation and Recycling*, 218,108211.

Chapter 2 was carried out together with dr. Beartiz Pozo Arcos. Together, we set up and performed the experiments, collected, and analyzed the data. Whilst the first author Beatriz Pozo Arcos focused on writing the process of diagnosis, I focused on the design aspects related to diagnosis. For chapters 3, 4 and 5, I set up and performed the experiments, collected and analyzed data, and wrote the main body of the manuscripts. For chapter 4, dr. Linda Ritzen and Alma van Oudheusden, MSc, contributed by helping analyze the data. For chapter 5, MSc Sonia Martinez and MSc Julietta Bolanos contributed by helping perform the experiments, as well as data collection. My promoter prof. dr. Ruud Balkenende, and co-promotor dr. Jeremy Faludi supervised the process and provided input and feedback on the experiments and manuscripts.

This work was funded by the European Commission under the Horizon 2020 Premature Obsolescence Multi stakeholder Product Testing Program (PROMPT) (Grant Agreement number 820331).

Note: In order to adapt the articles coherently with the dissertation chapters, a number of changes have been made in the layout, table styles and word spellings. No adjustments have been made to the content of the published articles.

1.4. References

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2.

Faults in consumer products are difficult to diagnose, and design is to blame:

a user observation study

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2.1. Abstract

The process of fault diagnosis is an essential first step when repairing a product: it determines the condition of the parts and identifies the origin of failure. We report on how product users go through the process of fault diagnosis in consumer products and the influence of design features on this process. Two groups of 12 participants were asked to determine the fault in a defective product we supplied; the groups differed in their self-reported repair expertise. Four types of products were used for the study: a vacuum cleaner, kitchen blender, radio CD player, and coffee maker. During the experiment, the participants were asked to think aloud to explain their actions and understandings. Afterwards, they were interviewed regarding their experience. The results from the verbal and video analysis provided input for an updated framework of the diagnosis process, describing user actions at each diagnosis stage. Furthermore, we show that the way a product is designed and constructed (the positioning, accessibility, and visibility of relevant product components) has a significant influence on the success of the fault diagnosis. An important factor is user experience: product use facilitates signal recognition, while repair expertise facilitates disassembly. However, user experience is still less influential than the product's design. Based on these findings, we propose a set of design guidelines to facilitate the process of fault diagnosis in consumer products.

2.2. Introduction

Repair practices can positively contribute to the decoupling of consumption from resource use in a circular economy [1]. Repairing instead of replacing products has the potential to increase resource efficiency and decrease the environmental impact resulting from premature product replacements [1], [2], [3]. Consequently, improving the repairability of consumer products is one of the measures proposed in the European Commission's Circular Economy Action Plan to reduce waste and consume more sustainably [4]. Moreover, there is a growing societal interest in repairs stirred by consumers and grassroots associations which aim to repair their products [5].

Repairing a product requires identifying the component at fault (fault diagnosis), disassembly to make the component accessible, repair of the defective component, followed by product reassembly [6], [7]. Without the process of fault diagnosis, subsequent repair steps cannot be taken. Easy diagnosis could improve users' confidence about what needs to be repaired and motivate them to repair instead of replacing their product. Easy and effective fault diagnosis can reduce intangible costs influencing the repair-or-replace decision: travel and waiting times, user frustration between breakdown and the uncertainty of the repair outcome [8], [9].

While there are studies on the process of fault diagnosis, it is unclear how designers can create products that can be successfully diagnosed by end users. Design guidelines addressing the diagnosis process are scarce, and mostly focused on technicians and complex, industrial products [7], [10], [11]. Den Hollander [12] distinguished 16 design principles relevant for facilitating repairs in consumer products. However, it remains unexplored to what extent these design principles relate to the diagnosis process. Similarly, recent studies investigating the diagnosis of appliances have not addressed the influence of design for the diagnosis process and are focused on how technology can facilitate it instead. For instance, recent studies aim to improve product-specific algorithms and methods for fault detection in home appliances [13], [14], [15]. Other studies focus on integrating home appliances to smart networks to facilitate their service by using technology like the internet of things, cloud computing, and machine learning to monitor and diagnose them [16], [17], [18]. Moreover, most academic studies on the repair process focus on product disassembly [19], [20] and the development of repair indicators (measuring the repairability of a product) [21], [22], [23]. In some of these studies, fault diagnosis is mentioned as a necessary precursor to any successful repair, but the process and its design remain under-investigated. Furthermore, academic studies investigating the user's perspective on repairs are focused on consumer attitudes to repair, and do not study the practice of diagnosis and repair in appliances [5], [24], [25]. Thus, the available literature is insufficient to provide guidance for designing easy-to-diagnose appliances: the product-user interaction is insufficiently understood, and existing guidelines on design for diagnosis are lacking for household appliances.

Our previous study [26], developed a model of the fault diagnosis process and identified product design features that have an influence on the time and expertise required for fault diagnosis. In this study, we take a next step towards a more detailed understanding of the process of fault diagnosis for repair. The aim of our paper is to investigate how users with different repair skills carry out the process of fault diagnosis on consumer products and how this is affected by a product's design and the end-user's repair skills. Data was collected in a user observational study in which participants with different self-reported repair experience performed the process of fault diagnosis in four consumer products. In this study of the process of fault diagnosis, we add to the current, technology-focused academic perspectives by including user perspectives on fault diagnosis. In this way, we contribute to the body of knowledge of design for repairability by providing an initial set of design guidelines to facilitate user fault diagnosis.

In Section 2, we present the theoretical framework that guided our analysis. Section 3 describes the methodology, and in Section 4 we present the results of our analysis: a description of the diagnosis process followed and the influence of repair skills and design features on the process. In Section 5 we discuss and compare the results with preliminary findings, yielding an initial set of design guidelines for easing the process of fault diagnosis. In the final section, we present our conclusions.

Fault Diagnosis Model and Analysis Framework

In this section, we present the theoretical framework that guides our analysis. We start by introducing the diagnostic steps we expect participants to follow based on the framework of the diagnosis process. We then present a set of search strategies that participants could use to find faults in the products.

The Diagnosis Process

The process of fault diagnosis determines the defective component of a malfunctioning product in three steps [26] (Figure 1): fault detection identifies a functional malfunction in the product; fault location determines the possible causes of the failure; and, fault isolation pinpoints the component at fault, thus diagnosing the product.

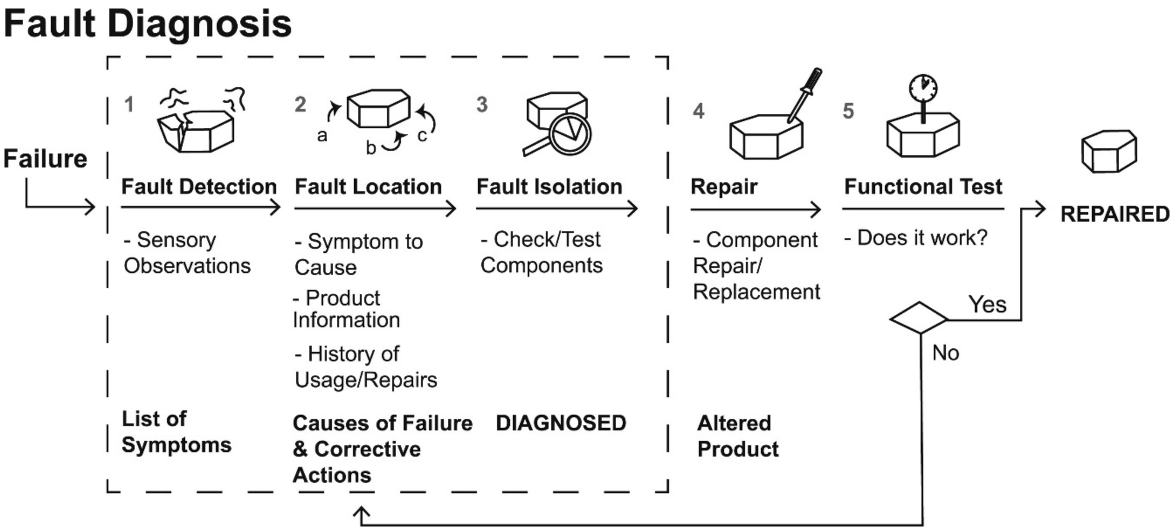


Figure 2: Model of the process of fault diagnosis by product users [26].

The process starts by detecting symptoms of malfunction in the product. The symptoms provide different types of information that help users locate the faults. These symptoms, together with symptom-to-cause knowledge, product information, and the product's history of use and repairs are used to determine the possible causes of failure (possible defective components) and corrective actions. Thereafter, users isolate the fault by checking or testing components suspected to be at fault.

Strategies for Fault Diagnosis of Consumer Products

Diagnosing a fault in a product is most likely comparable to any human problem-solving mechanism. Jonassen and Hung [27] and Angeli [28] refer to the diagnosis process as a complex reasoning process similar to solving a problem. Therefore, we used recent literature on problem-solving strategies to understand what can be expected from participants during the diagnosis process.

As Whalen [29] describes, solving a problem consists of devising actions to move from an existing situation to a desired one. It is a cognitive search through a large set of possibilities that requires understanding and is guided by heuristic knowledge [30], [31]. Similarly, fault diagnosis requires an ability to combine repair experience and technical knowledge to relate symptoms to possible problems [32], [33], [34].

Robertson [31] describes two main strategies people use to search for a solution: “strong” and “weak” strategies. “Strong” strategies are domain-specific, are guaranteed to get a solution, and are used when the solver knows how to go about solving the problem. “Weak” strategies are general-purpose strategies that solvers use when they do not know what to do directly to solve the problem. Within this latter category, the author recognizes two different types: hill climbing and means-end analysis. “Hill climbing” only applies when there is some way of determining whether the solver is getting closer to the goal. Means-end analysis involves breaking a problem into sub goals; solving each sub-goal should eventually solve the whole problem. Duris [35] defines “blind search” as a type of weak strategy whereby all potential solution candidates are checked randomly. Jonassen and Hung [27] add that novice troubleshooters tend to go for low performance strategies, while expert troubleshooters use the recall of historical information as a strategy for fault diagnosis. In Robertson’s terms, this would mean novices would go for general-purpose (“weak”) strategies and experts would follow domain-specific (“strong”) strategies. Applying one strategy or the other provides feedback to the solver about the results, and consequently, the solver may change the initial strategy, thereby applying multiple strategies in the search for a solution [31], [36].

Collectively, these studies indicate that, when diagnosing a product, we can expect participants to follow the diagnosis steps in the order presented in Figure 1, and adopt strong or weak search strategies depending on repair experience and technical knowledge. Their heuristic, product-specific knowledge gained in everyday life by using, maintaining, and repairing a similar product could be relevant for diagnosis. Therefore, we can expect that those participants with more repair experience will follow more directed (“strong”) search strategies. Moreover, we could expect users to follow more than one strategy if the results of an initial strategy do not lead to identifying the defective component.

2.3. Method

The think aloud method

We used the think aloud method to conduct the study. This is a method used in studies designed to understand users’ cognitive processes when carrying out a task [37], [38]. It has been shown to be a useful and reliable technique because it poses minimal interference with the participants' reasoning. Participants are instructed to speak their thoughts as they work on problems and do so as if they are “speaking to themselves”. No explanations for their reasoning or their feelings are required, which allows eliciting the tacit knowledge of the participants [39].

The participants

In order to recruit participants, a questionnaire was sent to a participants of a university-based research panel, who live within a radius of 30 km from TU Delft. This panel includes 1000+ volunteers (52.6% male and 47.4% female) aged 21-70 (average age 59), with different education and professional backgrounds, recruited by TU Delft over the years. They were asked about: (a) their experience using standard tools for repair: a plier, a screwdriver, a wrench, and an Allen key; and (b) previous experience repairing different durable goods: bikes, small and large household appliances, and electronic products. The participants specified how often they had repaired the durable goods from 5 options: never, once, a few times (2-5 times), several times (more than 5 times) or “at a professional level”. From the responses (n=273), we selected two groups of 12 participants based on their self-declared repair experience, their availability to participate in the test, age, and gender. We recruited (a) “Users with repair experience”: users who claimed to have repaired appliances 2-5 times, and (b) “Users without repair experience” i.e. those who claimed to never have repaired an appliance but knew how to use standard tools. The two groups had similar characteristics regarding age (45-65 years), repair experience, and gender ratio.

After gaining approval from the ethics committee at TU Delft, we proceeded inviting the 24 participants to the TU Delft facilities in February 2020 where they signed a consent form and were asked to diagnose a malfunctioning consumer product while thinking aloud. The observations were carried out in a laboratory setting and lasted 40 minutes or until the participants diagnosed the product. Immediately after, the participants were briefly interviewed about their experience. Both the observations and interviews were video recorded.

The products and the faults

Four small consumer products (blender, vacuum cleaner, coffee maker, and a radio CD player) were chosen based on the criteria:

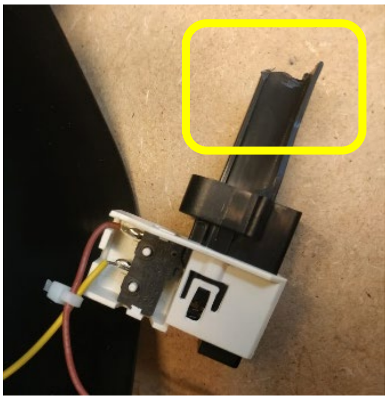
- The products include a variety of design features that could influence the diagnosis. Using Pozo Arcos et al. [26], we selected products with different features to access the components, to provide feedback to users, to interchange components, and with different types of functional modules.
- The products cost less than €150 each due to the focus on small, common consumer products and budget restrictions.
- The products can be disassembled and reassembled multiple times without damage, so that they could be used repeatedly during the experiment.

A controlled fault was introduced in each of the products (Table 1 and Figure 2) based on the criteria:

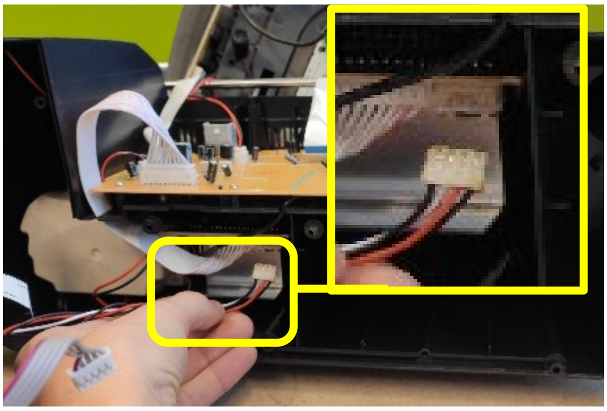
- The fault would cause symptoms frequently occurring in consumer products. Symptom frequency was extracted from iFixit’s forum of technical repairs [40] and the Repair Café’s report on frequently repaired faults in 2019 [41].
- The fault was provoked in an internal component to observe the participants interacting with a large diversity of design features and components.

- Each fault would provoke one of the different types of symptoms described in Pozo Arcos et al. [26]: under-performance, absence of response to commands, abnormal inbuilt signals, and designed signals. The symptom of intermittent failure was excluded because it would be hard to replicate and control.

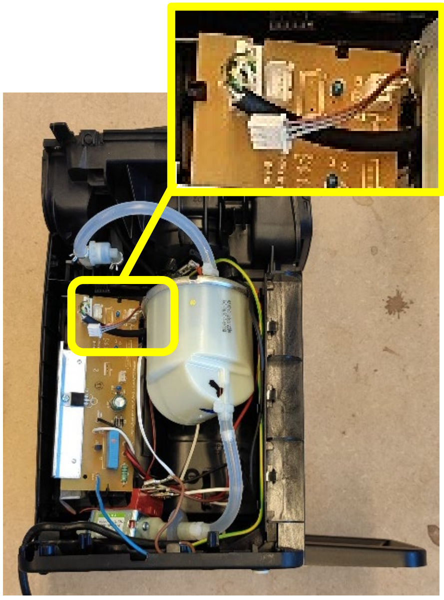
In the radio, we introduced two faults: discharged batteries and a disconnected cable plug; the participants could only diagnose the second fault after diagnosing the first one.



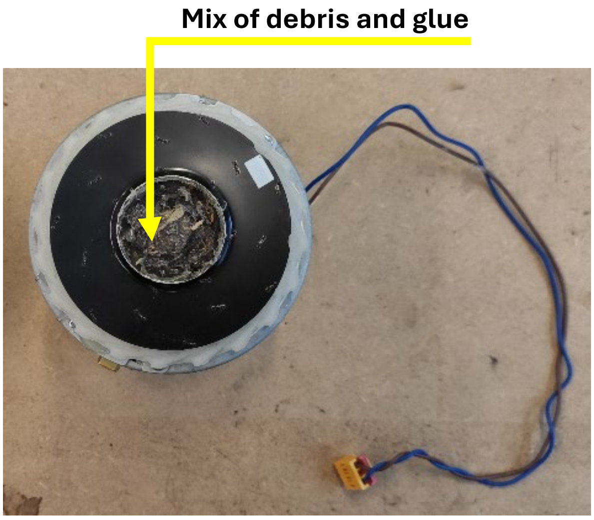
(A) Broken safety switch in kitchen blender



(B) Disconnected speakers from PCB in radio CD player



(C) Disconnected water sensor from PCB in coffee maker



(D) Clogged motor from vacuum cleaner with mix of debris and glue

Figure 3: Introduced faults in the products.

Table 1: Overview of the consumer products used, and the faults provoked in them.

Product	Model No.	Introduced Fault	Figure	Symptom
Kitchen blender	Philips Daily HR2100 / 90 Blender	Plastic pin that actuates the safety switch broken	2a	Unresponsiveness
Radio CD player	Philips AZ700T	Discharged batteries	none	Unresponsiveness
		Disconnected cable plug from the speakers to PCB. Signs of burns were introduced to look like a short circuit	2b	No sound
Coffee machine	Philips Senseo Quadrante HD7865/60	Unplugged water level sensor cable from PCB	2c	Error signal: blinking light
Vacuum cleaner	Samsung VC07M3130V1/EN	Clogged motor fan	2d	Low suction, loud noise during operation

The room set up for the experiment is shown in Figure 3. Three video cameras were placed in the room: two on each side of the walls pointing towards the interaction space, and one action camera worn by the participant during the experiment. Microphones were suspended from the ceiling.

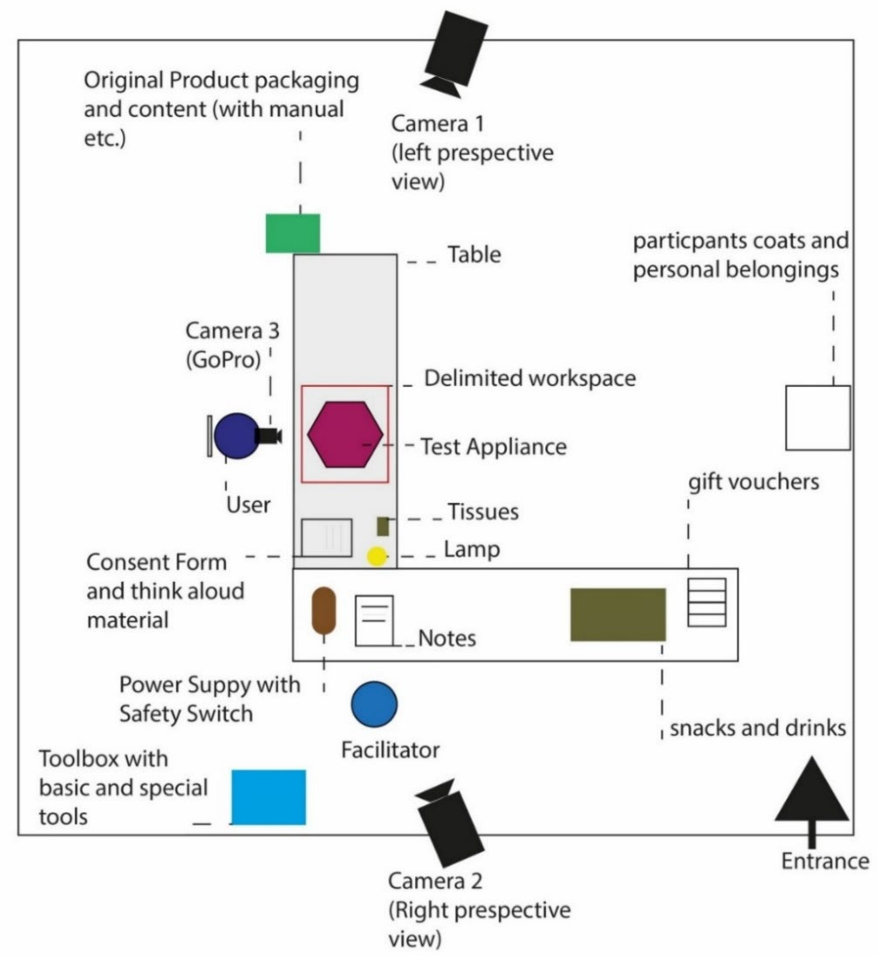


Figure 4: Room set-up for participant observation.

Procedure of observations

Each participant diagnosed one randomly selected consumer product. In total, each product was diagnosed by three participants from the group with experience and three from the group without repair experience. The participants were given a maximum of 40 minutes to find the defective components, however, to avoid stressing them, this was not communicated. They were able to use tools and the user manual, but only upon request.

The observations started by showing participants how to perform a common task with a fully functional product: a) make a smoothie with the blender, b) play a CD in the radio/CD player, c) make a cup of coffee with the coffeemaker, and d) vacuum rice from the floor with the vacuum cleaner. We then described the think aloud method [42], and how they should use it. We made sure they understood the method and how to use the product by asking the participants to perform the demonstrated task themselves thinking aloud. They were given two minutes to further familiarize themselves with the product. This was then swapped with a malfunctioning one and again, we asked the participants to perform the demonstrated task while thinking aloud. We made them aware that there could be something wrong in the product, and asked them to tell us what it was.

Two researchers observed the participants. One was in charge of facilitating the sessions; the other stayed in the control room and ensured correct video recording. The facilitator only intervened if participants stopped thinking aloud or showed no progress for more than three minutes. In the first case, the facilitator would remind them and prompt them on their thoughts or motivation underlying a certain action. In the second case, if the user showed either no progress or the intention to give up, the facilitator prompted them on the issue and offered a hint to help them continue the diagnosis. The hint suggested the next action step to be taken in the disassembly process. Essentially, in a household environment, they would not be able to go further without this help and would likely stop; this was later noted as a clear barrier.

After the fault was identified or the time limit was reached, a short interview was conducted to further understand the diagnosis process and the difficulties they faced (Table 2).

Table 2: Interview questions.

Topic	Question
Behavior at home	What would you normally do at home if this occurred to you?
Diagnosis difficulty	How difficult, on a scale of 1 to 10, was it to find the fault? 1 = easy, 10 = difficult; could you explain why?
Design features	What helped you find what was wrong with the product?
	What made it difficult for you?
	How would you improve the product to make it easier for you?

We slightly modified the questions for participants who had not found the fault. For instance, instead of “how difficult was it to find the fault?” we would say, “what features made it difficult to find the fault?” After the interview, the session ended.

Data Analysis

The purpose of the analysis was to understand the influence of the product's design and the users' self-reported repair experience on the diagnosis process. Therefore, we analyzed the data qualitatively and quantitatively.

For the qualitative analysis, we created a case record for each participant (see example in Figure 4). Using Adobe Illustrator software, the participants' verbatim speech, their actions, and product disassembly steps were transcribed from the videos in chronological order (see Figure 4 – column 1). We used De Fazio's et al. [19] disassembly map method for noting the disassembly steps. Then, we analyzed the transcribed content (Figure 4 – columns 2 and 3).

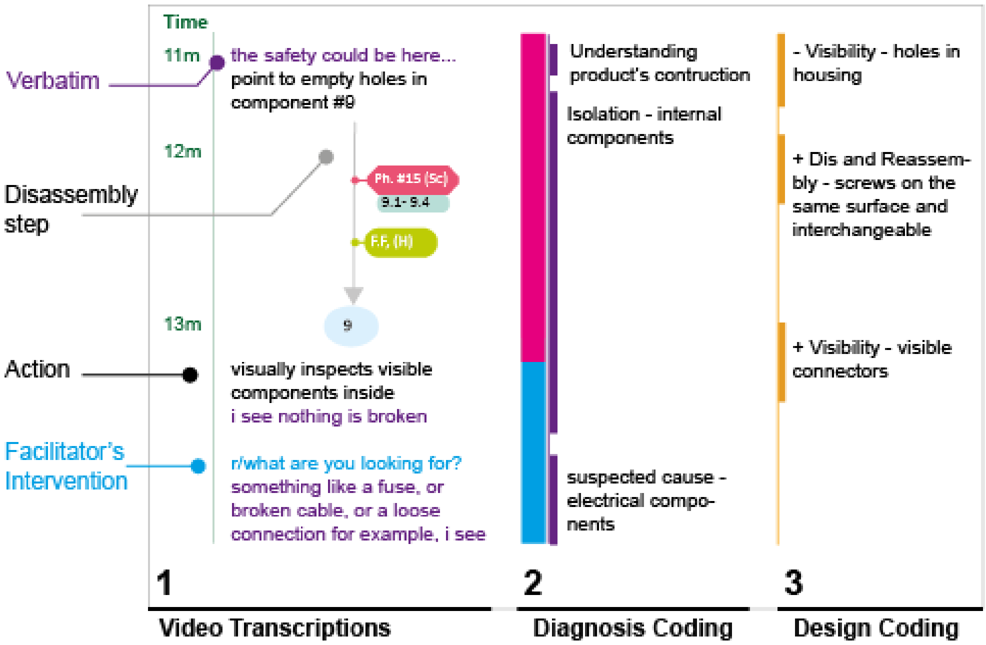


Figure 5: Example of Case Record with labelled entries. The left column shows the transcription of the participants' thinking aloud, the observed actions, disassembly steps, and facilitator interventions in chronological order. The middle column shows the search strategies (blue bar represents a systematic strategy) and diagnosis steps and tasks related to the transcription. The right column shows coding of design principles, features, their influence (+ or -) and purpose.

The diagnosis process and search strategies were analyzed first; design features were analyzed later. We used indexing to trace the fault diagnosis process. Indexing (or coding) is "a qualitative data analysis method where the researcher applies meaning to raw data by assigning key words" which "then act as signposts to themes within the data" [43]. We related the verbatim transcription, observed actions, and disassembly steps presented in the case record to each of the three diagnosis steps: fault detection, location, and isolation (see Table 3). We added quotes and codes to capture the participants' expressions of frustration and facilitator interventions during the diagnosis. These codes were developed from the insights obtained during the observations.

To code the participants', search strategies, we analyzed their verbalized search process and their actions. Based on the data, we could identify one strong search strategy and two types of weak strategies, which we defined using literature (see section 2.2) and our observations (see table 3). We labelled the strong strategy as "pinpointed", and the weak strategies as a "systematic" and "unstructured".

Table 3: Coding scheme for the analysis of the diagnosis process.

Category	Definition	Code	Subcode	Example of Quotes/Action
Diagnosis Steps		**Diagnosis Tasks**		
Fault Detection	User detects the faults in the product by sensory observations	Visual	-	"[the blade] doesn’t rotate''
		Designed Signal	-	“there’s a blinking light”
		Auditory	-	“the sound is different”
		Tactile	-	“is very slow, there is almost no air going through”
Fault Location	User determines possible causes of failure	Suspected Cause	General Cause	"somewhere is blocking '
			Specific Component	"there's a bag .. and its full..."
			Unknown	“I don't know "
		Understanding working mechanism	-	“the air is coming in here, and its coming out this way”
Fault Isolation	user checks the condition of the components	Understanding a product’s construction	-	“behind here there must be the motor” “I need three screws to get it (the motor) out”
		Isolation	[Action]	Example of actions: check blockage, clean, use subassembly without X
		Successful diagnosis of	[Component]	'"this is not the problem, and this is not the problem" “this looks ok”
Process interruptions				
Interruption during diagnosis	The diagnosis process is interrupted by the participant or the facilitator	User	Giving up	"If I did it at home, I would put it back together again" "I think I would throw it away at this moment"
			Expressing doubts/confusion	''strange'' ''I don't know what to do..."
			Unable to access the interior	“I can’t get it open”
			Expressing difficulties	"This isn't so easy" "It's more difficult than I thought"
		Facilitator intervention	-	(instances where the facilitator intervened)
Search Strategies				
Pinpointed Strategy	The participant knows how to go	Based on codes:	-	

	about solving the problem. User has a correct suspicion of possible component at fault and directly searches those	“suspected cause” and “[action]”	
Systematic strategy	The participant does not know what to do directly to solve the problem. User has a general suspected cause of failure e.g. Blockage and follows an ordered and structured search in the product	Based on codes: “suspected cause” and “[action]”	-
Unstructured strategy	Checking all potential solution candidates in no particular order. No clear suspected cause of failure and follows an unordered search in the product.	Based on codes: “suspected cause” and “[action]”	-

In a second analysis step, we set out to identify the products’ design features that facilitated or hindered fault diagnosis and created a list of associated design features (for instance: “deeply recessed fasteners”, “hidden snap fits”, “long cables”, etc.) by looking at instances where participants either successfully completed their diagnosis process, or wanted to give up on it. We also looked at instances where participants changed their search strategies (i.e. going from systematic to pinpointed, or from pinpointed to unstructured) to understand the design feature that might have caused this change in search strategy. See Table 7 for a full overview.

Next, we clustered the design features under a set of design principles as described in Table 4. For example, the design features “ergonomic geometry” is clustered under “accessibility”. These design principles were based on the literature review of design principles relevant for product repairs as presented by Den Hollander [12]. We also considered design features affecting the diagnosis process from our previous study [26]. This provided an initial set of design principles relevant for fault diagnosis, which was later used for the analysis: interchangeability of components, modularity of subassemblies, accessibility to the product’s interior, visibility of the internal parts, and the feedback and information provided from the product to the user. Table 4 provides definitions for each of these design principles. Based on our data, we identified and defined two new design principles: “enable testing” and “robustness”. In Table 7, we list all design principles and related design features, with short descriptions of how these facilitate or hinder fault diagnosis.

Table 4: Design principles relevant for fault diagnosis.

Design Principle	Definition used in this study
Interchangeability	"Controlling dimensional and functional tolerances of manufactured parts and assemblies to assure that [a part that is expected to fail or has failed] soon can be replaced in the field with no physical rework required for achieving a physical fit, and with a minimum of adjustments needed for achieving proper functioning" [44].
Modularity	Enforcing "conformance of assembly configurations to dimensional standards based on modular 'building block' units of standardised size, shape, and interface locations (e.g., locations for mating attachment or mounting points and input/output line connectors), in order to simplify maintenance tasks by enabling the use of standardised assembly/ disassembly procedures" [44].
Accessibility	Features and spatial arrangements in the product or parts that provide access to components without the complete removal of a part [44].
Visibility	Features related to the visible surfaces of a component or its visual inspection [26].
Feedback to user and information to user	Designed signals in the form of text, light, sound or movement provided by the product in response to an interaction and information provided to the user not embodied in the main assembly e.g. Manual, stickers [26].
Dis- and reassembly	Facilitating the process of removal of parts from and/or placement of parts in a product "while ensuring that there is no impairment of the parts [or product] due to the process" [56].
Redundancy	Providing an excess of functionality and/or material in products or parts, for example to allow for normal wear or removal of material as part of a recovery intervention [54] or to prevent interruptions in the functioning of a product [55].
Enable testing	Features that allow testing the condition of the components or subassemblies.
Robustness	Features that allow the user to perform rough actions to inspect the component without disturbing its condition.

All data were coded and analyzed by two researchers to minimize the risk of bias. Following recommendations for teamwork qualitative research by Milford et al. [45], both researchers coded the case reports and checked for intercoder agreement. The reports with discrepancies in the coding were discussed and co-analyzed until both researchers agreed.

Once all data had been coded and qualitatively analyzed, we performed a statistical analysis to understand the influence of repair experience and design features on the diagnosis process. We tested the average time each participant spent on each strategy against the repair experience and the product type.

Time spent on each strategy was measured in minutes. We considered the time on each of the three strategies as a percentage of the total time of the experiment. The sample size was small, and data was not normally distributed. Therefore, non-parametrical tests were conducted [46]. We conducted one-tailed Man-Whitney U tests (N=12) to test the difference in time spent on each strategy between the two groups of participants: with repair experience vs without repair experience. We also conducted Kruskal Wallis one way analysis of variance three times to test the difference in strategies followed for the four different products (N=6). This test is an extension of the Man-Whitney U test when more than two independent samples (products) are compared [46].

2.4. Results

In this section, we present the results of the qualitative and statistical analysis of the user observations. Section 4.1 describes the diagnosis process and the strategies followed to diagnose the products; Section 4.2 presents factors relevant to the diagnosis process; and Section 4.3 presents a summary of the results.

Diagnosis Process and Strategies

The diagnosis process started with fault detection. All participants were able to detect the symptoms in the product (e.g. "not working", "low suction" etc.). However, in some cases, not all users noticed the same symptom. For instance, in the coffee maker, three participants noticed the error code and directly related it to a problem with the water level, whereas the other three just noted unresponsiveness and did not see the error code. The participants who detected the error code had used a product with a similar error code in the past.

Fault detection triggered the search strategy; participants performed iterative fault location and isolation tasks on the suspected components until the fault was found. During fault location, the participants interacted with the product to make an, not necessarily correct, educated guess about possible causes of malfunction and to understand how the product was built in order to reach the suspected components during fault isolation.

Fault isolation consisted of checking the condition of the "possible causes". This required accessing the components, often by first disassembling the product. We observed two ways of inspecting components: (a) directly, by checking the suspected component; or (b) indirectly, by checking the system without the suspected component, for instance, by running the vacuum cleaner without the hose to check the suction power if a clogged hose was suspected. The diagnosis process was restarted if functional testing revealed that the product continued to malfunction.

A summary of the user observations is presented in Figure 5, visualizing the search strategies followed by the participants and key observations such as diagnosis steps, instances of the user willing to give up, and facilitator interventions.

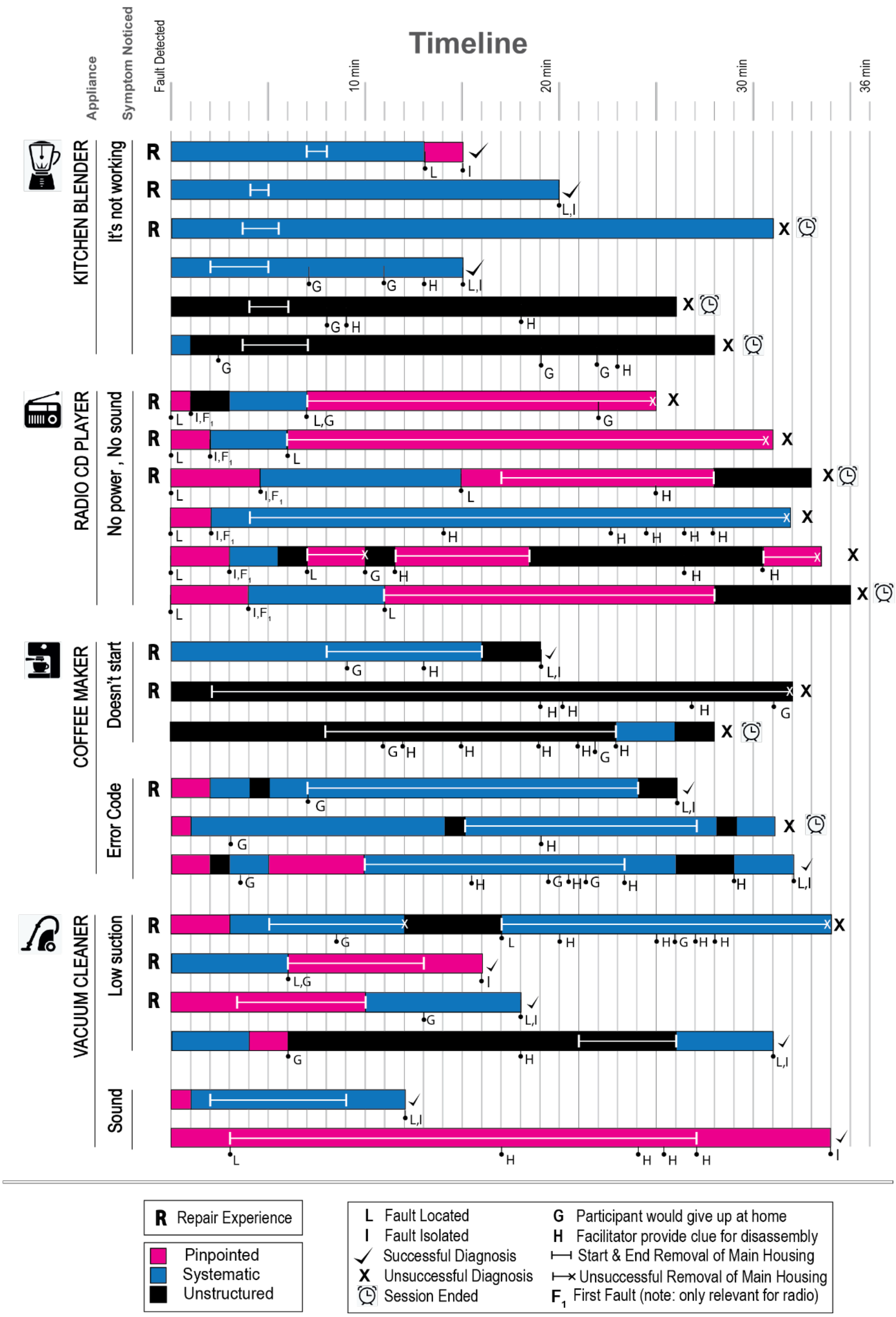


Figure 6: Summary of 24 user observations grouped by product type and symptom detected by the participants.

We distinguish between initial search strategies, adopted directly after noticing the symptom; and subsequent search strategies followed after obtaining feedback from the initial strategy. Table 5 presents a quantitative summary of the initial strategies. The results show that noticing the radio's unresponsiveness, the coffeemaker's error code, and the vacuum cleaners sound signal led to pinpointed initial strategy. The participants directly related the symptoms to a possible fault without further interacting with the product, which indicates that easily recognizable signals such as light or sounds and/or previous experience with similar products facilitate symptom-to-cause associations.

Table 5: Overview of detected symptoms and initial search strategies per product.

Product	Observed Symptoms	Participants	Initial Strategy		
			Pinpointed	Systematic	Unstructured
Blender	Unresponsiveness	6	0	5	1
Radio	Fault 1: unresponsiveness	**6**	**6**	0	0
	Fault 2: underperformance	**6**	0	6	0
Coffee	underperformance	3	0	1	2
	Error code	**3**	**3**	0	0
Vacuum Cleaner	underperformance	4	2	2	0
	Sound Signal	**2**	**2**	0	0

Note. Results in bold text highlight instances in which all the participants of the observational study followed the same initial strategy.

Initial pinpointed strategies only resulted in a successful diagnosis in the case of the radio for the fault caused by the discharged batteries, which indicates that the initial suspected cause was plausible and correct. Changes from an initial pinpointed to less directed strategies (Figure 5) occurred after all the initially suspected components were diagnosed, but not defective. In these instances, design cues were absent or participants were unable to follow them properly, causing them to change to a less directed strategy.

Changes towards directed strategies (showed in Figure 5) occurred when the participants were able to follow different design cues. Participants went from systematic to pinpointed once they had located the fault. In the case of the radio, we could clearly relate the change from systematic to pinpointed to the text display that communicated the process being executed in the product such as reading CD and playing audio. All the participants that interacted with this feature followed the same search strategy, which indicates that design can offer diagnosis guidance by directing the participants towards more directed strategies. However, while five of the six participants were able to locate the fault without disassembly and attempted to isolate the fault, the subsequent difficulty of the disassembly made it impossible for them to achieve a successful diagnosis. None of the participants could isolate the fault despite having located it. Therefore, it seems that if participants are able to locate the fault without disassembly, they are more likely to continue the diagnosis; and that product disassembly hinders a successful diagnosis.

Figure 5 also shows moments when the participants would have given up the diagnosis if in a real-life situation. The majority of these moments were noted for the group of participants "without repair experience" (8/12). The most frequently expressed reason was being afraid of worsening the product or breaking it due to the difficulty of disassembly. Consequently, during the interview, 7 of the 12 non-experienced participants stated preferring to give it to someone with more repair experience (friends/family with expertise in repairing products, or repair cafes and professionals). Furthermore, the lowest number of participants who would give up was observed for the radio.

Of the 24 participants, 17 were able to locate the faults, but only 11 could successfully diagnose the product (that is to isolate the fault). In 6 of 13 instances, the diagnosis failed because the participants could not remove the outer casing, hence, they could not progress with the diagnosis. Other unsuccessful instances (7/13) occurred because the session ended while the participants were following unstructured strategies (5/7). Therefore, the lack of design guidance and the need to disassemble the product hindered the steps of location and isolation.

Influential Factors for the Diagnosis Process

(Self-reported) Repair Experience

Table 6 shows that the group with self-reported repair experience used more structured strategies; they had higher averages for pinpointed and systematic. In contrast, the group without repair experience scored higher for unstructured strategy. These differences are not significant, so can only be regarded as being indicative.

Table 6: Statistical analysis on search strategies for both participant groups.

Strategy	**Time Spent on Strategy** with repair experience	without repair experience	**P Value** Mann-Whitney U Test*
Pinpointed	32 %	20 %	0.26
Systematic	54 %	44 %	0.22
Unstructured	14 %	36 %	0.15

*(significance at P<0.05)

We also analyzed whether the participants' self-reported repair experience influenced the required time for disassembly; however, we did not run a statistical test because some participants required clues from the facilitator, which would invalidate the analysis. Almost all the participants "without repair experience" (10/12) required help during the disassembly process compared to 3/12 from the group "with repair experience" (see Figure 5). This indicates that self-reported repair experience does influence the disassembly process.

Product type

We observed major differences in the time required for the disassembly and the chosen search strategy between the products. The kitchen blender took the least time to disassemble (2 min), followed by the vacuum cleaner (12 min), the coffee maker (17 min), and the radio CD player (18min). Regarding the search strategies, the results showed a significant difference in the use of the pinpointed strategy (p=0.010), with the highest use for the radio and the vacuum cleaner (Figure 6). Both products showed the least use of unstructured strategies. Our results indicate that enabling and hampering design features strongly affects the choice of specific strategies.

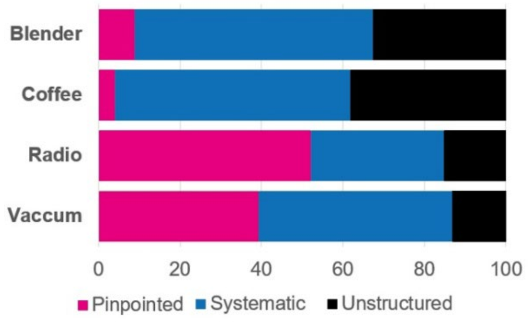


Figure 7 : Ratio of followed search strategies per product type.

Qualitative analysis revealed how design features affected the different search strategies and the feasibility of the diagnosis tasks (see Table 7). In the following sections, we discuss the relationship between design features and the success of search strategies.

In a pinpointed strategy, the features providing "feedback to user" were most useful for a correct symptom-to-cause deduction, which led to a correct location of the fault. The combined principles of component accessibility and visibility were most useful during fault isolation when the participants inspected specific components. However, accessibility alone does not seem to be sufficient. For the kitchen blender, we observed that the broken safety pin was accessible but not easily visible. The color of the pin and the housing were the same which resulted in the blender being disassembled to the pin by 4/6 users instead of simply accessing the pin from the outside. Pinpointed strategies were unsuccessful in cases where the participants relied on their own heuristic knowledge in the absence of guidance by the product.

In a systematic strategy, participants identified possible causes of failure by learning how the components were assembled and worked together. In successful systematic search strategies, location and isolation occurred simultaneously (see Figure 5). The visibility of components in the product offered guidance during fault location. However, when the components were visible but assembled at different disassembly levels (same level components can be disassembled in parallel), the participants had difficulties understanding how the product was constructed, resulting in a delay in locating the fault and unsuccessful diagnosis. Both strategies show that component accessibility and visibility are key to facilitating fault location.

Unstructured strategies resulted in a successful diagnosis for the coffee maker once all components were visible at the same disassembly level, i.e. a full view of component location and isolation facilitate an unstructured strategy.

Table 7: Design principles and features facilitating (+) or hampering (-) the diagnosis process and its relevance at each diagnosis stage: Detection (D), Location (L), and Isolation (I).

Design Principles, Design Features			**Relevance for the Diagnosis Process**
ACCESSIBILITY	Ergonomic geometry of access points to components Sectionable component Long cables Lid Opening in the casing	+L +I	Quick inspection of components without removal of fasteners or components.
	Non-ergonomic geometry	-I	Difficult inspection of components, could imply further disassembly
	Non removable encapsulation	-I	Components cannot be checked
DISASSEMBLY	Seams (of housing) Visible fastener head	+I	Understand product's construction
	Easy-to-detach (Detachment within 2 actions, low force and without any tools)	+I	Component release
	Many (5+) screws on different surfaces for a single component (housing) Hidden high force snap fits* Screws located away from component they fasten Deeply recessed fasteners	-I	Understand product's construction + Component Release * and provokes fear of breaking the product when attempting to detach

Design Principles, Design Features		**Relevance for the Diagnosis Process**			
INTERCHANGEABILITY	Easily replaceable standard components			+I	Able to quickly isolate the faulty component by replacing with a working one (If spare parts are readily available)
MODULARITY	The device is built from individually distinct functional units		+L	+I	Allows condition inspection of individually distinct functional units (in particular, when these can operate independently)
REDUNDANCY	More than one way of delivering a function	+D	+L	+I	Certainty for fault location
ROBUSTNESS	Materials and construction are unlikely to fail, even if the product is treated roughly			+I	Allows inspection and disassembly without fear of damaging the device or components
TESTING	Non-isolated electrical measuring points			+I	Facilitate the measurements with multimeter
USER FEEDBACK & INFORMATION	Light when powered Click sound during attachment/ detachment	+D	+L	+I	Confirms the user that components are working
	Error Signal in the form of Blinking lights	+D	+L		Directs repair to potentially defective components, however, the study shows that interpreting their meaning required previous experience with using similar products.
	Display with text	+D	+L		Communicates the process being performed or executed
	Colour contrasting with grime			+I	Quickly check the condition (cleanness) of component
	Engraved labels and marking in the product	+D		+I	Guidance on correct usage of product
VISIBILITY	Material transparency Full view of components*	+D	+L	+I	Quick Inspection without disassembly * and understand working mechanism of the product
	Coloured wires Visible relationship between components		+L		Understand working mechanism of the product
	Symmetric positioning of components			+I	Inspection by comparison
	Non-contrasting colour between components		-L	-I	Identify different components
	Components of same functional subsystems at different disassembly levels (>2 level)		-L		Understand working mechanism of the product

Summary of results

All participants started the diagnosis process and attempted to identify the faults. Their search strategies were significantly influenced by the product's design and not significantly influenced by the participants' self-declared repair experience. Almost half (46%) of the participants could successfully diagnose the products within the given timeframe (40 minutes). Design features that most hindered the fault diagnosis process were the difficulty of the product's disassembly (in particular for the non-experienced group) and the lack of guidance provided by the product, which resulted in the pursuing of unstructured search strategies and, as a consequence, insufficient time to finish the diagnosis.

2.5. Discussion

We set out to understand the effects of self-reported repair skills and the product's design on the process of fault diagnosis. In this section, we discuss our findings and provide an initial set of design guidelines to facilitate fault diagnosis for end-users.

About the process of fault diagnosis

Our results reflect the framework of the process of fault diagnosis presented in section 2.1: participants go through the diagnosis steps of fault detection, location, and isolation. However, we also observed that participants iterated between the stages of fault location and isolation instead of following a linear sequence as suggested by the framework. Consequently, a framework incorporating this new insight is presented in figure 7. This framework indicates that, for an effective diagnosis, symptom-to-cause deduction should be facilitated so that the number of iterations between location and isolation is minimal.

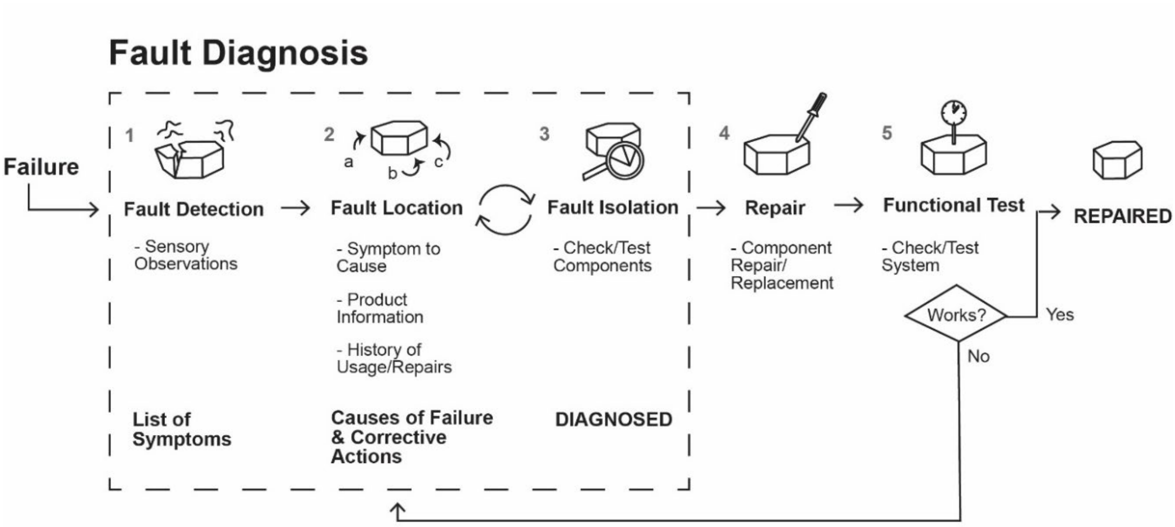


Figure 8: Updated framework of the process of fault diagnosis by end-users.

About influential factors for fault diagnosis

Our findings show that repair experience and product-specific knowledge (provided by previous experience using similar products) can facilitate the diagnosis process, but that design features are more influential for successful diagnosis. We observed that the product's design determines the feasibility of the diagnosis tasks and offers guidance during the diagnosis and, thus, influences the user's decision to proceed with the diagnosis. Self-reported repair experience appears helpful for the disassembly process but not decisive for structured search strategies, hence it does not influence the symptom-to-cause deduction process. Furthermore, product-specific knowledge facilitates the recognition of designed signals but does not guarantee successful diagnosis.

The difficulty of product disassembly, especially removing the outer housing of the product, often hindered the diagnosis process. It was the most common cause of frustration among participants, frequently provoking the reaction of giving up, and was a major cause of unsuccessful diagnosis. Difficulty of product disassembly is reported as one of the barriers for repair [47], [48], [49]. Our study adds to this literature by indicating that difficulty of disassembly is also a barrier for successful fault diagnosis.

In addition, difficulty of product disassembly particularly affected the group “without repair experience”. They required more clues for disassembly and were more likely to give up the diagnosis. Thus, self-reported repair experience appears to play a role in overcoming the difficulty of the disassembly. This result coincides with the findings of Morris and Rouse [33] who concluded that a successful troubleshooter should have the skill of knowing how to repair or replace a component.

Although the study revealed that using product-specific knowledge during diagnosis resulted in more directed search strategies, these were not always successful as they were based on product-specific knowledge from previous experiences and not on the product being diagnosed. Therefore, while our findings recognize the benefits of end user product-specific knowledge, for optimal fault diagnosis and repair by all end users, the diagnosis should be more reliant on the product’s design.

Initial Design Guidelines to Facilitate Fault Diagnosis

Some products gave participants more information and guidance when detecting and locating faults, resulting in more structured search strategies. Moreover, we observed that in the absence of guidance features, the participants relied on component visibility and accessibility to discover how the product was built and how the different components worked together. As a result, they could deduce possible causes of failure and corrective actions, i.e., if components could be seen and accessed, successful diagnosis was achievable. Furthermore, faults in components were easier to isolate when disassembly was minimal and easy to perform, e.g. no tools required, and the components were functionally independent. These observations led us to develop a set of design guidelines that facilitate fault diagnosis. These are based on the design principles and design features of Table 7.

The design guidelines are listed in table 8. They encapsulate multiple design principles relevant for an easy diagnosis. In the context of this study, “design guidelines” are defined as practical recommendations on how to apply design principles for fault diagnosis. “Design principles” are defined as general directions of improvement, e.g., increasing accessibility generally improves diagnosis, as does increasing modularity and visibility. Designers can use these guidelines to create easy-to-diagnose products. The guidelines we present here are a first step towards a complete set of design guidelines for fault diagnosis; additional research, iteration, and validation are needed for the guidelines to fully mature.

Table 8: Design Guidelines to Facilitate Fault Diagnosis and Design Principles to which they are associated.

Design Guidelines	***Design Principles***								
	Accessibility	Disassembly	Interchangeability	Modularity	Redundancy	Robustness	Testing	User Feedback & Information	Visibility
1. Facilitate fault detection and symptom-to-cause deduction by giving timely and understandable feedback that does not require product specific knowledge. For instance by providing sound or text signals that communicate the correct appliance usage or the process being executed in the product.					●			●	●
2. Facilitate navigating through the product's construction. For instance, by arranging components at the same disassembly level and making their relationship visible.		●							●
3. Facilitate the inspection of product components. For instance, by making components functionally distinct, providing them with testing ports or including features that inherently communicate their condition.	●	●	●	●	●	●	●	●	●
4. Minimize the need to disassemble the product. For instance, by including lids or doors to access to the components, or features that facilitate knowing their condition onsite such as testing ports, transparent materials or contrasting material colors.	●						●	●	●
5. If product disassembly is needed, facilitate it. For instance, by giving ergonomic dimensions to points of access to components, reducing the number and diversity of fasteners and making them visible.	●	●		●		●			●

These preliminary guidelines show similarities with previous guidelines on design for repair. Guidelines 2 and 5 aim to ease product disassembly to the component level. Ease of disassembly is a well-recognized design principle for circular products. It is usually valued for facilitating replacement of broken components [50], [51], [52]. Also, visibility of components, needed to guide users through the disassembly (guideline 2) has been identified as a relevant criterion for product repairability [22].

However, our guidelines provide new directions to ease the diagnosis, and consequently, the repair of products for end users. First, they include design principles that were not related to diagnosis and repair before, e.g. the principles of robustness and enabling testing [12], [26]. Second, guideline 3 expands guidelines for inspection from Go et al. [11]. It provides additional means to ease fault isolation. Third, guideline 1 aims to facilitate fault detection and fault location. Such a recommendation had not been recognized in literature on design for repair before. Fourth and last, guideline 4 puts forward the idea of avoiding the need to disassemble the product and instead facilitate means to know the condition of components from outside.

These guidelines are a valuable addition to the currently available "design for repair" guidelines. They show how design for fault diagnosis stresses the importance of providing relevant and easy-to-access feedback to end-users about the state of the product and its components. Where design for repair guidelines tend to focus on product architecture and disassembly, the design for fault diagnosis guidelines presented here focus on the end-user's ability to "read" the condition of the product, preferably without the need for disassembly.

Limitations and recommendations for further study

Due to the response and availability, we mainly recruited participants aged 45-65. Therefore, the data may not be fully representative of the general population. A different age group might have had different experiences using the product and repairing it. Furthermore, we note that our experiment may not be a fully accurate representation of a real-life scenario, as some participants stated that they would not have repaired the product if at home. However, as our primary aim was to investigate how design features and experience affect search strategies, this is not considered to limit the validity of the results. Finally, we only included four products, which limited the number of analyzed design features and faults. Extending the range of products is likely to bring forward additional relevant design features.

We recommend that future studies use a greater range of products and that they analyze the impact of design guidelines on design and repair practice. Research questions could include:

- What would be the impact on diagnosis and repairs if products were designed following our set of initial guidelines?
- How could designers use these initial design guidelines and how could these be implemented into practice?

2.6. Conclusion

We investigated the effects of repair skills and the product's design on the fault diagnosis of consumer products by end-users. The diagnosis process was studied qualitatively and quantitatively through an observational study with 24 participants who were asked to repair four defective consumer products in a controlled setting while thinking aloud.

Analysis of the findings resulted in a detailed description of the end user fault diagnosis process. The product's design had a major influence on the effectiveness of fault diagnosis, both in terms of time and search strategy. It affected the feasibility of the diagnosis tasks and the information and guidance the user could obtain from the product during the diagnosis. Product disassembly was found to be a major barrier to diagnosis, and a reason for users wanting to stop the process.

This study is one of the first to explore in detail the process of fault diagnosis of consumer products by their end-users. It gives rich insights into the way people struggle with fault diagnosis and provides evidence of the importance of the product's design for a successful diagnosis. These insights, translated by us into a set of preliminary product design guidelines, will assist the development of better Design for Repairability methods and contribute to the body of knowledge of product repairability. Furthermore, these results are relevant for future product repairability policy and legislation. The Circular Economy Action Plan by the European

Commission aims to support the “Right to Repair” [53]. Accordingly, Ecodesign Regulations include repairability requirements. The process of fault diagnosis is an essential step in a repair process. Hence, the insights and guidelines provided in this study could be used to put in place measures to promote designs that ease the fault diagnosis process.

2.7. Acknowledgements

This work was funded by the European Commission under the Horizon 2020 Marie Skłodowska Curie Action 2016 (Grant Agreement number 721909) and Premature Obsolescence Multi stakeholder Product Testing Program (PROMPT) (Grant Agreement number 820331).

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3.

Modelling disassembly and reassembly times (DaRT) for assessing repairability

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3.1. Abstract

Repair plays a pivotal role in the circular economy by reducing electronic waste and improving resource efficiency. Evaluating repairability factors such as disassembly could be complex and time consuming. This study introduces the Disassembly and Reassembly Time (DaRT) model, a simplified, time-based tool developed from over 10,000 data points on household products. By categorizing actions with comparable median times, it generates proxy times that accurately capture most disassembly and reassembly tasks while highlighting occasional differences, such as part-handling steps. Validated through comparisons with independent disassembly data for vacuum cleaners, washing machines, and smart TVs, DaRT demonstrates strong correlation and minimal bias. Balancing ease of use with reliability, it outperforms simpler step-count methods and offers greater practicality than the complex eDiM. Overall, DaRT enhances repair scoring systems, guides more repairable product design, and fosters a more circular electronics industry, ultimately fueling more sustainable innovation.

3.2. Introduction

Repair is a vital strategy in the circular economy for electronic appliances, representing an approach to waste reduction, resource efficiency, and environmental sustainability. The European Union's recent policies on the right to repair reflect this growing importance [1], [2], [3]. Various repairability scoring systems [4], [5] have been established to assess repairability and to promote better repairable products.

Ease of disassembly is an important criterion in repairability scoring systems [6], [7]. As a result, the ability to determine the ease of disassembly and reassembly reliably and easily is not merely a technical concern. It's crucial for developing a robust repairability scoring system that influences policymakers, designers, and manufacturers. Currently, two distinct methods are used to assess the ease of disassembly: “proxy time methods”, such as eDiM (ease of Disassembly Metric) [7] and iFixit Proxy time [8], which estimate disassembly times through modelling the required actions, and the “step method” [9], which counts the number of disassembly steps. Although the step method has been widely used in various repairability scoring systems [4], [5], proxy time method (specifically eDiM) has shown to provide a better representation of ease of disassembly [10], [11]. Compared to the step method, eDiM's time-based approach aligns better with practical repair scenarios, where time is a crucial factor for professional repair services and provides a better indication of the level of difficulty to end-users. As a result, a scoring system directly based on required time instead of number of steps can more reliably assess ease of disassembly and incentivize manufacturers to design products with reduced repair time and complexity.

For assessment purposes, a disadvantage of eDiM is its demanding time-consuming calculations, frequent updates, and grappling with the complexity of countless tool and connector combinations [12], [7]. Furthermore, the model operations that are at the core of eDiM are currently limited to monitors, laptops and TVs. These limitations hinder the application of the eDiM approach to other product types and towards implementation in scoring systems. The aim of this paper is, therefore, to explore the opportunities of a model for disassembly and reassembly based on experimental data that is easier to use and applicable towards a broader range of products.

To achieve this, a twofold approach was followed. First, disassembly and reassembly times were determined for a large set of different household products with very different product architecture: washing machines, vacuum cleaners and smart TVs. The data for all disassembly and reassembly times were subsequently divided into suitable groups to develop a simplified time-based disassembly and reassembly assessment model. The resulting model (DaRT) was compared with eDiM to understand the extent of its similarities and differences.

To check the model’s validity and applicability, a separate set of appliances (washing machines, vacuum cleaners and TVs) was dismantled by external testing bodies and DaRT times were calculated and compared with the actual disassembly times.

3.3. Methods

Choice of Appliances

Washing machines, vacuum cleaners, mobile phones and smart TVs were used for this study as a result of a multi criteria analysis within the Horizon 2020 PROMPT project [13]. The selection is based on their ubiquity in homes, their varying complexity in mechanical and electronic design, and repair frequency.

Additionally, products across different price ranges and made by different companies were chosen to ensure a broad perspective. Different price points and brands reflect variations in design complexity and assembly methods. This diversity enables us to establish generalizability of the findings to a variety of product groups and market segments in the wider category of household appliances.

In total 12 washing machines (disassembly and reassembly), 12 vacuum cleaners (disassembly and reassembly), 7 TVs (prying actions only), and 35 smart phones (adhesive removal actions only) were analyzed (See supplementary material 3c. for information on all the investigated products).

Protocol for establishing disassembly and reassembly action times

The disassembly was done by professional repairers from iFixit [14] and RUSZ [15] with more than 5 years of experience. The entire disassembly and reassembly process was conducted in a typical repair environment, closely replicating the conditions encountered by actual repair professionals. This included adequate lighting, sufficient space for the disassembly process, all necessary tools within the repairer's reach, and convenient access to space for placing disassembled components.

Standard tools used in the industry were employed, adding to the study's realism and relevance. Power tools were, however, omitted to maintain the simplicity of the protocol. The following protocol for disassembly and reassembly was followed for all products:

- The products were first disassembled to their individual components and then reassembled. The disassembly of a part ended when it reached permanent fixtures, such as soldering, welding, or thermal molding.
- All disassembly and reassembly actions were noted, this included: tool type, action, force used, fastener type, the visibility of fastener and the component being removed.
- During the disassembly, the actions were described aloud, mentioning and describing the target component, its location, the tool being used, and the detached/reattached fasteners.
- A disassembly map [16] was created for each product following the procedure outlined in [10].
- The products were disassembled to their individual component and reassembled a second time by the same person.
- The entire process was video recorded from the front and top view.

The timing and nature for each action was extracted from the second video. Table 1 lists and defines the actions timed during the disassembly and reassembly process.

Table 9: Actions and their details recorded during the disassembly and reassembly. PT= the tool in hand is in position for the action to perform; Touch= tool or hand touches component; Released= hand or tool stops touching affected component/fastener. Prior end= end of the previous action. Note: the fasteners mentioned in brackets () of action column are examples and the actions are not limited to the mentioned fasteners.

Action	**Details**	**Start moment**	**End moment**
Grab and position tool/component/screw	Grabbing a (tool) and placing it in position for next action	Touch	Tool/Component/Screw positioned (PT in case of tool)
Position tool (PT)	Tool, already in hand, is positioned ready for intended operation	Prior end	Tool in position and ready for next action (is PT)
Put tool aside	Tool in hand is placed on the table	Prior end	Tool on the table + Released
Open (hinge)	Rotational motion to open (e.g., door)	PT	Open action + Released
Close (hinge)	Rotational motion to close (e.g., door)	PT	Close action + Released
Loosen (friction fit)	Loosen friction fits (often by slowly pulling or small twists)	PT	The loosened part stops touching its housing
Pry (snap fit)	Pry using lever action	PT	Pried + Released
Attach (friction fit/snap fit)	Attach two components together with friction fit or snap fit (often hand is used)	PT	Attached + Released
Pull (friction fit)	Pull action (e.g., tabs)	PT	Pulled + Released
Push (friction fit)	Push action (e.g., buttons)	PT	Pushed + Released
Screw (wrench/screwdriver)	Screw motion often using wrench or screwdriver	PT	Screw fully tightened + released
Unscrew (wrench/screwdriver)	Unscrew motion often using wrench or screwdriver	PT	Screw fully loosened + Released
Plug (hose/wires)	Plugging (e.g., wires and hoses)	Touch	Plugged + Released
Unplug (hose/wires)	Unplugging (e.g., wires and hoses)	PT	Unplug + Released
Detach (wires within product)	Remove cable from housing/cable guide	PT	Unrouted + Released
Route (wires within product)	Attach cable to housing/cable guide	Touch	Routed + Released
Pry friction-fitting/ glued circumference (per 5cm)	Pry series of fasteners around a circumference.	PT	Pried along + Released
Cut	Cut (cable tie/wire) using pliers/scissors	PT	Cut + Released
Heat adhesive (plate)	Using heat plate to loosen the glued surface	Part picked up	Part heated
Remove component/screw	Remove a detached part/fastener and place it on the (desk)	Prior end + PT	Removed + Released on (desk)
Turn product (with both hands)	Turn product with two hands	PT	Turn + Released
Tilt product	Tilt heavy parts (>150 Newtons) to access (e.g., underneath)	PT	Tilted + Released
Untilt product	Tilt back straight heavy parts (>150 Newtons) after accessing e.g. underneath	PT	Placed back in standing position + Released

Data Analysis

A total of 10569 datapoints of the actions mentioned in Table 1 were obtained. Only actions with more than 15 datapoints were used for statistical analysis to avoid the impact of coincidental variations. The data was visualized using a combination of histogram and box plot. Histograms provide the data frequency distribution and uncover aspects like bimodality or skewness. Concurrently, the box plot provides a concise summary of the data's central tendency, variability, and potential outliers, and offers a quick overview of key statistical information.

In order to compare disassembly and reassembly times the data was checked to see if the medians of both disassembly and reassembly of a specific reciprocal action fell within the first and third quartiles of a box plot. This is a measure of the degree of similarity of the median values of disassembly-reassembly pairs. Median values that fall outside the interquartile range are considered meaningful differences.

In the same way, to explore the potential for reducing the differentiating between a large variety of tools, similar actions, like screwing with differently sized screw drivers, were grouped, and their median values were compared. Medians of actions that fall outside the interquartile range of a group were again considered meaningfully different and not belonging to the group. The media of each group were used as model timings for the respective group.

The median was used instead of the mean for model timings since the median is more robust against uncertainties, especially when dealing with outliers or skewed data distributions. Additionally, the use of the median mitigates the impact of non-random errors, such as systematic overestimations [17], [18]. Initially, a more advanced statistical technique, namely the Mann-Whitney test, was employed (see Supplementary Material 3d for these results). While the majority of the results were consistent with those obtained using the current method, the Mann-Whitney test occasionally indicated statistically significant differences that were not meaningful in the context of identifying practical distinctions between actions. Therefore, we decided to determine whether the medians of different actions fall within each other's interquartile ranges, as this provides a more appropriate indicator of meaningful difference.

For comparison with eDiM timings taken from Vanegas et. al [7], type 3 connectors actions (>20N force, D>6mm screws) from eDiM were considered as these connector actions provided the closest representation to the DaRT conditions.

Model verification

This section outlines the method used to test the DaRT model on its validity and ease of use. This was carried out using data obtained on a large-scale disassembly of products in professional testing labs experienced in disassembly of the products.

Four washing machines, five vacuum cleaners and five smart TVs were evaluated as the result of a collaboration with consumer organizations within the framework of the European PROMPT project based on large variation in design features [19]. Investigated priority parts are as follows:

- Vacuum cleaner: suction hose, dust cover, handle, cord reel, motor, on/off switch, wheels;
- Smart TVs: main board, timing control board, display assembly, internal power supply;
- Washing machine: door lock, door seal, electronics, hoses, pump, shock absorbers, tub assembly.

These priority parts were chosen due to their high failure likelihood and high functional relevance.

Disassembly and reassembly protocol for product evaluation.

The following protocol was used to score criteria related to disassembly.

1. The disassembly and reassembly process of the product to access all the priority parts was first determined.
    - The official website was checked for a disassembly manual or instructions.

    - If this was not available, other non-official disassembly/reassembly instructions websites such as iFixit and YouTube disassembly channels were consulted.
    - If none of these sources provided the necessary information, the product was disassembled and reassembled in order to determine the disassembly process.
2. The device was then disassembled until each priority part was separated.
    - Any non-standard accessories, such as display protectors or rubber bumpers, were removed before the start of the disassembly process. These accessories were not considered part of the disassembly.
    - The disassembly of a priority part ended when it reached permanent fixtures, such as soldering, welding, or thermal molding.
    - If multiple tools were required during a single disassembly action, the tool would only change once all fasteners requiring that specific tool have been removed.
3. The product was subsequently reassembled.
4. The product was tested again to confirm it worked correctly and disassembly had not influenced its functionality.
5. The entire disassembly and reassembly process was recorded in top and side-view videos.
6. During the disassembly, the actions were described aloud, mentioning and describing the target component, its location, the tool being used, and the detached/reattached fasteners.
7. Using the described information and the disassembly sequenced from the video, a disassembly map [16] was created.
8. The proxy times for the model were calculated using the disassembly map.
9. The product was disassembled a second time. However, this time the researcher did not think out loud during the disassembly process.
10. The entire disassembly process was recorded on video.
11. The actual times needed for disassembling (and putting aside) each priority part was extracted from the second video.

Assessment of ease of use

The DaRT assessment methodology was used by independent testing bodies (VDE [20] and BBM [21]) with the request to inform us if any part of the process was unclear or required further explanation. Over the course of the testing bodies assessing the product using DaRT methodology, we noted the number of times they requested clarifications. Additionally, at the end of the process, these testing bodies were qualitatively interviewed in online focus groups on the clarity of the process. Two focus groups with 3-4 people (one for each testing body) were held.

The following open questions were asked:

1. Did you find any aspects of the DaRT methodology unclear?
2. How long did using the DaRT methodology take, compared to just disassembling the product?
    a. What part took the longest time?
3. Do you have further recommendations that could be beneficial towards overall usability of the methodology?

After each question, the group was further asked for more details. Approximately 15 minutes were spent on each interview.

During the analysis of the interviews, the similarities and differences in responses from both focus groups were examined. Any overarching themes that reflected the participants' experiences and suggestions were grouped. These themes encompassed common perceptions of the DaRT methodology's clarity, time efficiency, and usability. Although the analytical and interview process was not thorough, it offered valuable preliminary insights into the experiences of using the DaRT methodology.

3.4. Results

The timings of the actions distinguished during disassembly and reassembly are represented in Figure 1, which shows the histograms and median and quartile values. This figure presents the results, distinguishing a) tool positioning action for different tools, b) disassembly and reassembly for turn and crank action using different tools, and c) other disassembly and reassembly actions. Similarly, Table 2 presents: the details on observed median timings for disassembly and reassembly actions, and a comparison of the observed times to the equivalent eDiM time.

Disassembly and reassembly

By comparing the disassembly and reassembly actions from Figure 1 and Table 2 it is evident that in most cases disassembly and reassembly timings are similar enough to be represented by a single value. For example, for “position tool” and “grab and position tool” actions, and most of the “screw” and “unscrew” actions (6/9), no significant differences between disassembly and reassembly times were observed.

On the other hand, significant differences are observed between disassembly and reassembly for removal/grab and position action for component and screw. Grabbing and placing components or screws takes significantly more time than removing and putting them away. Similarly, routing cables is more time consuming than removing them. Further, “unplug hose” takes significantly less time than “plug hose”. Additional time is required to properly align screws, components, and cables during reassembly, ensuring they are correctly positioned. The extra time for attachment actions is necessary to align and position the attachment accurately. An exception to this is “tilt” and “untilt” product where “tilt” takes significantly longer than “untilt”, as “tilt” generally requires more work against gravity than “untilt”. However, “tilt” and “untilt” are actions observed in both disassembly and reassembly process.

When considering similar actions on washing machines and vacuum cleaners, most of the actions for washing machines and vacuum cleaners were comparable. However, times needed for “grab and position tool”, “plug/unplug hose” and “turn product” were significantly longer in washing machines than in vacuum cleaners (see supplementary material 3a.). The “grab and position tool” action is explained by the larger range of motion that is required from the position of the tool to the position of the fastener. Further, hoses of washing machines need to be watertight and are subjected to higher pressure in contrast to hoses of vacuum cleaners, therefore, longer time and higher force is required to do so. Similarly, turning a heavy object like a washing machine requires significantly higher force than turning a vacuum cleaner. Actions are, therefore, distinguished between larger and smaller appliances for the forementioned three actions.

Some scoring systems and eDiM distinguish between low, medium, and high force needed for an action. However, for the products investigated, operators could not distinguish between low (<5N) and medium force (5-20N) and did not observe a clear difference in difficulty performing these actions. But a clear difference was distinguished between medium and high force (>20N) actions.

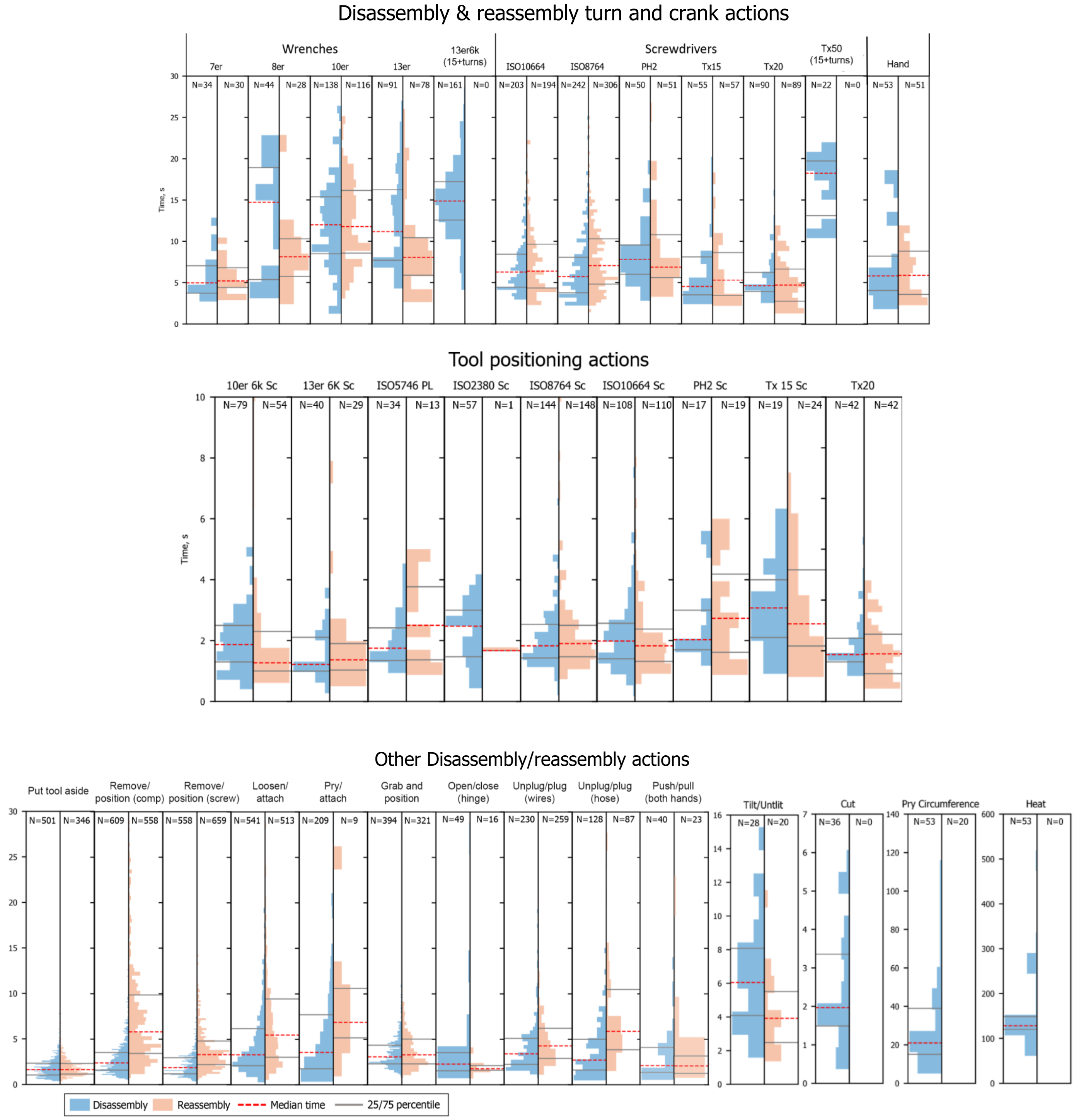

Figure 9: Timing of disassembly and reassembly actions, distinguished by nature of activity and tool used. See supplementary material 3b. for further information on tool types.

*Table 10: Observed median timings for disassembly and reassembly, and its comparison to eDiM timings. Disass = Dissassembly, Reass = Reassembly, empty cell = Not enough data available for evaluation. *= Action used for both disassembly and reassembly** = This penalty is added to the corresponding action time and is not a stand-alone action. Actions in bold = disassembly and reassembly are significantly different. Delta DaRt vs eDiM % = (Median time disass - eDiM time)/ ((Median time disass + eDiM time)/2)) *100.*

Action (disassembly/reassembly)	Disass N	**Median time disass (s)**	Reass N	**Median time reass (s)**	Difference disass vs Reass (%)	Overall median time (s)	eDiM Time (s)	% Delta DaRt vs eDiM (%) (disass)
*Grab and position tool**	394	3.1	321	3.3	7.2	3.2		
*Position tool**	541	1.9	444	1.8	- 3.7	1.8	1.4	30
*Put tool aside**	501	1.6	346	1.6	0.0	1.6		
*Open/close (hinge) **	49	2.3	16	1.8	- 24.8	2.1	2.2	4
Pry/attach (snap fit; <20 Newton)	467	4.1	161	5.5	29.4	4.5	2.2	60
Pry (snap fit; >20 Newton)	22	12.7	<15					
***Loosen/attach (friction fit; <20** Newton)*	541	3.3	513	5.5	49.5			
Loosen/attach (friction fit; >20 Newton)	19	12.1	<15					
*Pull/push with both hands (friction fit) **	40	2.1	23	2.1	-1.4	2.1	2.2	-5
Unscrew/screw (wrench; =>15 turns)	161	14.9	<15					
Unscrew/screw (wrench; <15 turns)	307	10.9	252	9.0	- 19.4	9.7		
Unscrew/screw (screwdriver; <15 turns)	693	5.7	748	6.3	10.0	6.0	3.6	45
Unscrew/screw (screwdriver; =>15 turns)	22	18.2	<15					
Unplug/plug (hose)	128	2.7	87	5.9	74.0			
Unplug/plug (wires)	230	3.4	259	4.3	22.7	3.8	2.2	43
Detach/route (wires within product)	95	4.1	71	8.3	67.0			
Pry friction-fitting circumference	15	3.0	<15					
Pry glued circumference (per 5cm)	53	21.0	N/A					
Cut (cable ties, wires)	36	2.0	N/A				2.2	-10
Heat adhesive (plate)	53	128	N/A				120.0	6
Remove/grab and position component	737	2.4	649	7.7	104.7		1.4	53
Remove/grab and position screw	558	1.9	659	3.3	55.3		1.4	30
Turn product	79	3.4	98	3.2	- 7.4	3.2	2.5	31
Tilt product (>150 Newtons)	28	6.1	20	3.9	- 42.9			
*Overcoming low accessibility***	32	13.9					3.4	121

Grouping comparable actions

Grouping comparable actions helps simplify the method, because it gives users looking up values a shorter list to choose from, but actions with significantly different timing must be distinguished. Based on the data in Figure 1 and Table 2, the following actions have been investigated for potential grouping based on similarity of the activity carried out and the overlap of their distributions: a) tool positioning of different tools, b) unscrewing/screwing timings with different screwdriver and wrench types, c) place/put away for screws, tools and components.

The “position tool” required similar timing regardless of the tool type. This observation is supported by the fact that the distribution for a single tool is much larger than the distribution of the medians of all tools. This indicates a consistency in the timing needed for positioning regardless of the tools used and implies that all positioning actions can be considered as a single group of actions. Taking the median value of this group as representative for all these actions largely simplifies the proxy timing system without introducing significant errors.

The timing of unscrew/screw actions was generally consistent across different screwdriver types, except for the Phillips head size 2. A comparable trend is observed with wrenches, where these actions are largely uniform across types, except for size 7. Both actions exhibited broad distributions and an almost multimodal pattern, reflecting significant variation in the required time. Further, observations of video recordings clearly showed the effect of long and short screws in disassembly time, with longer screws demanding more turns, thereby increasing the time needed to either loosen or fasten them. For simplicity and available data quality we decided to distinguish between screws shorter or longer than 15 turns. Similarly, wrench actions were grouped using the same criterion.

The time required to put away tools, screws or components also showed significant variation. Putting away tools took the least time, while putting away components took the most time. This discrepancy is due to the extra precision needed to grab and place screws or components compared to tools, which are already in hand. Placing screws and components also shows significant differences in time. Screws are placed in a single alignment slot, whereas components require alignment in various dimensions, leading to longer placement times. Therefore, removing and positioning tools, screws and components cannot be grouped.

Based on these observations and grouping, the overall histogram and box plot data of each group of actions considered for the model is re-presented in Figure 2.

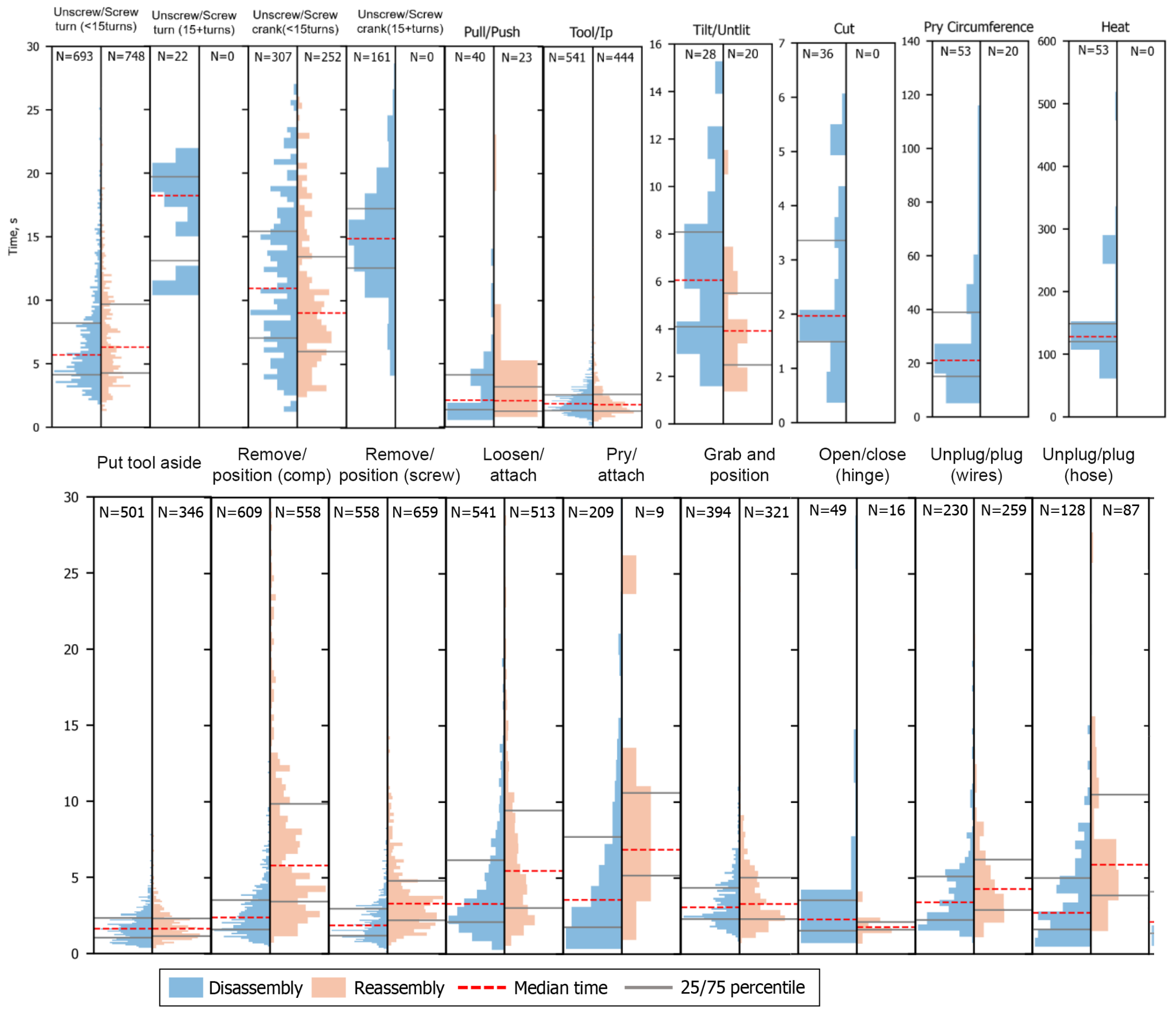

Figure 2: Timing of groups of disassembly and reassembly actions, constituting the basis for DaRT. "Pry Circumference", "Cut" and "Heat" are irreversible and, therefore, do not contain reassembly action, "Unscrew/Screw turn (15+ turns)" and "Unscrew/Screw crank (15+ turns)" do not have sufficient data for reassembly. (n<15).

DaRT model

Based on the analysis, the Disassembly and Reassembly Timing (DaRT) model was established by integrating the median of observed timings and grouping actions as discussed. This approach ensures that the model accurately reflects typical disassembly and reassembly times while maintaining simplicity and broad applicability. Table 3 shows the groups, and their timings used in the DaRT model.

*Table 11 : DaRT Timings Disass = Disassembly, Reass = Reassembly. - = No data available. "Correction Time" are values added to the other actions. * = same mean value as disassembly based on assumption, not from measurement. Reassembly times that are different than disassembly are indicated in grey cells.*

Handling type	Disassembly/reassembly action	DaRT Time (Disassembly) [s]	DaRT Time (Reassembly) [s]
Tool handling	*Grab and position tool*	3.2	3.2
	Position tool	1.8	1.8
	Put tool aside	1.6	1.6
Reversible connection actions	*Open/close (hinge)*	2.1	2.1
	Loosen/attach (friction fit, <20 Newton)	3.3	5.5
	Loosen/attach (friction fit, > 20 Newton)	13.0	13.0*
	Pull/push (friction fit)	2.1	2.1
	Unscrew/screw (wrench <15 turns)	6.0	6.0
	Unscrew/screw (screwdriver <15 turns)	9.7	9.7
	Unscrew/screw (wrench =>15 turns)	21.0	21.0*
	Unscrew/screw (screwdriver =>15 turns)	18.0	18.0*
	Unplug/plug (hose)	1.2	3.4
	Unplug/plug (watertight hose)	3.4	6.6
	Unplug/plug (wires)	3.8	3.8
	Detach/route (wires within product)	4.1	8.3
	Pry/attach (snap fit, < 20 Newton)	4.5	5.5
	Pry/attach (snap fit, >20 Newton)	12.0	12.0*
	Pry friction-fitting circumference (per 5cm)	2.0	2.0*
Irreversible connection actions	*Pry glued circumference (per 5cm)*	3.0	-
	Cut (cable ties, wires)	6.0	-
	Heat adhesive (plate)	15.0	-
Product/component handling	*Remove/grab and position component*	2.4	7.7
	Remove/grab and position screw	1.9	3.3
	Turn product (<150 Newtons)	2.7	2.7
	Turn (heavy appliance > 150 Newton)	1.3	1.3
	Tilt/untilt product (>150 Newton)	6.1	3.9
Correction Time	*Overcoming low accessibility*	14.0	14.0*
	Grab and position tool (large appliance)	1.2	1.2

Validation of DaRT

The DaRT method for disassembly times has been evaluated by comparing actual disassembly times with DaRT proxy times for the removal of priority components in washing machines, vacuum cleaners and smart TVs by independent product testing bodies. Only in one instance a testing body approached us on how to deal with multiple components attached via long-soldered wires. For the rest, they indicated that the method is clear and straightforward to use. They indicated that majority of the time required for assessing was creating the disassembly map [16], not using Table 3's lookup table of action times.

Figure 3 compares the DaRT method's times against the actual times to disassemble priority parts of a TV, vacuum cleaner, and washing machine. They showed an R^2 correlation of 0.98 with the observed times. The longer times (above 300s) are dominated by washing machine components while shorter time is a mix of washing machine, vacuum cleaner and TV components. Both shorter and longer time maintain a very high correlation, 0.99 and 0.96, respectively [10].

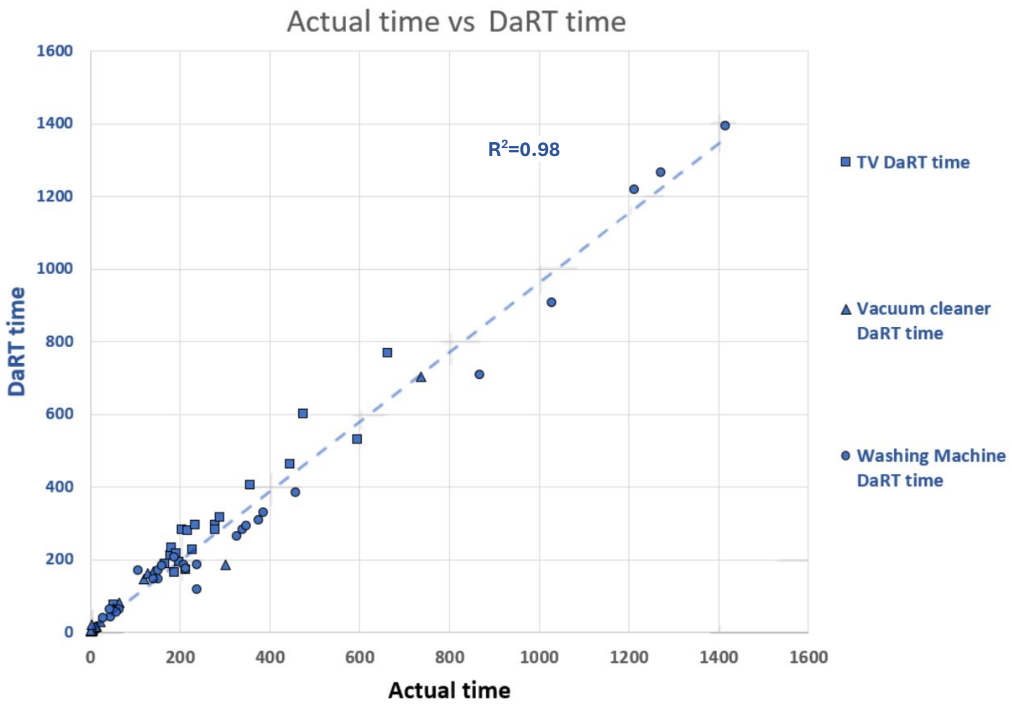

Figure 3: DaRT disassembly timings vs actual disassembly timings for priority parts of three appliances.

Comparison with eDiM

The DaRT proxy times were also compared with related eDiM proxy times. As presented in the last columns of Table 2, proxy times for most of the actions closely fit to the eDiM proxy times, even though eDiM has been developed for different types of ICT equipment. The agreement between eDiM timing and the median values used in DaRT is considered to be acceptable (within 30% delta). The eDiM values for similar actions usually deviate by less than 30% from the median values and are within the observed quartiles. The eDiM proxy times in general tend more towards the lower quartile values. Further, eDiM underestimates the timing for some actions compared to DaRT, such as "pry" (snap fit; <20 Newtons), "unscrew" (screwdriver; <15 turns), "unplug" (wires), and "overcoming low accessibility". Additionally, some actions were not described in eDiM. These include "detach/route (wires within product)", and "pry friction-fitting circumference" for adhesive removal.

3.5. Discussion

Based on our observations, there is no significant difference between disassembly and reassembly times for the majority of investigated actions. This is an important result as this is implicitly assumed in most of current repairability scoring systems [5], [22], but had not been shown unambiguously for a range of different products and actions. However, reassembly requires significantly more time for actions that necessitate precise positioning or alignment.

Furthermore, our results show that disassembly and reassembly can generally be considered similar and grouped for similar actions such as "position tool" and "unscrew". The model has been validated against actual disassembly times for a range of products, demonstrating a high degree of correlation. This substantiates its broad applicability and suggests a low likelihood of significant biases. Therefore, the groupings proposed in this study, based on a variety of different products, largely simplify the proxy times model and improve the ease of use [23], scalability [24], and broader applicability [25].

The grouping of actions, however, could introduce significant uncertainties and systematic biases [26], [27]. This is partly alleviated by the use of median values in timing models, which enhances robustness against uncertainties by minimizing the influence of outliers and symmetrically distributed errors [17]. Additionally, having large datasets as used in this research significantly reduces biases and uncertainties since standard error of parameter estimates decreases, allowing more precise and robust inferences. Furthermore, the influence of outliers, which can disproportionately affect smaller datasets, is diluted in larger datasets, ensuring that grouped summaries better reflect the central tendencies and true variability of the data [28], [29].

It should be realized that the width of timing distributions is not only due to coincidental variations, but also relates to real differences in product architecture. For instance, DaRT actions such as "pry/attach" and "loosen/attach" exhibit exceptionally broad distributions. This variability arises from the nature of these actions inherently involving a range of times, due to differing levels of force, precision, and architectural differences. These variations are difficult to assess and integrating them to a finer level would complicate the assessment and be counterproductive to the aim of the new model. In this scenario, the simplicity and ease of use of the model was chosen over potential higher accuracy. This also implies that for specific products that are uniquely simple or complex, the use of the DaRT values might lead to underestimation or overestimation of the required time. However, we consider the DaRT times a reasonable compromise between useability and accuracy.

Unique actions such as removing door seals from the washing machines are not directly covered by DaRT actions. To address such unique actions, a feature termed "complex/difficult action" might be introduced, allowing users to input the approximate time required for such action. While this action does not follow a similar approach as other DaRT actions, it allows mitigation of biases towards unique actions while maintaining the simplicity of the model. This correction term serves to make proxy time comparable to actual time, but within a product category the ranking will not be dependent on it.

The DaRT proxy times in general are somewhat higher than equivalent eDiM proxy times. This can be attributed to two primary reasons. First, eDiM was developed and tested with ICT equipment (mainly laptops and monitors), making it less comparable to larger appliances. Second, eDiM was derived from the timing of MOST (Maynard operation sequence technique) [30], which are standardized timings acquired from repeated motions (e.g., in assembly lines). In the context of repair, these motions are not fully repeated and additional correction term may be required to account for this, which might partly explain the larger DaRT values.

When comparing the ease of use and accuracy of DaRT with other disassembly assessment methods, such as counting the number of disassembly steps, the step method is anticipated to remain the easiest to use, as it considers only two primary parameters: tool changes and component removals. However, this simplicity comes at a significant cost to accuracy, as research indicates a low correlation between the number of steps and actual disassembly times [10]. The eDIM method, as previously discussed, is more complex, as it considers numerous tools, fasteners, and parameters, while offering accuracy comparable to the DaRT. The DaRT method, therefore, strikes a favorable balance between ease of use, versatility and accuracy.

For future work, establishing DaRT proxy times for a larger variety of product types beyond household appliances, for example furniture and cars, would be interesting. Furthermore, desoldering actions as well as reassembly timings for actions that did not have enough data could be populated with further research. Additionally, the use of power tools, which are becoming more common, could be incorporated into the model. These activities would provide a more complete model of the DaRT proxy times. Actions with exceptionally broad distributions in disassembly and reassembly timings such as loosening and prying, may require further exploration to understand how they behave with unique products. This would help determine if these actions should be categorized differently to improve accuracy, for example, based on force or newly defined actions.

3.6. Conclusion

The DaRT proxy time model has been established based on a large number of repair actions on a variety of domestic products. This model represents a significant step forward in assessing disassembly and reassembly times for household appliances, striking a favorable balance between accuracy and ease of use compared to existing methods like eDiM and step counting. By leveraging large datasets and simplifying the list of actions through grouping, the model achieves scalability and applicability to a broader range of products. Its validation against actual disassembly times shows its robustness, though it reveals limitations in handling uniquely complex products.

Overall, DaRT delivers a straightforward yet effective way to assess ease of disassembly, overcoming limitations of existing methods. Its accuracy and ease of use make it a powerful tool for building robust repairability scoring systems. These can drive change by influencing policymakers, designers, and manufacturers to create products that are easier to repair, supporting resource efficiency and sustainability goals central to the circular economy.

3.7. Acknowledgements

This work was funded by the European Commission under the Horizon 2020 Premature Obsolescence Multi stakeholder Product Testing Program (PROMPT) (Grant Agreement number 820331).

We would like to thank iFixit and RUSZ for their assistance in performing disassembly and timing actions, which were instrumental in the development of the DaRT model. We also extend our sincere thanks to VDE and BBM for their efforts in assessing products using the DaRT model, providing critical verification and validation of its application.

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3.9. Supplementary Material

3a. Comparison between Washing machine and vacuum cleaner actions

*Table 12: Actions comparing washing machine (WM) and Vacuum cleaner (VC). IQR = Inter quartile range. IQR median overlap is "TRUE "if the medians of VC and WM falls within P25 and P75 of each other. Difference VC vs WM % = ((Median WM-Median VC)/ ((Median VC+Median WM)/2)) *100.*

Phase	Action	N VC	Median VC	MAD VC	P25 VC	P75 VC	N WM	Median WM	MAD WM	P25 WM	P75 WM	Difference VC vs WM %	IQR median overlap
Disassembly	Remove (comp)	433	1.9	0.6	1.4	2.6	958	2.4	1.0	1.5	3.6	23	YES
Disassembly	Grab and position tool	135	2.4	0.6	1.9	3.0	452	3.2	1.0	2.4	4.5	29	NO
Disassembly	Loosen	184	2.5	1.1	1.7	4.2	395	3.6	1.7	2.2	6.7	36	YES
Disassembly	Open (hinge)	24	2.2	0.8	1.5	3.2	35	2.4	0.9	1.7	3.4	9	YES
Disassembly	Push	23	1.2	0.4	0.8	1.6	21	1.1	0.3	0.9	2.0	-9	YES
Disassembly	Pry	100	4.1	2.4	1.8	7.6	153	3.5	2.0	2.1	6.2	-16	YES
Disassembly	Put tool away	124	1.5	0.5	1.1	2.1	377	1.7	0.7	1.0	2.5	13	YES
Disassembly	Position tool	124	2.1	0.7	1.5	2.9	504	1.8	0.6	1.3	2.5	-15	YES
Disassembly	Unplug (wire)	49	2.9	1.5	2.1	5.4	183	3.0	1.2	2.0	4.3	3	YES
Disassembly	Unplug (hose)	28	1.2	0.5	0.8	2.0	95	3.4	1.6	2.0	5.1	96	NO
Disassembly	Unscrew	151	6.0	2.2	4.2	8.7	581	6.9	2.4	4.7	10.2	14	YES
Disassembly	Detach (wires)	23	3.8	1.7	2.4	6.4	71	4.1	1.7	3.3	6.9	8	YES
Reassembly	Turn product	70	2.7	0.6	2.0	3.3	107	4.0	1.1	2.9	5.2	39	NO
Reassembly	Close (hinge)	15	2.1	0.5	1.5	2.6	23	2.1	0.6	1.6	3.3	0	YES
Reassembly	Grab and position	453	4.1	1.7	2.8	7.4	794	5.2	2.8	2.9	9.7	24	YES
Reassembly	Position tool	91	6.6	2.8	4.1	10.1	435	5.3	2.8	3.0	9.3	-22	YES
Reassembly	Plug (wire)	52	4.6	1.4	3.4	6.3	203	4.1	1.5	2.8	6.1	-11	YES
Reassembly	Plug (hose)	19	3.4	1.2	2.8	5.1	68	6.6	2.7	4.8	10.9	64	NO
Reassembly	Screw	168	5.5	2.8	3.2	9.2	566	7.2	2.4	5.0	9.8	27	YES
Reassembly	Pry	27	5.3	3.4	2.1	13.7	125	5.2	2.9	2.7	8.3	-2	YES
Reassembly	Route (wires)	24	7.8	3.7	5.0	16.6	41	8.3	3.9	5.2	15.5	6	YES
Reassembly	Put tool aside	65	1.4	0.4	1.0	1.8	282	1.7	0.6	1.2	2.4	19	YES
Reassembly	Tool IP	111	2.2	0.8	1.6	3.4	386	1.7	0.5	1.2	2.4	-26	YES

3b. Tools

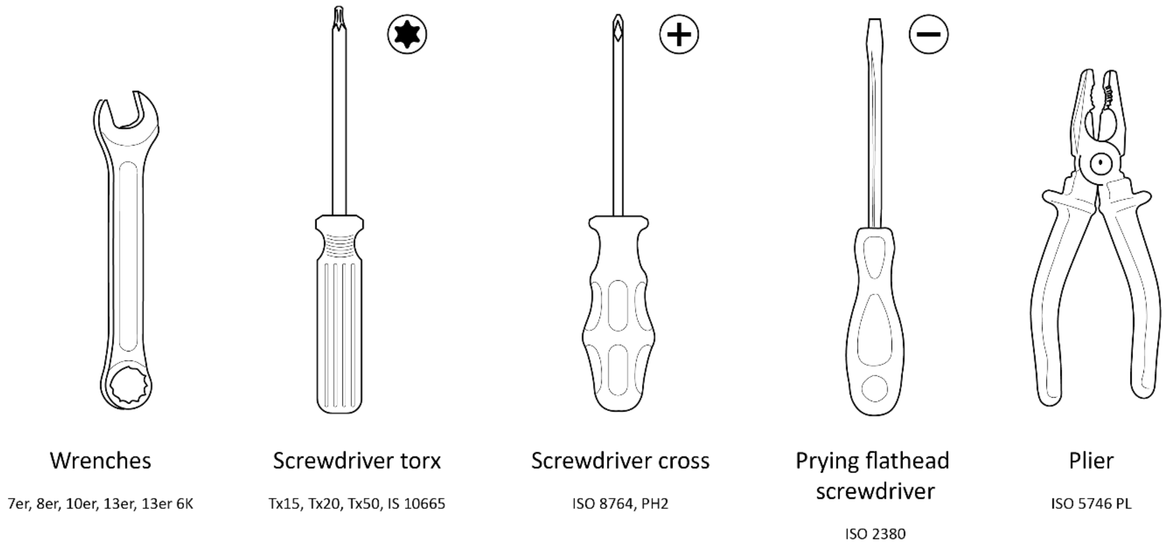

Figure 4: Tools.

3c Analyzed products

Table 5: Analyzed products.

Vacuum Cleaners			
Simens VSZRK212	AEG SH360L25	Dyson SV12	Grundig VCC5850
Simens VSQ8MSA332	Inventum STS725RC	Bosch BBS1U224	Rowenta RO7230EA
AEG VX9	Vorwerk VK200		
Washing Machines			
Samsun g WW7X M642O	LG FH4J3TDN0	LG 910PWAWL2808	Siemens WM6HXF90NL
Gorenje W2A744T	AEG L6FB64470	Siemen s WM14N270	BEKO WQY9736XSWBT
Miele WDB330 WPS	Bauknecht care 8418		
Smart TV			
Samsung UE55NU7179	Loewe Connect 48	LG OLED55B8LLA	Metz Fineo 49
Samsung GQ55Q80	HiSense H55B7100	Sony Bravia XG70	Philips US7393
Sony Bravia XG90	LG 49UM71	Samsung QE55	Philips S7502
Smartphones			
Apple iPhone 6s	Huawei Nexus 6P	Samsung Galaxy A5	HTC One M8
Apple iPhone 7	Huawei P9 Lite	Samsung Galaxy S7	HTC One M9
Apple iPhone 8+	Huawei P10	Samsung Galaxy J3 Duos	Nokia 6.1
Fairphone 2	Huawei Mate 20	Samsung Galaxy S8	Oppo R9s
Google Pixel 2	LG G5	Samsung Galaxy XCover Pro	Shift 6m

3d Statistical Analysis

Table 6: Mann Whitney U test comparing Disassembly action to Reassembly.

Action	U Statistic	p-Value	Disassembly N	Reassembly N	Disassembly Median	Reassembly Median	Median Difference %	Disassembly Mean	Reassembly Mean	Disassembly Std Dev	Reassembly Std Dev	Significance (0.05)
Screw/Unscrew (10er)	7704.00	0.61	138	116	12.00	11.78	-1.81	11.89	12.26	5.38	5.04	NO
Screw/Unscrew (13er)	4746.00	0.00	91	78	11.17	8.03	-28.06	12.32	9.20	5.52	5.33	YES
Screw/Unscrew (7er)	492.00	0.81	34	30	4.97	5.20	4.69	5.83	5.61	2.87	2.04	NO
Screw/Unscrew (8er)	796.00	0.04	44	28	14.72	8.12	-44.84	12.89	8.67	6.88	4.76	YES
Screw/Unscrew (ISO10664)	18696.50	0.38	203	194	6.27	6.38	1.88	6.87	7.53	3.09	4.16	NO
Screw/Unscrew (ISO8764)	29846.00	0.00	242	306	5.72	7.05	23.31	6.65	7.85	3.74	4.03	YES
Screw/Unscrew (PH2)	1362.00	0.56	50	51	7.80	6.87	-11.97	8.22	8.58	3.42	5.06	NO

Screw/Unscrew (Tx15)	1494.50	0.67	55	57	4.53	5.30	16.92	6.07	6.44	3.91	3.88	NO
Screw/Unscrew (Tx20)	4426.50	0.22	90	89	4.63	4.70	1.45	5.51	5.08	2.56	2.79	NO
Screw/Unscrew (H)	1397.50	0.77	53	51	5.80	5.87	1.14	7.37	6.25	5.09	2.93	NO
away (tool)	82417.00	0.22	501	346	1.63	1.63	0.01	1.79	1.86	0.99	0.98	NO
away/place (comp)	59778.00	0.00	737	649	2.40	7.67	219.46	2.86	10.40	1.78	9.79	YES
away/place (screw)	93562.50	0.00	558	659	1.87	3.30	76.75	2.21	4.01	1.33	2.90	YES
Unplug/Plug hose	2477.50	0.00	128	87	2.70	5.87	117.26	3.63	7.98	2.68	6.56	YES
Unplug/Plug	22426.00	0.00	230	259	3.40	4.27	25.50	4.04	5.44	2.69	4.87	YES
Unsnap/Snap	16801.50	0.02	258	152	4.42	5.37	21.50	6.49	7.99	6.90	7.70	YES
Loosen/Attach (H)	74850.00	0.00	460	468	3.32	5.43	63.82	4.90	8.12	5.44	8.60	YES
Loosen/Attach (Pl)	1222.00	0.00	81	45	3.30	6.66	101.73	6.74	7.55	7.86	5.22	YES
Thread/Unthread	1737.50	0.00	95	71	4.13	8.30	100.80	5.93	11.96	5.21	10.30	YES
Manupulate <100N	4280.00	0.23	79	98	3.43	3.18	-7.29	4.80	3.64	4.75	2.16	NO
open/close	498.00	0.11	49	16	2.27	1.77	-22.08	4.29	1.97	6.31	0.82	NO
Pry/Attach (Sp)	615.50	0.08	209	9	3.57	6.87	92.49	6.80	8.94	8.92	7.26	NO
pull/push	487.00	0.71	40	23	2.10	2.07	-1.57	3.26	5.24	2.90	9.79	NO
Tilt/Untlit (>150N)	398.00	0.01	28	20	6.05	3.92	-35.27	6.39	4.24	3.37	2.44	YES
Tool Grab & iP (Tx 15 (Sc))	73.50	0.86	14	10	2.58	2.62	1.36	3.34	3.42	1.82	1.74	NO
Tool Grab & iP (ISO5746 (PL))	1584.00	0.53	83	41	3.10	3.23	4.19	3.50	3.85	1.65	2.05	NO
Tool Grab & iP (Tx 20 (Sc))	369.00	0.94	27	27	2.40	2.60	8.33	2.67	2.78	0.82	1.33	NO
Tool Grab & iP (ISO8764 (Sc))	3105.00	0.00	92	90	3.29	3.95	20.24	3.41	4.45	1.46	2.91	YES
Tool Grab & iP (ISO8976 (PL))	51.50	0.66	13	9	4.50	5.50	22.22	5.13	5.04	2.80	1.88	NO
Tool Grab & iP (10er 6k (Sc))	1029.00	0.26	44	54	2.54	3.20	26.23	3.32	3.88	1.62	2.22	NO
Tool Grab & iP (13er 6K (Sc))	529.50	0.08	27	31	4.20	2.87	-31.67	3.87	3.25	1.52	1.66	NO
Tool Grab & iP (ISO10664 (Sc))	1236.00	0.19	66	44	3.00	3.28	9.52	3.41	3.97	1.83	2.27	NO
Tool Grab & iP (ISO5749 (C))	41.00	0.71	18	4	3.80	3.25	-14.47	3.89	3.56	1.28	1.13	NO
Tool Grab & iP (8er 6K (Sc))	72.00	0.24	10	11	2.92	2.30	-21.10	3.35	2.82	1.40	1.52	NO
Tool iP (Tx 15 (Sc))	254.00	0.53	19	24	3.07	2.55	-16.86	3.18	3.36	1.47	2.78	NO
Tool iP (Tx 20 (Sc))	793.00	0.43	42	42	1.52	1.77	16.41	1.70	1.99	0.62	1.26	NO

Tool iP (ISO5746 (PL))	169.00	0.22	34	13	1.75	2.50	42.82	2.02	2.75	0.88	1.52	NO
Tool iP (ISO8764 (Sc))	10244.50	0.57	144	148	1.83	1.90	3.60	2.07	2.28	0.96	1.47	NO
Tool iP (PH2 (Sc))	148.00	0.68	17	19	2.03	2.73	34.43	2.65	3.01	1.38	1.68	NO
Tool iP (10er 6k (Sc))	2515.50	0.08	79	54	1.87	1.27	-32.14	1.97	2.39	0.96	2.73	NO
Tool iP (13er 6K (Sc))	556.00	0.78	40	29	1.22	1.37	12.29	1.54	1.74	0.82	1.42	NO
Tool iP (ISO10664 (Sc))	6382.00	0.34	108	110	1.98	1.83	-7.54	2.14	2.10	1.11	1.19	NO

Table 7: Mann Whitney U tests among different pairs of actions within groups.

Phase	Group	Action 1	Action 2	N1	Median1	N2	Median2	U Statistic	P-Value	Significance
Disassembly	Group 1	Screw/Unscrew (10er)	Screw/Unscrew (13er)	138	12.0	91	11.2	6173.00	0.83	NO
Disassembly	Group 1	Screw/Unscrew (10er)	Screw/Unscrew (7er)	138	12.0	34	5.0	3920.00	0.00	YES
Disassembly	Group 1	Screw/Unscrew (10er)	Screw/Unscrew (8er)	138	12.0	44	14.7	2752.00	0.35	NO
Disassembly	Group 1	Screw/Unscrew (13er)	Screw/Unscrew (7er)	91	11.2	34	5.0	2714.00	0.00	YES
Disassembly	Group 1	Screw/Unscrew (13er)	Screw/Unscrew (8er)	91	11.2	44	14.7	1944.00	0.79	NO
Disassembly	Group 1	Screw/Unscrew (7er)	Screw/Unscrew (8er)	34	5.0	44	14.7	302.00	0.00	YES
Disassembly	Group 2	Screw/Unscrew (ISO10664)	Screw/Unscrew (ISO8764)	203	6.3	242	5.7	26813.00	0.10	NO
Disassembly	Group 2	Screw/Unscrew (ISO10664)	Screw/Unscrew (PH2)	203	6.3	50	7.8	3686.00	0.00	YES
Disassembly	Group 2	Screw/Unscrew (ISO10664)	Screw/Unscrew (Tx15)	203	6.3	55	4.5	7010.00	0.00	YES
Disassembly	Group 2	Screw/Unscrew (ISO10664)	Screw/Unscrew (Tx20)	203	6.3	90	4.6	11818.00	0.00	YES
Disassembly	Group 2	Screw/Unscrew (ISO10664)	Screw/Unscrew (H)	203	6.3	53	5.8	5865.50	0.31	NO
Disassembly	Group 2	Screw/Unscrew (ISO8764)	Screw/Unscrew (PH2)	242	5.7	50	7.8	4136.00	0.00	YES
Disassembly	Group 2	Screw/Unscrew (ISO8764)	Screw/Unscrew (Tx15)	242	5.7	55	4.5	7568.50	0.11	NO
Disassembly	Group 2	Screw/Unscrew (ISO8764)	Screw/Unscrew (Tx20)	242	5.7	90	4.6	12702.00	0.02	YES
Disassembly	Group 2	Screw/Unscrew (ISO8764)	Screw/Unscrew (H)	242	5.7	53	5.8	6391.50	0.97	NO
Disassembly	Group 2	Screw/Unscrew (PH2)	Screw/Unscrew (Tx15)	50	7.8	55	4.5	1982.00	0.00	YES
Disassembly	Group 2	Screw/Unscrew (PH2)	Screw/Unscrew (Tx20)	50	7.8	90	4.6	3463.00	0.00	YES

Disassembly	Group 2	Screw/Unscrew (PH2)	Screw/Unscrew (H)	50	7.8	53	5.8	1694.00	0.02	YES
Disassembly	Group 2	Screw/Unscrew (Tx15)	Screw/Unscrew (Tx20)	55	4.5	90	4.6	2430.50	0.86	NO
Disassembly	Group 2	Screw/Unscrew (Tx15)	Screw/Unscrew (H)	55	4.5	53	5.8	1257.00	0.22	NO
Disassembly	Group 2	Screw/Unscrew (Tx20)	Screw/Unscrew (H)	90	4.6	53	5.8	2024.00	0.13	NO
Disassembly	Group 3	Tool Grab & iP (10er 6k (Sc))	Tool Grab & iP (13er 6K (Sc))	44	2.5	27	4.2	469.50	0.14	NO
Disassembly	Group 3	Tool Grab & iP (10er 6k (Sc))	Tool Grab & iP (8er 6K (Sc))	44	2.5	10	2.9	201.00	0.68	NO
Disassembly	Group 3	Tool Grab & iP (13er 6K (Sc))	Tool Grab & iP (8er 6K (Sc))	27	4.2	10	2.9	163.00	0.35	NO
Disassembly	Group 4	Tool Grab & iP (Tx 15 (Sc))	Tool Grab & iP (Tx 20 (Sc))	14	2.6	27	2.4	234.50	0.22	NO
Disassembly	Group 4	Tool Grab & iP (Tx 15 (Sc))	Tool Grab & iP (ISO8764 (Sc))	14	2.6	92	3.3	584.50	0.58	NO
Disassembly	Group 4	Tool Grab & iP (Tx 15 (Sc))	Tool Grab & iP (ISO10664 (Sc))	14	2.6	66	3.0	444.50	0.83	NO
Disassembly	Group 4	Tool Grab & iP (Tx 20 (Sc))	Tool Grab & iP (ISO8764 (Sc))	27	2.4	92	3.3	852.50	0.01	YES
Disassembly	Group 4	Tool Grab & iP (Tx 20 (Sc))	Tool Grab & iP (ISO10664 (Sc))	27	2.4	66	3.0	671.50	0.06	NO
Disassembly	Group 4	Tool Grab & iP (ISO8764 (Sc))	Tool Grab & iP (ISO10664 (Sc))	92	3.3	66	3.0	3181.00	0.61	NO
Disassembly	Group 5	Tool iP (10er 6k (Sc))	Tool iP (13er 6K (Sc))	79	1.9	40	1.2	2014.00	0.01	YES
Disassembly	Group 6	Tool iP (PH2 (Sc))	Tool iP (Tx 15 (Sc))	17	2.0	19	3.1	113.00	0.13	NO
Disassembly	Group 6	Tool iP (PH2 (Sc))	Tool iP (Tx 20 (Sc))	17	2.0	42	1.5	522.00	0.01	YES
Disassembly	Group 6	Tool iP (PH2 (Sc))	Tool iP (ISO8764 (Sc))	17	2.0	144	1.8	1556.00	0.07	NO
Disassembly	Group 6	Tool iP (PH2 (Sc))	Tool iP (ISO10664 (Sc))	17	2.0	108	2.0	1121.00	0.14	NO
Disassembly	Group 6	Tool iP (Tx 15 (Sc))	Tool iP (Tx 20 (Sc))	19	3.1	42	1.5	663.00	0.00	YES
Disassembly	Group 6	Tool iP (Tx 15 (Sc))	Tool iP (ISO8764 (Sc))	19	3.1	144	1.8	2044.50	0.00	YES
Disassembly	Group 6	Tool iP (Tx 15 (Sc))	Tool iP (ISO10664 (Sc))	19	3.1	108	2.0	1496.00	0.00	YES
Disassembly	Group 6	Tool iP (Tx 20 (Sc))	Tool iP (ISO8764 (Sc))	42	1.5	144	1.8	2299.50	0.02	YES
Disassembly	Group 6	Tool iP (Tx 20 (Sc))	Tool iP (ISO10664 (Sc))	42	1.5	108	2.0	1708.50	0.02	YES

Disassembly	Group 6	Tool iP (ISO8764 (Sc))	Tool iP (ISO10664 (Sc))	144	1.8	108	2.0	7586.00	0.74	NO
Disassembly	Group 7	Tool Grab & iP (ISO5746 (PL))	Tool Grab & iP (ISO8976 (PL))	83	3.1	13	4.5	304.50	0.01	YES
Disassembly	Group 7	Tool Grab & iP (ISO5746 (PL))	Tool Grab & iP (ISO5749 (C))	83	3.1	18	3.8	561.00	0.10	NO
Disassembly	Group 7	Tool Grab & iP (ISO8976 (PL))	Tool Grab & iP (ISO5749 (C))	13	4.5	18	3.8	144.50	0.28	NO
Disassembly	Group 8	away (tool)	away/place (comp)	501	1.6	737	2.4	109811.50	0.00	YES
Disassembly	Group 8	away (tool)	away/place (screw)	501	1.6	558	1.9	115522.00	0.00	YES
Disassembly	Group 8	away/place (comp)	away/place (screw)	737	2.4	558	1.9	254091.00	0.00	YES
Disassembly	Group 9	Loosen/Attach (H)	Pry/Attach (Sp)	460	3.3	209	3.6	46148.50	0.41	NO
Disassembly	Group 9	Loosen/Attach (H)	Loosen/Attach (Pl)	460	3.3	81	3.3	17484.00	0.38	NO
Disassembly	Group 9	Pry/Attach (Sp)	Loosen/Attach (Pl)	209	3.6	81	3.3	8235.50	0.72	NO
Reassembly	Group 1	Screw/Unscrew (10er)	Screw/Unscrew (13er)	116	11.8	78	8.0	6213.50	0.00	YES
Reassembly	Group 1	Screw/Unscrew (10er)	Screw/Unscrew (7er)	116	11.8	30	5.2	3108.00	0.00	YES
Reassembly	Group 1	Screw/Unscrew (10er)	Screw/Unscrew (8er)	116	11.8	28	8.1	2346.00	0.00	YES
Reassembly	Group 1	Screw/Unscrew (13er)	Screw/Unscrew (7er)	78	8.0	30	5.2	1711.00	0.00	YES
Reassembly	Group 1	Screw/Unscrew (13er)	Screw/Unscrew (8er)	78	8.0	28	8.1	1095.00	0.99	NO
Reassembly	Group 1	Screw/Unscrew (7er)	Screw/Unscrew (8er)	30	5.2	28	8.1	208.00	0.00	YES
Reassembly	Group 2	Screw/Unscrew (ISO10664)	Screw/Unscrew (ISO8764)	194	6.4	306	7.0	27728.00	0.21	NO
Reassembly	Group 2	Screw/Unscrew (ISO10664)	Screw/Unscrew (PH2)	194	6.4	51	6.9	4395.00	0.22	NO
Reassembly	Group 2	Screw/Unscrew (ISO10664)	Screw/Unscrew (Tx15)	194	6.4	57	5.3	6626.50	0.02	YES
Reassembly	Group 2	Screw/Unscrew (ISO10664)	Screw/Unscrew (Tx20)	194	6.4	89	4.7	11762.50	0.00	YES
Reassembly	Group 2	Screw/Unscrew (ISO10664)	Screw/Unscrew (H)	194	6.4	51	5.9	5813.00	0.05	YES
Reassembly	Group 2	Screw/Unscrew (ISO8764)	Screw/Unscrew (PH2)	306	7.0	51	6.9	7348.00	0.51	NO
Reassembly	Group 2	Screw/Unscrew (ISO8764)	Screw/Unscrew (Tx15)	306	7.0	57	5.3	10893.50	0.00	NO
Reassembly	Group 2	Screw/Unscrew (ISO8764)	Screw/Unscrew (Tx20)	306	7.0	89	4.7	19423.50	0.00	YES
Reassembly	Group 2	Screw/Unscrew (ISO8764)	Screw/Unscrew (H)	306	7.0	51	5.9	9588.00	0.01	NO
Reassembly	Group 2	Screw/Unscrew (PH2)	Screw/Unscrew (Tx15)	51	6.9	57	5.3	1915.00	0.00	YES

Reassembly	Group 2	Screw/Unscrew (PH2)	Screw/Unscrew (Tx20)	51	6.9	89	4.7	3335.00	0.00	YES
Reassembly	Group 2	Screw/Unscrew (PH2)	Screw/Unscrew (H)	51	6.9	51	5.9	1649.00	0.02	YES
Reassembly	Group 2	Screw/Unscrew (Tx15)	Screw/Unscrew (Tx20)	57	5.3	89	4.7	3005.00	0.06	NO
Reassembly	Group 2	Screw/Unscrew (Tx15)	Screw/Unscrew (H)	57	5.3	51	5.9	1397.00	0.73	NO
Reassembly	Group 2	Screw/Unscrew (Tx20)	Screw/Unscrew (H)	89	4.7	51	5.9	1753.00	0.03	YES
Reassembly	Group 3	Tool Grab & iP (10er 6k (Sc))	Tool Grab & iP (13er 6K (Sc))	54	3.2	31	2.9	952.00	0.30	NO
Reassembly	Group 3	Tool Grab & iP (10er 6k (Sc))	Tool Grab & iP (8er 6K (Sc))	54	3.2	11	2.3	391.00	0.10	NO
Reassembly	Group 3	Tool Grab & iP (13er 6K (Sc))	Tool Grab & iP (8er 6K (Sc))	31	2.9	11	2.3	201.00	0.39	NO
Reassembly	Group 4	Tool Grab & iP (Tx 15 (Sc))	Tool Grab & iP (Tx 20 (Sc))	10	2.6	27	2.6	164.50	0.32	NO
Reassembly	Group 4	Tool Grab & iP (Tx 15 (Sc))	Tool Grab & iP (ISO8764 (Sc))	10	2.6	90	4.0	336.50	0.19	NO
Reassembly	Group 4	Tool Grab & iP (Tx 15 (Sc))	Tool Grab & iP (ISO10664 (Sc))	10	2.6	44	3.3	186.00	0.46	NO
Reassembly	Group 4	Tool Grab & iP (Tx 20 (Sc))	Tool Grab & iP (ISO8764 (Sc))	27	2.6	90	4.0	652.50	0.00	YES
Reassembly	Group 4	Tool Grab & iP (Tx 20 (Sc))	Tool Grab & iP (ISO10664 (Sc))	27	2.6	44	3.3	381.00	0.01	YES
Reassembly	Group 4	Tool Grab & iP (ISO8764 (Sc))	Tool Grab & iP (ISO10664 (Sc))	90	4.0	44	3.3	2244.50	0.21	NO
Reassembly	Group 5	Tool iP (10er 6k (Sc))	Tool iP (13er 6K (Sc))	54	1.3	29	1.4	801.00	0.87	NO
Reassembly	Group 6	Tool iP (PH2 (Sc))	Tool iP (Tx 15 (Sc))	19	2.7	24	2.6	229.00	0.99	NO
Reassembly	Group 6	Tool iP (PH2 (Sc))	Tool iP (Tx 20 (Sc))	19	2.7	42	1.8	541.00	0.03	YES
Reassembly	Group 6	Tool iP (PH2 (Sc))	Tool iP (ISO8764 (Sc))	19	2.7	148	1.9	1771.00	0.07	NO
Reassembly	Group 6	Tool iP (PH2 (Sc))	Tool iP (ISO10664 (Sc))	19	2.7	110	1.8	1376.50	0.03	YES
Reassembly	Group 6	Tool iP (Tx 15 (Sc))	Tool iP (Tx 20 (Sc))	24	2.6	42	1.8	711.00	0.01	YES
Reassembly	Group 6	Tool iP (Tx 15 (Sc))	Tool iP (ISO8764 (Sc))	24	2.6	148	1.9	2320.00	0.02	YES
Reassembly	Group 6	Tool iP (Tx 15 (Sc))	Tool iP (ISO10664 (Sc))	24	2.6	110	1.8	1791.00	0.01	YES
Reassembly	Group 6	Tool iP (Tx 20 (Sc))	Tool iP (ISO8764 (Sc))	42	1.8	148	1.9	2633.00	0.13	NO

Reassembly	Group 6	Tool iP (Tx 20 (Sc))	Tool iP (ISO10664 (Sc))	42	1.8	110	1.8	2154.00	0.52	NO
Reassembly	Group 6	Tool iP (ISO8764 (Sc))	Tool iP (ISO10664 (Sc))	148	1.9	110	1.8	8870.50	0.22	NO
Reassembly	Group 7	Tool Grab & iP (ISO5746 (PL))	Tool Grab & iP (ISO8976 (PL))	41	3.2	9	5.5	110.50	0.06	NO
Reassembly	Group 7	Tool Grab & iP (ISO5746 (PL))	Tool Grab & iP (ISO5749 (C))	41	3.2	4	3.3	76.00	0.83	NO
Reassembly	Group 7	Tool Grab & iP (ISO8976 (PL))	Tool Grab & iP (ISO5749 (C))	9	5.5	4	3.3	30.00	0.08	NO
Reassembly	Group 8	away (tool)	away/place (comp)	346	1.6	649	7.7	11748.00	0.00	YES
Reassembly	Group 8	away (tool)	away/place (screw)	346	1.6	659	3.3	42527.00	0.00	YES
Reassembly	Group 8	away/place (comp)	away/place (screw)	649	7.7	659	3.3	339992.00	0.00	YES
Reassembly	Group 9	Loosen/Attach (H)	Pry/Attach (Sp)	468	5.4	9	6.9	1746.50	0.38	NO
Reassembly	Group 9	Loosen/Attach (H)	Loosen/Attach (Pl)	468	5.4	45	6.7	9461.00	0.26	NO
Reassembly	Group 9	Pry/Attach (Sp)	Loosen/Attach (Pl)	9	6.9	45	6.7	228.00	0.56	NO

4.

Design aspects in repairability scoring systems:

comparing their objectivity and completeness

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4.1. Abstract

The Circular Economy Action Plan adopted by the European Commission aims to keep value in products as long as possible through developing product-specific requirements for durability and repairability. In this context, various scoring systems have been developed for scoring product repairability. This study assessed the objectivity and completeness of six major repair scoring systems, to see what further development may be required to make them policy instruments for testing product repairability. Completeness of the scoring systems was assessed by comparing them to the latest literature on what design features and principles drive product repairability. Objectivity was determined by assessing whether the scoring levels in each criterion were clearly defined with a quantifiable and operator-independent testing method. Results showed that most of the criteria in the scoring systems were acceptably objective and complete. However, improvements are recommended: the health and safety

criterion lacked objectivity and has not yet been fully addressed. Further research is required to expand the eDiM database, and to identify whether the additional accuracy provided by eDiM compared to disassembly step compensates for the increased difficulty in testing. Finally, assessment of reassembly and diagnosis should be expanded. Addressing these gaps will lead to the development of a scoring system that could be better used in policymaking, and for assessment by consumer organizations, market surveillance authorities, and other interested stakeholders, to promote the repairability of products.

4.2. Introduction

Consumer goods are nowadays less durable and repairable than in the past, and the average product lifetime of products seems to be decreasing [1]. This contributes towards an increase in waste electronic and electrical equipment (WEEE), which has been growing at the rate of 2–5% per year [2]. A report by the Organization for Economic Co-operation and Development (OECD) indicates that extending product lifetime could help solve this issue [3]. As a response, The Circular Economy Action Plan adopted by the European Commission sets out to keep value in products as long as possible through developing product-specific requirements for durability and repairability [4]. In this context, various scoring systems have been developed for scoring the repairability of electronic and electrical equipment (EEE) [5], [6], [7], [8], [9], [10]. Such scoring systems could also contribute to ongoing and future standardization to provide designers and market surveillance authorities (MSAs) with recommendations on improving the repairability of products. Additionally, this could empower consumers to make informed choices when buying their products.

A good scoring system should be objective and provide a complete assessment of the repairability of products [11]. The scoring system should be assessed on whether it reflects science-based literature on design aspects related to repairability. These elements are crucial for application in policymaking, and for assessment by consumer organizations, MSAs, and other interested stakeholders, to promote the repairability of products.

Bracquene et al. [12] compared three scoring systems: AsMeR (Assessment Matrix for ease of Repair) [6], ONR:192012 (Label of Excellence for Durable, Repair Friendly, Designed Electrical and Electronic Appliances) [7], and iFixit 2018 [9] for vacuum cleaners. Following this, they also provided a comparison of AsMeR and RSS (Joint Research Centre Repair Scoring System) [5] for washing machines [13]. However, this research does not assess the completeness of these scoring systems. Furthermore, the following recent scoring systems have not been assessed: iFixit 2019 (smartphone repairability scoring system) [8], FRI (French Repairability Index) [14], and EN45554 (general methods for the assessment of the ability to repair, reuse and upgrade energy-related products) [15].

This paper fills the gaps by answering the following questions: First, how do the current scoring systems reflect science-based literature on design aspects related to repairability? Second, how objective are the current scoring systems? By answering these research questions, this study aims to provide insights and opportunities for improvements in repairability scoring systems in general.

This research was conducted in two steps: firstly, research of literature was conducted to identify what design features and principles influence the repairability of the products. This was carried out to determine what design elements should be captured by the repairability scoring system. Afterwards, those design features and principles taken from the literature were compared with six chosen scoring systems and standards: Assessment Matrix for ease of Repair (AsMeR) [12]; Joint Research Centre Repair Scoring System (RSS) [5]; iFixit 2019 (smartphone repairability scoring system) [8]; General methods for the assessment of the ability to repair, reuse and upgrade energy-related products (EN 45554) [15]; Label of Excellence for Durable, Repair-Friendly, Designed Electrical and Electronic Appliances (ONR:192012) [7]; and French Repairability Index (FRI) [14]. This comparison assessed the completeness of the scoring systems. Secondly, this study assessed the objectivity of the scoring systems by analyzing and comparing the scoring methods of the different scoring systems.

Scoring Systems for Repairability

Several repairability assessment systems are currently available. Six scoring systems were chosen for this study based on the following criteria:

- The criteria for these scoring systems are publicly available in the English language.
- The evaluation method used is quantitative or at least semi-quantitative in nature, to provide a more objective assessment and enable ranked comparisons of products.
- It must be the latest iteration or version of the assessment system from the organization/group.

Table 1 provides an overview of the chosen six scoring systems. These criteria were expected to overlap, firstly because they all measure the repairability of electrical and electronic equipment (EEE), but also because newer scoring systems tend to have been developed after consideration and study of previous scoring systems.

Table 1: Overview of the chosen six scoring systems ("VC" = Vacuum cleaner, "WM" = washing machine, "DW" = Dishwasher).

Scoring system	Mainly based on	Products that can be tested	Details
EN 45554 (2020)	• Literature research on product repairability. • Co-construction by professional organizations, manufacturers, distributors, repairers, NGOs, and experts.	All EEE	The general method of assessment for repair, reuse, and upgrade. Provides a generic set of tools and is not tailored to specific products. Intended for both professional repairers and self-repairers.
FRI (2020)	• Literature research on product repairability. • Co-construction by professional organizations, manufacturers, distributors, repairers, NGOs, start-ups, and experts.	Washing machines, TVs, Laptops, Smartphones, Lawnmowers,	Based on five criteria: documentation, disassembly, spare part availability, spare part price, and additional product-based criteria. Intended for both professional repairers and self-repairers.
iFixit (2019)	• Literature research on product repairability. • Co-construction by iFixit experts, and sustainability (SMART) consortium.	Mobile phones	Eight criteria focused on assessing ease of self-repair.
RSS (2019)	• Literature research following preliminary EN45554 and AsMer2018. • Co-construction by industry, trade associations, repairers, academia). • Case studies.	VCs, laptops, TVs, mobile phones, WMs, DWs	Assessment of repairability, reusability, and upgradability. Intended for professional repairers.
AsMer (2018)	• Literature research on product repairability. • Case studies.	All EEE	Based on five main repair steps: product identification, failure diagnostic, disassembly and reassembly, spare part replacement, and restoring to working condition. Three different repairability criteria: information provision, product design, and service. Intended for professional repairers and self-repairers.
ONR 192102 (2014)	• Co-construction by repairers and the Federal Ministry of Land, Forestry, Environment, and Water.	Brown goods and white goods	Assessment of both durability and repairability. Criteria are related to product design, provision of information and services. Intended for professional repairer.

4.3. Method

Assessing Completeness of the Scoring Systems

From December 2020 to February 2021, a review of the literature was conducted to identify design principles, features, and guidelines related to the repairability of household electronic and electrical equipment. Relevant scientific literature related to design aspects of repairability was identified via the Google Scholar search engine and SCOPUS citation database.

Search terms were “design”, “features”, “principles”, and “guidelines”. These were followed by “repair OR maintain”. Additionally, the search term focused on the following product categories: “appliance”, “household products”, “EEE”, “white goods”, “brown goods”, “electrical and electronic equipment”, “mobile phones”, “vacuum cleaner”, “laptop”. This was an iterative process where different combinations of the provided terms were used. Wildcards were used to ensure wide coverage, and a proximity criterion of within 5 was used to narrow down the relevant results with co-occurring search terms (see Figure 1). The search was conducted within titles, abstracts, and keywords, in papers published from 2000 to 2021. The search was also focused on the following subject areas: engineering, material science, environmental science, industrial design, and design.

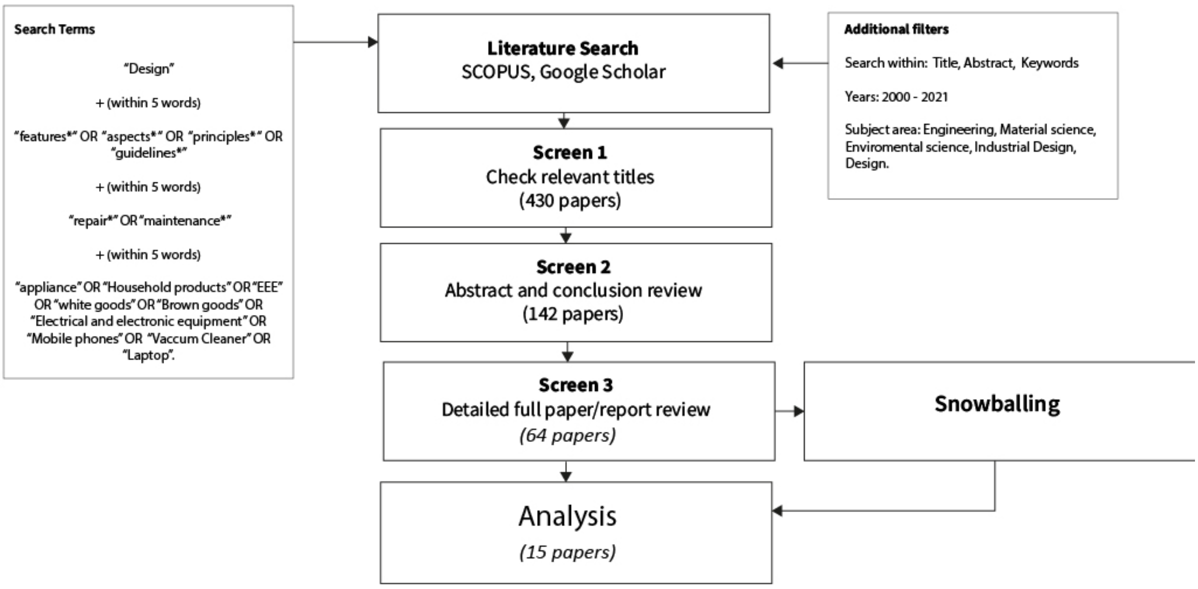

Figure 1: Overview of the search process followed.

This review focused on aspects related to the physical design of the product. These included design features, principles, and guidelines related to the repairability of household electronic and electrical equipment. Articles beyond the aforementioned scope were excluded. These included elements related to automotive products and textiles, and also user and market aspects related to repairability (such as spare part prices and availability). The results were screened for their relevancy firstly by checking headings, then by reviewing the abstract and conclusion. A full review of the paper was then conducted, and relevant articles selected. Additional papers were identified via snowballing using the reference list of a paper or its citations to identify additional articles [16].

During the analysis phase, each chosen paper was read, and sections marked wherever design-related aspects related to repairability were mentioned. The design aspects were considered relevant only if the addressed repairability aspects were an outcome of an empirical study.

Two studies have been conducted previously on design guidelines and principles related to repairability: The paper by Boeva et al. [17] provides nine relevant recommendations related to repairability originating from 34 different sources. Similarly, Den Hollander provides 16 design principles related to the repairability of products originating from six different pieces of literature published before 2016. To avoid multiple references, the literature already addressed by Boeva et al. [17] and Den Hollander [18] was not considered in our study.

Results of our analysis were clustered into design features and principles empirically shown in the literature to improve repairability and to enable a comparison with the criteria measured by the different scoring systems. The completeness of the scoring system was determined by checking whether the identified design elements were reflected in the scoring system.

Assessing Objectivity of the Scoring Systems

Objectivity is important for the repeatability of scores. To assess objectivity, the criteria presented in the different scorings systems were clustered within the identified design features and principles (see Table 2). Afterwards, each criterion and its testing method were categorized into three levels: objective, semi-objective, and subjective, based on the following criteria:

- Objective: Each level score that can be achieved is clearly defined, the testing action to achieve the score can be quantified and is operator-independent.
- Semi-objective: Whilst the testing action can be quantified, no clear indication is given on how each level of the score is achieved, causing a degree of operator dependence.
- Subjective: One or more testing actions cannot be quantified objectively; the result is operator-dependent.

Table 2: Overview of design features and principles empirically shown to drive repairability, and their descriptions in the literature.

Design features and principles	Definition and how it relates to repair
Disassembly	The product is taken apart so that it can subsequently be reassembled and made operational [19]. Required to access components for most repairs [20].
Reassembly	Assembling a product to its original configuration after disassembly [21]. Required to return a product to operation.
Fastener removability and reusability	Facilitation of removability of fasteners while ensuring that there is no impairment of the parts [or product] due to the process. Required for disassembly and ease of reassembly.
Fastener visibility	Whether more than 0.5 mm^2 of the fastener surface area is visible when looking at fastening direction [20], and visual cues [8]. Facilitates product disassembly.
Tools required	Number and type of tools necessary for repair of the product [15].
Modularity	The product design is composed of different modules. A module can consist of one or more components. Modules can be separated from the rest of the product as self-contained, semi-autonomous chunks; and they can be recombined with other components [22]. Modularity improves diagnosis [23], product disassembly, [24] and spare part price. The degree of modularity needs to be balanced—bundling into bigger modules decreases disassembly time but makes spare parts expensive, and vice versa.
Diagnosis	Process of isolating the reason for product failure. Diagnosis is facilitated by designed signals (text, light, sound, or movement) [23]. Even without these features, visible surfaces and component accessibility for inspection can also promote failure isolation [25].
Health and safety	Health and safety risks to the user during and after repair. Features minimizing safety risks also increasing confidence in product disassembly and reassembly [26].

Standard parts and interface	Enforcing “the conformance of commonly used parts and assemblies to generally accepted design standards for configuration, dimensional tolerances, performance ratings, and other functional design attributes” [27]. Standardization beneficially affects spare part cost and availability, tooling, component identification complexity, and skill levels required, and increases the interchangeability of components during maintenance and repair [28].
Information accessibility	Information available to the product user and repairers. Whilst this is not directly a design element, manuals and labels are provided with the product. Guides repair process [23], [25], [29], [30], [31].
Design simplicity/complexity	A minimal number of disassembly steps and/or disassembly time [24], and simplicity in understanding the interface and malfunction feedback to assist failure diagnosis [25].
Adaptability/ upgradability	Adaptability allows performance of the designed functions in a changing environment. Upgrading enhances the functionality of a product [18]. Software-related issues in the product can sometimes be repaired through updates.
Ease of handling	Features such as small size, low center of gravity and the presence of handles all promote ease of product handling [17], [18]. Facilitates disassembly process during product manipulation.
Interchangeability	Assuring components can be replaced in the field with no reworking required to achieve a physical fit. Allows for component testing [23], [25] and facilitates component replacement.
Robustness	Selecting designs that are robust. Assures products do not break during repair [8]; increases confidence during disassembly [25].
Redundancy	Providing an excess of functionality and/or material in products or parts. Allows removal of material as part of a recovery intervention [42]. Functional redundancy assists fault location and isolation [23].
Firmware reset	Software and the electronics-related issues can be fixed via reset [47] Reset functions facilitate cause-oriented diagnosis [23]

4.4. Results and Discussion

This section first shows how well each analyzed scoring system captures the design elements that have been empirically shown in the literature to drive repairability. It then assesses the completeness and objectivity of each scoring system, as well as highlighting differences between them.

Considering both the literature and different scoring systems, a total of 17 different design elements were identified that are considered important for repairability in EEE. Table 2 provides the list of design elements, and their descriptions based on the literature. Table 3 provides an overview of scoring systems compared to the literature. In general, all criteria in the scoring system seem to be reflected in the literature.

Table 3: Overview of scoring systems compared to the literature [17], [18], [23], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40]. Red rows = missing or partially addressed design elements in the scoring system. Hollow bullet points = partially addressed aspects. Numbers in the column of Bovea et al. (2018), and Den Hollander et al. (2018) = the number of papers they list relating to each design principle.

Design aspect related to repairability	Scoring system						Literature														
	EN 45554	RSS(JRC)	AsMer (Benelux)	ONR 192102	FRI	iFixit 2018	Bovea et al., 2018	Den Hollander, 2018	Shahbazi et al., 2020	Techhio et al., 2019	Pozo Arcos et al., 2019	Victoria et al., 2017	Deloitte, 2016	Sabaghi et al., 2017	Dewberry et al., 2016	I-Fixit 2019	Filpsen et al., 2016	Jaeger et al., 2020	Ackermann et al., 2018	Vanegas et al.,2018	Laitala et. Al 2021
Disassembly	•	•	•	•	•	•	24	6	•	•	•	•	•	•	•	•	•			•	
Reassembly	•	•	•					6									•				
Fastener removability and Reusability	•	•		•	•		16		•	•						•	•	•		•	
Fastener Visibility	•					•	11													•	
Tools Required	•	•	•	•	•	•	3		•	•				•	•	•	•			•	
Modularity			•	•			13	5	•		•					•					
Diagnosis	○	○	○				1	3	•	•	•	•					•	•			
Health and safety risk (design)		○		○		○					•			•							
Standard parts and interface	•	•	•	•				4	•												
Repair Information to user	•	•	•	•	•	•			•		•	•	•	•	•	•			•		•
Updatebility / Adaptability	•	•		•			28	2								•					
Design simplicity/ Complexity				•			29	1		•				•	•						•
Handling							7	1													
Interchangeability								2	•		•										
Material selection/ Robustness								1	•								•				
Redundancy								2													
Firmware Reset	•	•	•	•	•						•										

Table 3 shows that seven out of eighteen aspects related to repairability from the literature were well reflected in most (more than three) of the scoring systems. These include disassembly, fastener type, tools required, Information content, standardized parts and interface, and firmware reset. In contrast, seven aspects (colored in red) were not addressed or partially addressed. This is described below.

Aspects not addressed or only partially addressed by the scoring system.

Four aspects were not addressed directly by any of the scoring systems: "ease of handling", "interchangeability", "redundancy", and "material selection". These may be missing from the scoring system because, as the table shows, there is much less literature on them than other aspects of repair. Similarly, “diagnosis” and “health and safety risk” are only partially addressed. However, they may still be sufficiently important to include in the scoring.

The first aspect not addressed in the scoring system is “ease of handling”. Features such as small size, low center of gravity and handles make product manipulation (flipping, tilting, etc.) easier during disassembly and make it easier to take the product for repair. However, the absence of these features does not seem to severely alter the repairability of the product.

The second aspect not addressed by the scoring system is “interchangeability”. Interchangeability allows for component testing [23] as well as facilitating the removal and replacement of the component. Additionally, interchangeability allows for part replacement with third-party spare parts. Interchangeability of components could also enable extracted components from old products to be used for repair; however, minimal data are available on how often this repair scenario occurs in the EU. Further investigation may be required to determine the extent of component extraction from old products, and to what extent third-party spare parts are used for repair within the EU. This could be achieved by surveying and observing repairers and their repair process.

The third aspect not addressed is “robustness”. This principle ensures that handling and disassembling actions during repair do not break or damage the product [36]. It also increases confidence during disassembly [25]. The majority of the scoring systems (4/6) indicate that if breakage occurs during the disassembly process, the fastener for the part being disassembled is considered “non-removable”, and this “fastener removability and reusability” criterion is partially addressed by that of “material selection”/ “robustness”. However, testing the robustness of the product is normally carried out through complex simulations, destructive stress tests and accelerated life tests [41], all requiring significant resources. This most likely outweighs the benefit of having this criterion in the repairability scoring system. Further research may be needed to determine if an easier testing method could be developed to test for material selection/robustness of products. One method to achieve this is by checking products for features which influence robustness (e.g., a curved screen is generally more prone to breakage than a flat screen). These features can be extracted from a database of failed products. This is currently under investigation and will be published in an upcoming paper under the EU Horizon PROMPT project. However, initial research shows that product failure can be caused by multiple design principles, and it is difficult to reliably assess the robustness of products by considering design features alone.

Similarly, the literature is unclear on the extent to which redundancy in a product promotes repair. “Redundancy” relates to providing an excess of functionality and/or material in products or parts that allow for normal wear or removal of material as part of a recovery intervention [42]. This principle was found to help users locate and isolate faults [23], [25]. However, this redundancy normally increases the material requirements and cost of the product. Therefore, this design feature may not justify the additional cost and materials needed for manufacture.

One of the two partially addressed aspects is “diagnosis”. For most of the scoring systems (4/6), the ability of the products to sense faults and alert the user via a display or error codes is regarded as diagnosis, and a criterion for it is developed accordingly. However, according to Arcos et al. [25], various other design features also play a role in ease of diagnosis for users (such as transparent housing and having easily accessible testing points). This parameter in the scoring systems could be developed by incorporating the results from Arcos et al. [25].

Additionally, ONR 192102 consists of "low-level function when faulty" and "operation after removal of the cover" as criteria for diagnosis; these two features have not been addressed by any other scoring system and could be an interesting feature to be incorporated towards assessment of diagnosis.

The other incompletely addressed aspect is health and safety risk. Safety concerns include the safety of the person performing the repair, the safety of using the product after repair, and safety related to damaging the product during or after the repair. Aspects of safety during repair have been addressed by the majority of scoring systems (En 45554, RSS, ONR192102, iFixit), but safety after a repair has not been addressed by any of them. Safety after repair is important if a product that has been incorrectly repaired becomes dangerous when operated (e.g., an incorrectly reattached lawnmower blade might fly out at high speed). There is only limited literature on product and user safety during and after repair of EEE. The public report of Inegmardotter et al. [43] indicates that most repair actions are safe to perform and others could be made safe through relatively small design changes. However, repair safety has been identified as one of the barriers to pushing forward product repair from political and company perspectives [44]. Therefore, to overcome this barrier, it is crucial that health and safety aspects are fully and transparently addressed in a repairability scoring system.

Interdependencies between design elements

Several interdependencies were observed between the design elements: fastener type, tools required, fastener visibility, reassembly, modularity, interchangeability, material robustness, design simplicity, information availability, and handling. These elements have all been identified as influencing the overall ease of disassembly of the product [8], [18], [20], [21], [36]. Additionally, diagnosis related to physical design seems to be influenced by the aspects of interchangeability, modularity, disassembly, design simplicity/complexity, robustness, and information availability [23], [25].

These interdependencies between different design elements might lead to double counting in scores and may also indicate that not all the identified design elements need to be scored to provide a useful assessment of repairability. An assessment addressing the relation between the related disassembly and repairability elements can be observed in the Ease of disassembly Metric (eDiM) [20]. eDiM already addresses the following elements: disassembly, reassembly, tool type and fastener visibility. If a scoring system (such as AsMer) already uses eDiM, then these aspects are implicitly covered and may not need a separate scoring criterion. In essence, a scoring system might be simplified by eliminating some metrics without losing important information. Simplifying a scorecard could ease its application since it simplifies implementation and testing by manufacturers and surveillance authorities [20].

Comparing Scoring Systems

Table 4 shows how well the scoring system reflects design principles and features identified in the literature. Additionally, this table shows how scores are determined and assesses their objectivity. All the criteria from the French repairability index were identified as objective. However, it was the least complete of the scoring systems and lacks criteria that currently are more qualitative (such as diagnosis and safety aspects). RSS was the most complete scoring system, covering 11 criteria, out of which 6 were objective. The scorecard with the least objectivity was ONR 192102, specifically because most of the criteria could be scored out of 5 or 10 but no specific instruction was provided on how each increment should be assessed.

Table 4: Scorecard analysis for criteria on diagnosis and component accessibility. Green cells = objective, yellow cells = semi-objective, and red cells = subjective. "Dis." = Disassembly, "Rea." = Reassembly, "Mfr." = Manufacturer, "c." = check, "#" = number of.

Design Elements		Scoring System						Testing method details
		EN 45554	RSS (JRC)	AsMer (Benelux)	ONR 192102	FRI	iFixit	
Disassembly	Test	Dis. time or # steps	Dis. time or # steps	Dis. time	Dis. possibility	Dis. # steps	Dis. time, Path	• Dis. required • "Possibility" = Possibility of full Dis. • * = c. with reference value • cont.: Continuous levels
	scoring levels	levels not determined. Dis. step or time (EdiM)*	4 levels of Dis. step / time (EdiM)	4 levels of Dis. step / time (EdiM)	10 levels for possibility of Dis. 5 levels of Dis. Effort	4 levels of Dis. Step	Continuous Dis. time, Path of entry*	
Reassembly	Test	Rea. time	Rea. time, c. info	Rea. time	------	------	------	• Dis. & Rea. required • " c. info" = check Information on Rea. • * = check with reference value
	scoring levels	Rea. time (EdiM)*	2: Description of Rea., Reass. time (EdiM)*	4: Rea. time (EdiM)*	N/A	N/A	N/A	
Modularity	Test	------	------	Dis. Ability	Dis. Ability	------	------	• Dis. & c. disassembly & possibility for critical components to be reducible
	scoring levels	N/A	N/A	3: 50% replaceable, 75% replaceable, all replaceable	10: all reducible to individual components	N/A	N/A	
Fastener Type	Test	Dis. & c. type	Dis. & c. type	------	Dis. & c. type	Dis. & c. type	------	• Disassemble & check fastener type * = (reusable > removable > non removable)
	scoring levels	3*	3*	------	10: Non removable	3*	N/A	
Fastener Visibility	Test	Dis. c. visibility	------	------	------	------	Dis & c. visibility	• check fastener visibility during • Dis: Dis. required
	scoring levels	3: Visible, not visible > hidden	N/A	N/A	N/A	N/A	3: highlighted, visible, not visible	
Tools Required	Test	Dis. & c. tools	Dis. & c. tools	Dis. & c. tools	Dis. & c. tools	Dis. & c. tools	Dis. & c. tools	• check tools needed during Dis. • dis: Dis. required • "prop." = proprietary
	scoring levels	4: No or basic, product specific, commercially available, prop., not removable	3: Basic, product specific, prop.	3: Basic, product specific, prop.	5: Intuitive device operation	4: Basic or supplied, product specific, prop., not removable	4: basic, product specific, prop., requires heat gun	
Diagnosis	Test	cause f. & c. interface operability, c. interface, c. available documents.	cause f. & c. interface operability, c. interface, c. available documents.	cause f. & c. interface operability, c. interface,	cause f. & c. interface operability	------	------	• "f." = fault • documents availability could be manual, official website or through service center call.
	scoring levels	4: Intuitive, coded, additional software/Hardware & prop.)	4: Intuitive, coded, additional software/Hardware & prop.)	4: Intuitive interface, coded, additional software/Hardware & prop.)	10: display & test mode, 10: low level operation, operation after cover removal	------	N/A	
Health & Safety risk during repair (design)	Test	------	c. mfr. instructions	------	Dis. & c. features	------	Dis. & c. features	Instructions could be included via, manual, official website or by service center call.
	scoring levels	N/A	1: Instruction from mfr.	N/A	5: Protection in control processors, 4: danger warning signs, 5: warnings on sensitive components .	N/A	8: Battery case type, adhesive use & type. Requirement of heating & sharp tools	

Working Environment (safety)	**Test**	c. mfr. Instruction	c. mfr. Instruction	------	------	------	------	check Instruction from mfr. for work environment required for repair (via, manual, official website or through service center call.)
	scoring levels	3: any condition, workshop, production environment	3: any condition, workshop, production environment	N/A	N/A	N/A	N/A	
Skill Required (safety)	**Test**	c. mfr. Instruction	c. mfr. Instruction	------	------	------	------	check Instruction from mfr. for skill required for repair (via, manual, official website or by service center call.)
	scoring levels	4: Layman, Generalist, Expert, mfr., Not feasible	3: Layman, Expert, mfr.	N/A	N/A	N/A	N/A	
Information media	**Test**	------	------	c. info media	c. info media		c. info media	check information media as listed on the criteria.
	scoring levels	N/A	N/A	4: Attached to product, manual, website, not available	4: Attached to product, Manual, website, toll free contact support, local fee contact support	N/A	3: Attached to product, video, on website	
Information Content	**Test**	c. mfr. Instructions, c. media	mfr., c. media	mfr., c. media	mfr., c. media	mfr.	c. media	• check actual availability in different media • check manufacturers declaration
	scoring levels	9: c. presence (Table 5)	9: c. presence (Table 5)	9: c. presence (Table 5)	13: c. presence (Table 5)	13: c. presence (Table 5)	5: c. presence (Table 5)	
std. parts & interface	**Test**	c. mfr. Info.	c. mfr. Info.	c. mfr. Info.	dis. c. type	------	------	• check manufacturer Information • "std."= standardized • "prop." = proprietary
	scoring levels	3: std. part & interface, prop. part with std. interface, prop. part with non-std. interface	2: non-prop. & Has a std. interface, prop. or lacks std.	3 (all parts std., few parts std., no std.	2: std. interface, non std. interface	N/A	N/A	
Reset (firmware & Card)	**Test**	c. Possibility	c. possibility, c. information	c. information	c. possibility, c. information	c. instruction	------	• c. possibility to reset by trying to reset the product • c. information & instruction on firmware reset
	scoring levels	4: Integrated, external, service, not possible	4: Integrated, external, service, not possible	1: Possibility to reset	1: Possibility to reset	1: Possibility to rest	N/A	
Design Simplicity	**Test**	------	------	------	operate. c.	------	------	operate: operate the device & c. intuitiveness.
	scoring levels	N/A	N/A	N/A	intuitive device operation (5)	N/A	N/A	

Two criteria (diagnosis, and health and safety) were semi-objective across the majority of the scoring systems. Firstly, for diagnosis, the term "intuitive interface" in EN 45554, RSS, and AsMer needs further clarification to provide better objectivity. In terms of safety, the iFixit score is clear and objective, indicating specific tools (e.g., wire cutter and knife) and features (open pouch battery) that relate to safety risks. However, the RSS system is more subjective; it refers to the low voltage directive (2006/95/EC) and machinery directive (2006/42/EC) saying "machinery must be designed and constructed in such a way as to allow access in safety to all areas where intervention is necessary during operation, adjustment and maintenance of the machinery, and other safety information needed." Similarly, concerning safety, EN45554 and RSS indicate whether a process can or cannot be carried out in specific environments (home use, workshop, production) and whether specific skills (layman, generalist, expert, manufacturer) are required to carry out the repair process. However, details on what aspects are measured to determine the suitability of repair environments and also the skills required are lacking and are susceptible to subjectivity. Ingemarsdotter et al., [43] provide a risk assessment framework that could be applied to analyze the safety risk of household products. This framework is built on Failure Mode Effect Analysis (a widely applied method for failure analysis of products), and Rapid Exchange of Information System (a commonly agreed framework for risk assessment of consumer products). This framework could be further developed and implemented to assess the risk to safety objectively during and after the repair.

The majority of these scoring systems (RSS, ASMER, FRI, iFixit) have to be calibrated with a reference value to work effectively. This reference value is normally calibrated through scoring a range of products (cheap-to-expensive, and variation in designs) from a specific product category, and determining an average, a minimum, and a maximum threshold [45]. However, the number and range of products required for this calibration, and how often calibration should be carried out, are both still unclear and there is an opportunity to further research and establish a standard protocol to identify this reference value.

For ease of disassembly, most of the scoring systems (5/6) either measure time or the number of disassembly steps, and each method has both benefits and drawbacks. Disassembly time is subjective, depending on who is disassembling the product [20]. A more objective measurement is to record disassembly action based on Maynard Operation Sequence Techniques (MOST), where time represents the performance of an average skilled operator, under standard conditions at a normal pace [46]. This lets us create a proxy time as was carried out in Ease of Disassembly Metric (eDiM) [21]. This method is recognized as more representative of the ease of disassembly of the product than the number of disassembly steps. Furthermore, when assessing ease of disassembly, there is a significant difference between eDiM times and disassembly step counts [13], and eDiM captures the diversity of product designs better than the disassembly step counts. However, fully implementing eDiM would require a disassembly time database of all possible disassembly actions. Currently, the database is limited to ICT products, and the process of calculating eDiM is more labor-intensive than counting disassembly steps. Providing better representation of ease of disassembly might be important for a scoring system that places a high weight on disassembly, as well as for consumer organizations, manufacturers, designers, and MSAs that would like to assess the ease of product disassembly. Therefore, further research is required on eDiM to expand, simplify, and determine the balance between accuracy and ease of testing.

The iFixit scoring system also has another disassembly criteria called the “path of entry”, which describes the ease of disassembly to the point where critical components are visible [8]. This combines the criteria of disassembly time and tools required to disassemble until the critical components are visible and, therefore, seems to have a similar testing method as ease of disassembly. Although iFixit already has a separate criterion related to disassembly time and tools, the path of entry assesses tools required and disassembly until the point where all the critical components are visible. Furthermore, criteria related to the path of entry are reflected in the report of iFixit market observations [35], which describes how an easy path of entry builds confidence in users self-repairing their products. Additionally, these criteria also help in diagnosis since viewing the critical component could be required by users during the diagnosis process [23], [25]. Therefore, “path of entry” is a good addition to the disassembly criteria for a scoring system assessing self-repair.

An aspect of reassembly, "fastener removability and reusability" was addressed by most of the scoring systems. However, only two out of six scoring systems considered reassembly time in their criteria (EN 45554 and the AsMer scoring system indicate checking the reassembly time using the EDIM). However, the newer scoring criteria of RSS and iFixit only instruct to check if reassembly is possible; and they consider reassembly the opposite of disassembly. Therefore, there is a discrepancy in the importance given to this matter between the scoring methods. However, the report by Peters et al. [21] shows that reassembly time in some cases is higher than disassembly time. This is generally due to an additional action required to position fasteners (such as screws) and components. Furthermore, positioning design features such as spring-loaded components, and long routed cables further add to the reassembly time. eDiM partially covers the additional actions for positioning fasteners in its method, however specific reassembly actions such as assembling spring-loaded components and routing long cables are not considered in this method. Therefore, the eDiM database could be further expanded to address more reassembly-specific actions. Additionally, if a scoring system considered the disassembly step instead of eDiM, then, additional elements influencing the reassembly (e.g., criteria addressing cable routing) should be added as a step.

Two design elements for which most scoring systems agree and provided straightforward objective test procedures were "fastener removability and reusability" and "tools required". ADEME, EN 45554, and RSS apply similar criteria to fasteners (reusable, non-reusable, non-removable). These criteria, and also the testing method (disassemble and check fastener type) seem to be consistent across the different scoring systems and testing parameters seem to be straightforward and objective. Similarly, the "tools required" parameters appear to be in agreement across the scoring system. The list of tools is well defined, and most of the scoring systems (4/6) reference EN 45554 standards. The criterion and test for tools required seem to be clear and objective.

No list or other reference of standardized parts and interface is given for any of the scoring systems. Whilst RSS and EN 45554 consider the presence or absence of a standard interface per part, AsMer and ONR 192102 adopt a more subjective approach. RSS advises checking the manufacturer's information, whilst ONR 192102 suggests disassembling and checking the interface/part. However, objectively assessing standard parts and interfaces would require a list of standard parts and interfaces similar to that of the "tools required" criterion. Listing these standard parts, however, seems difficult given the large diversity of parts and components. Additionally, enforcing standardization may impede innovation. Instead, the benefits of standardization could be addressed by the following criteria: (a) spare parts cost and availability, (b) tool required, (c) information accessibility of product identification, (d) ease of diagnosis, (e) ease of disassembly, (f) safety, and (g) interchangeability of components. Most of these criteria are already present in scoring systems; therefore, if the aforementioned criteria are addressed, standardization as a separate criterion may not be required.

"Information accessibility" scores the ability of the public and of repairers to access repair information. The information content required by the different scoring systems is presented in Table 5. This table shows that "repair instruction", "exploded view", "diagnosis information", "safety measures", "procedure to reset to working condition", and "disassembly sequences" have been addressed by most (4/6) scoring systems. This is followed by; "product identification", "tools required", "replacement/supplier information", "circuit diagram", "component identification", "maintenance instructions", and "error codes". Most of the scoring systems seem to agree that information on diagnosis, safety, disassembly, and reset are important and that such information should be provided by the manufacturer. The testing procedure for obtaining this information seems to involve checking the official website, consulting a manual, or calling customer service. This criterion and its testing procedure seem straightforward and objective and could be easily implemented. However, apart from information on diagnosis, safety, disassembly sequences and factory reset, there is a discrepancy between scoring systems on what additional information from the manufacturer could be important. This may require further research.

In addition, the majority (4/6) of the scoring systems assess information accessibility on a product level and do not specify to what extent this applies to the most frequently occurring faults. This could result in invalid scoring (e.g., if the company gives repair information on just one fault, they may still attain a favorable score). Therefore, for information that is dependent on specific faults (such as repair information, and diagnosis information), it is important to provide information covering the most frequently occurring faults.

Table 5: Information required in different scoring systems.

Information Availability	Scoring System					
	EN 45554	RSS (JRC)	AsMer	ONR 192102	FRI	IFixit
Features being claimed in update	•					
Update method	•					
Documentation of updates offered after the point of sale	•					
repair Instructions/manual/bulletin	•		•		•	•
Product identification		•			•	•
Component identification						•
exploded view	•	•		•	•	•
Regular maintenance instructions		•		•	•	
Diagnosis information/testing procedure/ Troubleshooting chart	•	•	•	•	•	
Repair/Upgrade service offered by the manufacturer		•			•	
safety measures related to use, maintenance, and repair		•	•	•	•	
List of available updates		•				
Disassembly instruction	•	•	•		•	
Reassembly sequence			•			
Product identification			•			
Fault detection software			•			
PCB/Electronic board diagram			•		•	
Error codes	•		•	•	•	
3D printing of spare parts			•			
Reconditioning			•			
Procedure to reset to working condition	•	•	•	•	•	
Service centre accessibility				•		
Transportation instructions				•		
Circuit/Wiring diagram	•			•	•	
Replacement supplier/supply information			•	•		•
Tools required	•			•	•	
Service plan of electrical boards				•		
Training materials for repair	•			•		
Recommended torque for fasteners	•					
Compatibility of parts with other products	•					
functional specification of parts	•					
reference values for measurements	•					

Suitable media for communicating this information could include printed manuals, websites, digital information carriers such as QR codes, DVDs, or flash drives, and the telephone [15], [45]. AsMer, ONR 192102, and iFixit have clear criteria on how information on safety, disassembly, and product and component identification should be relayed; with "attached to the product" scoring highest, followed by access to a manual or website video. For the rest of the scoring systems, the medium of information does not seem to matter as long as it can be accessed by the public. Again, there are discrepancies concerning the importance of the information medium among the aforementioned systems. However, the literature shows that providing visual markings on the product (such as numbering wires, or warning signs) assists in correct reassembly and decreases the safety hazard [43]. Similarly, providing component identification numbers assists in buying the correct spare parts for replacement [36]. Therefore, it could be important to assess the information medium for disassembly, safety, and component identification.

Recommendations for Future Work

Our analysis found several opportunities for improvement in the current scoring systems and also identified their limitations. Both of these suggest recommendations for future work. Our primary recommendations are to improve the current scoring systems in the following ways:

- Assessments of health and safety were semi-objective across the majority of the scoring systems. Therefore, there is an opportunity to develop objective criteria and testing methodologies for assessing health and safety of the user and the product during and after repair.
- The eDiM method database could be expanded and further simplified to measure the ease of disassembly more universally. Additionally, the eDiM database needs to be expanded, and the question of whether the additional accuracy provided by eDiM compared to disassembly step compensates for the increased difficulty in testing needs to be considered.
- Since time for reassembly is sometimes higher than for disassembly, it might be important to consider ease of reassembly as a separate criterion whenever eDiM is not used.
- In terms of repair information content, it is important to establish what information is most critical to promote repair. Additionally, information that is dependent on specific faults/components should be addressed at the fault/component level instead of the product level.

This study's limitations may also provide opportunities for future work. Ease of testing and validity were both discussed only partially. Whilst a scoring system could be complete and objective with all the aspects required to score repairability, such a scoring system might be too burdensome to score products within a feasible budget and time. Therefore, future work could investigate balancing ease of testing versus objectivity and completeness of the testing program. Future work could also further test the validity and feasibility of different scoring systems by having multiple test personnel independently test different products with each scoring system and checking levels of agreement. This is planned for upcoming research.

This review focused on how scoring systems in the current literature reflect physical design features, principles, and guidelines related to the repairability of household electronic and electrical equipment and on how they are tested. However, research has also shown the importance of user and market aspects in repair. Future research could investigate how the current scoring systems reflect this, by testing user and market aspects related to repairability.

While this research was intended to create tools useful for policy makers, it was beyond the scope of this project to predict what specific policy types would be most effective in using the tools. Therefore, further research is recommended to find the most effective policies to best improve repairability, such as taxing, mandatory product labelling, mandatory minimum repairability scores, or other implementations.

4.5. Conclusions

This study assessed the objectivity and completeness of six major repair scoring systems, to see what further development may be required to make them policy instruments. The completeness of each scoring system was assessed by comparing it to the latest literature on the design features and principles that drive product repairability. Similarly, the objectivity of each scoring system was assessed by comparing whether the presented scoring levels per criteria in each scoring system were clearly defined, with a quantifiable and operator-independent testing method. In general, most of the scoring systems were acceptably objective and complete. FRI and iFixit scoring systems were found to be the most objective, and JRC was the most complete. However, they could all be further improved by the recommendations presented in the paper.

Addressing the gaps presented in this paper would lead to the development of an ideal scoring system with an effective testing program that could be used for policy making. Additionally, this scoring system could also be used for assessment by consumer organizations, MSAs, and other interested stakeholders, to promote the repairability of products which will, in turn, improve their lifetime.

Author Contributions: Conceptualization – All authors; Writing – original draft, Sagar Dangal; Writing – review & editing, Sagar Dangal, Jeremy Faludi, and Ruud Balkenende; Supervision, Jeremy Faludi and Ruud Balkenende. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the European Commission under the Horizon 2020 Premature Obsolescence Multi stakeholder Product Testing Program (PROMPT) (Grant Agreement number 820331).

Conflicts of Interest: The authors declare no conflict of interest.

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5.

Empirical evaluation of repairability scoring systems for validity and reliability

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5.1. Abstract

The validity and reliability of four prevalent repairability scoring systems has been investigated by comparing scores of ten smart phones and six vacuum cleaners versus empirically measured repair times, as well as comparing hypothetical ideal and problematic scenarios. Ease of disassembly methods was also assessed for five smart TVs, four washing machines and six vacuum cleaners. The scoring systems studied were the French Repairability Index (FRI), Joint Research Centre Scoring System (RSS/JRC), iFixit, and ONR19202. Overall scores of products across scoring systems were relatively well correlated, indicating a fair amount of overall reliability. However, the variability in scores for the best and worst cases of the same product was often larger than the differences between products. Validity was good for products that are easily repairable, but scorecards often failed to score low when repair is infeasible or too expensive. Repair scores greatly depend on disassembly; since some

scorecards count numbers of disassembly steps and other scorecards use proxy times, these two methods were compared against empirical disassembly times for five vacuum cleaners, five televisions, and four washing machines. The proxy time method was found to be highly accurate for all three product categories; the steps method was less so. It indicated the relative ease of disassembly well for washing machines, but not for televisions or vacuum cleaners. Finally, this study proposes improvements to scoring methods, including a limiting factor approach and the development of clearer protocols, to ensure the scoring systems are robust, reliable, and can effectively guide sustainable product design.

5.2. Introduction

The short average lifespan of many products has significant environmental impacts. The European Commission's circular economy action plan aims to address this issue by encouraging the production of more durable and repairable products, establishing specific requirements for the durability and repairability of products [1]. The right to repair movement aligns with these objectives, promoting an increase in the ability of consumers to repair their own devices, and challenging manufacturer-imposed restrictions [2].

Repairability scoring systems have emerged as a crucial tool in achieving these objectives. They provide a semi-quantifiable measure of a product's repairability, serving as a valuable resource for policy makers, designers, and manufacturers looking to enhance product repairability. Moreover, these systems empower consumers by enabling them to make informed decisions when purchasing products [2].

Within this context, various scoring systems (or repairability indicators) have been developed [3], [4], [5], [6], [7], [8] to evaluate the repairability of products. These systems evaluate a variety of factors, including the ease of disassembly, the availability of information and spare parts, pricing, and software aspects. Four scoring systems, namely French Repairability index (FRI) [9], Joint Research Centre scoring system (i.e. RSS or JRC scoring system) [4], iFixit [8], and ONR19202 [7], are particularly noteworthy. They have either been implemented or have a high likelihood of implementation in their respective contexts. For instance, the FRI system is currently in use in France and could possibly be implemented in in other European countries [10]. Similarly, the ONR19202 system has been established as the standard in Austria. The JRC scoring system is currently being adopted alongside an energy level scoring system across Europe [11]. The iFixit scoring system has potential for implementation on its website. Moreover, these systems can provide product-specific scores, and their usage instructions are publicly accessible.

For these scoring systems to be effective in policymaking and for assessment by consumer organizations, market surveillance authorities, and other stakeholders, they must be valid and reliable. Validity means that the scoring system accurately measures what it is intended to measure, while reliability means consistency and objectivity of the scores upon re-evaluation [12], [13], avoiding variations caused by subjective interpretations. However, the current evaluation of validity and reliability of scoring systems is limited, and this paper intends to address this gap.

Validity and reliability of scoring systems

Previous studies have identified several validity issues in scoring systems. A paper by Barros et al. [14] and a report by HOP [15] assessed the FRI scoring system and found that equal weighting of factors, such as the availability and cost of spare parts, as well as the removability of priority parts [16] could mean that products which are impractical to repair could still receive a high score, as a poor score in one area might be compensated in other areas.

Several studies [4], [14], [17] have compared scoring systems. These analyses help identify variances in repairability scores for identical products across different systems. If significant differences between scores cannot be justified, it may suggest the scoring system's validity needs further examination. These studies suggest that, within their contexts, scoring systems tend to provide similar scores. However, a comparison of the new iFixit, FRI, and JRC scoring system is currently absent. This can offer a comprehensive view of the similarities and differences between these scoring systems, providing insights into the extent of their validity.

Ease of disassembly is an important criterion in all repairability scoring systems [14], [18]. However, the validity of methods for assessing ease of disassembly remains unclear. Current scoring systems employ two distinct methods: “proxy time methods”, such as eDiM [18], and iFixit Proxy time [8] which estimate disassembly times assigning times to specific actions; respectively the “step method” [19], which counts the number of disassembly steps required to disassemble a specific component. While proxy time methods are suggested to be more representative of actual ease of disassembly than the step method [17], these have only been validated for a limited number of (ICT) products and there is a notable absence of comparing the results with the actual disassembly time for a larger range of products, like domestic appliances.

Reliability issues in the JRC and FRI scoring systems due to different interpretation of criteria have been identified in several papers and reports [15], [20]. These include the way of addressing spare part bundles (i.e., multi-functional modules with multiple components brought together using non removable fasteners) during disassembly, provision of repair information, and fluctuations in spare part prices. However, the extent to which these issues influence scores, and their effect on other scoring systems is not clear.

Overall, a complete picture regarding validity and reliability of the current scoring systems is lacking. This paper aims to address this gap for the four scoring systems mentioned above. The overarching research question of this study is: How valid and reliable are the current scoring systems? This question is explored through the following activities and analyses.

The scores of a variety of products in different product categories are compared across the different scoring systems, to examine the differences and their justification. While this comparison does not directly determine the validity of a scoring system, it provides indications of areas that may require further investigation in terms of validity.

The validity of a scoring system is evaluated by checking how the scoring system handles hypothetical scenarios where repair is considered not feasible.

For ease of disassembly, the proxy time method and steps method are compared with measured disassembly times for a range of different products to test the validity of each method.

The reliability of the scoring systems is determined first by scoring various products with best-case and worst-case interpretations per scoring criterion, then by identifying the cause and the extent of differences in scores.

In total, 16 products (10 smartphones and 6 vacuum cleaners) are evaluated from the perspective of self-repair and 3rd party professional repair. For assessing ease of disassembly 5 smart TVs are also investigated. Aspects related to OEM (authorized) repair are not assessed, due to lack of access to information and tools provided for authorized repair.

Based on the findings, the paper proposes recommendations to improve validity and reliability in the current scoring systems. These improvements may empower designers, repairers, consumer organizations, and policymakers to leverage these systems more effectively.

Scoring systems

This section provides an overview of the four scoring systems that will be analyzed. The criteria applied in the scoring system, the products analyzed in the study, and their weight per criteria is presented in Table 1.

Joint Research Centre (JRC) Scoring system.

The JRC scoring system has been developed based on the preliminary draft of the standard EN45554, which concerns general methods for the assessment of the ability to repair, reuse, and upgrade energy-related products [19](CEN/CLC TC10 European Standard, 2017) and the Benelux study on "repairability criteria for energy-related products" [4], and is intended to be implemented as part of the eco-design requirements for consumer products. This scoring system is mainly focused on professional repairers, with some criteria considered for consumer repair. It is currently suited for the assessment of vacuum cleaners, washing machines, smartphones, tablets, and TVs.

French Repairability index (FRI)

The French Repairability Index (FRI) was published in 2020 and is also develop based on EN45554 standard [19]. French law requires companies to analyze and score their own products and publish the score. This repairability index would most likely be part of sustainability index in the future which would include reliability index. FRI is focused on professional repairers and consumers, and some criteria are also considered for producers. This scoring system is currently used to assess washing machines, vacuum cleaners, smartphones, laptops, TVs, corded trimmers, lawn mowers, pressure washers and dishwashers [21].

iFixit scoring System.

This scoring system is mainly based on research publications by Flipsen et al. [8], [22] and input from researchers and repair experts. This scoring system has been developed as an objective alternative to the current scoring system used in the iFixit website [23]. This scoring system focuses on consumer repair and is currently only suited for smartphones.

ONR192102 (2014)

The ONR192102 scoring system [7] has been developed through a collaboration between repairers and the Austrian Federal Ministry of Land, Forestry, Environment, and Water. It is intended for professional repairers. This system is suited to evaluate the durability and repairability of both brown and white goods.

Table 13: Overview of FRI, JRC and iFixit scoring system. “PRO” = Producer, “CON” = consumer, “REP”= repairer, “M”=must have criteria.

Critera	FRI					JRC					iFixit			ONR (192102)		
	Sub criteria	Smartphone		Vaccum cleaner		Sub criteria	Smartphone		Vaccum cleaner		Sub criteria	Smartphones		Sub criteria	Vacuum	
		weight	total criteria weight	Weight	total criteria weight		weight	total criteria weight	Weigh t	total criteria weight		Weight	total criteria weight		Weight	total criteria weight
Ease of Disassembly	Disassembly step	10%	20%	10%	20%	Disassembly step	25%	55%	18%	55%	Disassembly time	21%	55%	Ability to disassemble	20%	33%
	tools required	5%		5%		tools required	15%		18%		Path of entry	21%		modularity	6%	
	Fastners type	5%		5%		Fastners type	15%		18%		Tools required	13%		ease of de-soldering	8%	
Informaiton availability	Type of information (REP, CON)	20%	35%	20%	40%	Type and cost of information (PRO, CON)	15%	15%	18%	18%	Availability of repair information	13%	17%	Availability of repair information (M)	38%	49%
	Information on update type	10%		-		-	-		-		Visual cues	4%		Telephone support (M)	-	
	Remote assistance availability (REP, CON)	5%		20%		-	-		-		-	-		Diagnosis design features (M)	11%	
Spare part availability	availability over time (PRO, RET, REP, CON)	15%	20%	15%	20%	availability over time	-	15%	9%	18%	Availabiltiy over time	5%	21%	Availabiltiy over time (M)	8%	11%
	Delivery time (PRO, RET, REP, CON)	5%		5%		who is spare part available to	15%		9%		Who is spare part available to	17%		Standarised parts (M)	3%	
Spare part price	Ratio between part and product price	20%	20%	20%	20%	-	-		-		-	-	-	-	-	-
Software aspects	Software reset (PRO,REP, CON)	5%	5%	-	-	availability over time	15%	15%	4.5%	9%	-	-	-	-	-	-
	-	-		-	-	Free avaiablity of update	-		4.5%							
Health and saftey	-	-		-		-	-	-	-	-	Tools risk	2%	4%	Warning signs	2%	4%
							-	-		-	Puncture risk	2%		information on series errors (M)	2%	
Repair endorsement	-	-		-		-	-	-	-	-	Repair allowed by	4%	4%	-	-	-

Methods

This section presents the method used to score products with different scoring systems. These scores are then used to assess scoring systems ability to address a hypothetical scenario, to compare differences between scoring systems, and to assess best- and worst-case interpretations per criterion. Also, the method used to analyze ease of disassembly is presented.

Scoring products

Products and priority parts for investigation.

Vacuum cleaners and smartphones were evaluated since they can be scored with most (3/4) of the scoring system under investigation. Furthermore, these two products offer perspectives from two distinct product categories and design complexity: one being highly integrated and miniaturized and another being relatively large and mechanically intensive.

The products are scored based on the protocol presented in the scoring system. The FRI, JRC, and iFixit scoring systems incorporate the concept of “priority parts” in their assessments. These parts are identified based on their likelihood of failure and functional relevance. However, what constitutes high and low failure likelihood, as well as functional relevance, can vary across different scoring systems. The priority parts for smartphones and vacuum cleaners, and their weight across various scoring systems is provided in supplementary material 5.9a. For JRC and iFixit scoring system, the relative weight given to the priority parts is indicated. Priority parts for FRI are categorized in List 1 and 2. Ease of disassembly, tools required, and spare part price criteria are only applicable for List 2. The ONR system considers all parts in its assessment.

Product score determination

For scoring the products with each scoring system, the following protocols were used for disassembly assessment, and for obtaining information from the manufacturers and the internet.

Disassembly assessment protocol.

The following protocol was used to score criteria related to disassembly.

1. The disassembly and reassembly process of the product to access all the priority parts is first determined.
    a. The official website was checked for a disassembly manual or instructions.
    b. If this is not available, other non-official disassembly/reassembly instructions websites such as iFixit and YouTube disassembly channels are consulted.
    c. If none of these sources provide the necessary information, the product is disassembled and reassembled in order to determine the disassembly process.
2. The product is tested to ensure that it functions as expected.
3. The device is then disassembled until each priority part is separated.
    a. Any non-standard accessories, such as display protectors or rubber bumpers, are removed at the start of the disassembly process. These accessories are not considered part of the disassembly.
    b. For battery-powered items, the shortest possible route to remove the battery is taken first as a safety measure.

c. Where needed, adhesive was removed using, combination of heat-gun, and iso-propanol. All other operations were carried out using basic tools (Class A) [19].
d. If there is a risk of damaging components during further disassembly, we took steps to avoid this risk, even if it results in a longer disassembly path. For example, when replacing an iPhone 12 battery, the display was disconnected and removed to avoid tearing the display cables by movements when pulling on the pull tabs.
e. The disassembly of a priority part ended when it reached permanent fixtures, such as soldering, welding, or thermal molding.
f. If multiple tools are required during a single disassembly action, the tool is only changed once all fasteners requiring that specific tool have been removed.

4. The product is subsequently reassembled.
5. The product was tested again to confirm it works correctly and disassembly has not influenced its functionality.
6. The entire disassembly and reassembly process is recorded in top- and side-view videos (see Supplementary material 5.9b).
7. During the disassembly, the actions are described aloud, mentioning and describing the target component, its location, the tool being used, and the detached/reattached fasteners.
8. A disassembly map [24] for the product is made based on the video and audio recording.
9. Based on the disassembly map, the criteria related to disassembly, and the disassembly sequence were extracted. The disassembly sequence considers the product fully assembled when analyzing each priority part's disassembly.

The 8th step in the disassembly assessment protocol evaluated the following criteria: a) disassembly steps; b) proxy disassembly time [18]; c) fastener visibility; d) fastener type; e) path of entry; f) safety during repair; and g) tools required. The proxy time method used was based on data regarding the Disassembly and Reassembly Times (DaRT) obtained from monitoring and timing the disassembly and reassembly process of 12 washing machines (disassembly and reassembly) and 12 vacuum cleaners (disassembly and reassembly), 35 smartphones (adhesive removal and prying actions), and 7 tv (prying actions) [21]. This method uses as a proxy the median time needed for a range of connections with a large number of specified tools. An overview of proxy time data for different tool-connection combinations can be found in Supplementary material 5.9d. This method was preferred over eDiM, because the results are based on a larger variety of different products, do not need adaptation to tools used and the actions are simpler than the eDiM model.

Protocol to assess criteria that require information from manufacturers.

To test the aspects related to the availability of repair information, the following protocol was used:

1. First, the local (EU, Netherlands (NL)) OEM website was searched to see if any repair guidance or links to repair guidance were available, including links provided by the OEM to YouTube or iFixit videos as well as service manuals.
2. A Google search was then conducted to identify if any service manuals, repair guides, or repair videos were available directly from the OEM. Note that unless suggested by

the OEM directly, repair information made available by third parties (e.g., iFixit) is not considered.
3. Finally, the local customer service of the OEM was called and asked if they were able to provide the repair information necessary to repair the product.
    a. This was done first as a repairer and then as a consumer.
    b. If customer service directed us to another body, this was followed through (e.g., a technician or official repair partner).
    c. This was done until no further personnel could be contacted, and no further information could be retrieved by phone.

To test the aspects related to the price and availability of spare parts, the following protocol was followed.

1. First, the local (EU, NL) OEM website was searched to see if spare parts or links to authorized spare parts providers were available or suggested.
2. A Google search was then conducted to identify if any other web shops sold official spare parts. Non-official parts supplied by third parties (e.g., iFixit or another website) are not considered for the scoring but serve as a reference to determine if components are available as spare parts.
3. Finally, customer service was called and asked if they could provide or direct us to authorized priority parts purchasing.

The protocol for obtaining information was subsequently evaluated the following criteria: a) repair and diagnosis information; b) spare part availability; c) spare part price; d) policy on self-repair; e) information on updates; and f) remote assistance. The information (including the spare part price and availability) was checked during the analysis (November 2022 - Jan 2023).

If multiple interpretations were possible in scoring a specific criterion, the scoring system protocol was rechecked to determine whether this was due to deviation from the protocol; if none was found, the different interpretations were considered as best- and worst-case scenario.

Researchers' co-agreement

Both the disassembly assessment and the scoring of the products were carried out by two researchers experienced in disassembly and product assessment. The results were checked against each other for co-agreement. Discrepancies between the results were first rechecked to determine whether they were the result of a deviation from the protocol. Remaining discrepancies were noted as difference in interpretation and provided input for evaluating reliability.

Analysis of scoring systems

Hypothetical scenarios

The validity of the scoring system was checked by creating hypothetical scenarios where repair is unfeasible and determining how different scoring systems handle the situation. In scenarios where it was clear that repair is not feasible, a valid scoring system should address this accordingly by giving it a low score. Therefore, two hypothetical scenarios were checked.

In the first scenario, a hypothetical product was assessed with a spare part price of one of its components (motor for a vacuum cleaner or screen for a smartphone) was over 50% the price of a new product, while all other criteria of the scoring system were met in an ideal way.

Similarly, in the second scenario, a hypothetical product was assessed in which the priority part (motor for a vacuum cleaner or screen for a smartphone) is attached by a permanent fixture and cannot be disassembled, while again ideally meeting all other criteria.

Figures 1 and 2 in addition show as “ideal” scenario, the one that represents the maximum score that is obtainable, which also shows the weight of the various scoring categories for the scoring system under study.

Comparing different scoring systems

To investigate the relationship between different scoring systems and identify whether the scores agree on the rankings of better products vs worse products, a regression analysis was conducted.

For scores of vacuum cleaners, Wilcoxon signed-rank test was conducted to determine whether the differences in scores were significant between the JRC and FRI scoring systems. Similarly, we conducted a Friedman's test for scores on smartphones to determine whether the differences in scores were significant between the three scoring systems (JRC, FRI, iFixit). These analysis methods were chosen since the scores were not normally distributed, dependent, and the number of samples was relatively low (n=10 for smartphones and n=6 for vacuum cleaners).

Best- and worst-case interpretations

The difference in interpretations when scoring on specific aspects was checked to determine the reliability of different scoring systems. This difference in best- and worst-case scenario provides an indication of reliability within each criterion.

Since the data is paired (same products used between the scoring systems) and is not normally distributed, Wilcoxon signed-rank test is conducted between the best- and worst-case scenarios to determine the significance of differences between the scores.

Analysis of ease of disassembly assessment method

This section outlines the method employed for analyzing two different methods to assess ease of disassembly, proxy time method (DaRT) and step method. This was carried out using data obtained on large scale disassembly of products in professional testing labs experienced in disassembly of the products.

Products and their priority parts for investigation

Four washing machines, five vacuum cleaners and five smart TVs were evaluated as the result of a collaboration with consumer organizations in the framework of the European PROMPT project based on large variation in design features [25]. Investigated priority parts are as follows:

1. **Vacuum cleaner:** suction hose, dust cover, handle, cord reel, motor, on/off switch, wheels
2. **Televisions:** main board, tcon board, display assembly, internal power supply
3. **Washing machine:** door lock, door seal, electronics, hoses, pump, shock absorbers, tub assembly.

These priority parts are chosen based on high failure likelihood and high functional relevance.

Protocol for ease of disassembly assessment method.

1. First, the products were disassembled using the disassembly protocol described in Section 3.1.
2. The number of disassembly steps and DaRT proxy times were extracted from the disassembly map.
3. The product was disassembled a second time following the third step of the disassembly protocol. However, the researcher did not think out loud during the disassembly process.
4. The entire disassembly process was recorded on video.
5. The actual times needed for disassembling (and putting aside) each priority part was extracted from the recorded video.

Analysis

Regression analysis was conducted to find the relation of actual disassembly time versus disassembly steps and DaRT time.

5.3. Results

Scoring results of tested products

The scores for the smartphones, including a breakdown of the scoring criteria, as determined using the scoring systems of JRC, FRI, and iFixit are depicted in Figures 1a, 1b, and 1c respectively. For each product the results for best- and worst-case interpretation of scoring criteria are shown. These figures also show in the first column the ideal scenario result which is the maximum score achievable, while the last columns (highlighted in purple) show the scores for the hypothetical scenarios in which repair is considered ideal except for either a spare part that is prohibitively expensive or a priority part that cannot be disassembled. Similarly, the scores for the vacuum cleaners, including a breakdown of the scoring criteria, as determined using the scoring systems of JRC and FRI, are shown in Figures 2a, and 2b, respectively.

Comparison of scores of the same smartphones obtained with the different scoring systems is presented in Figure 3a. Comparison of scores of the same vacuum cleaners obtained with the different scoring systems is presented in Figure 3b. The exact breakdown of the all the scores is provided in the Supplementary material 5.9c.

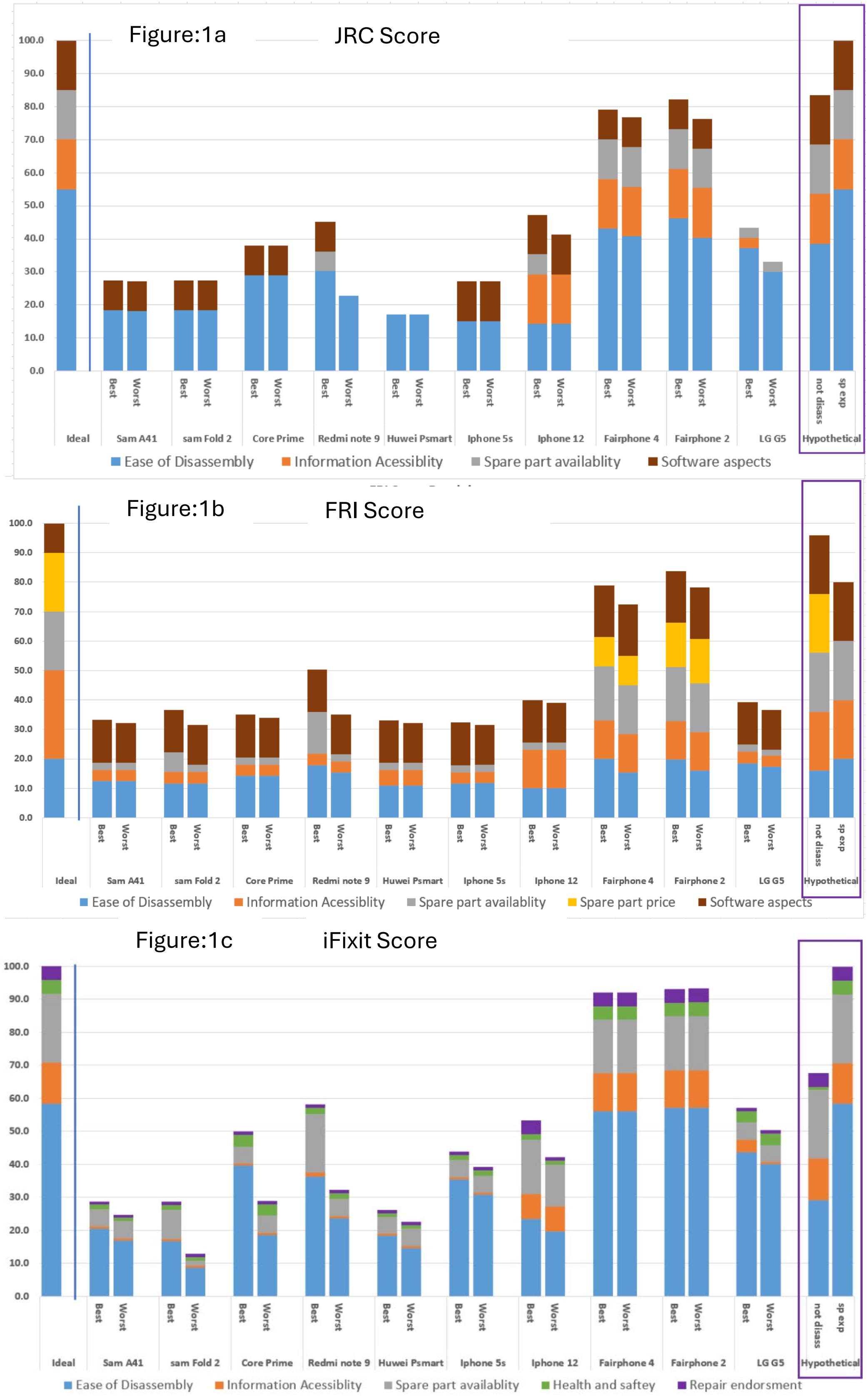


Figure 1: Score breakdown for smartphones. 1a JRC score, 1b FRI score, 1c iFixit score, "sp exp " = expensive spare part; "not disasss" = a priority part cannot be disassembled.

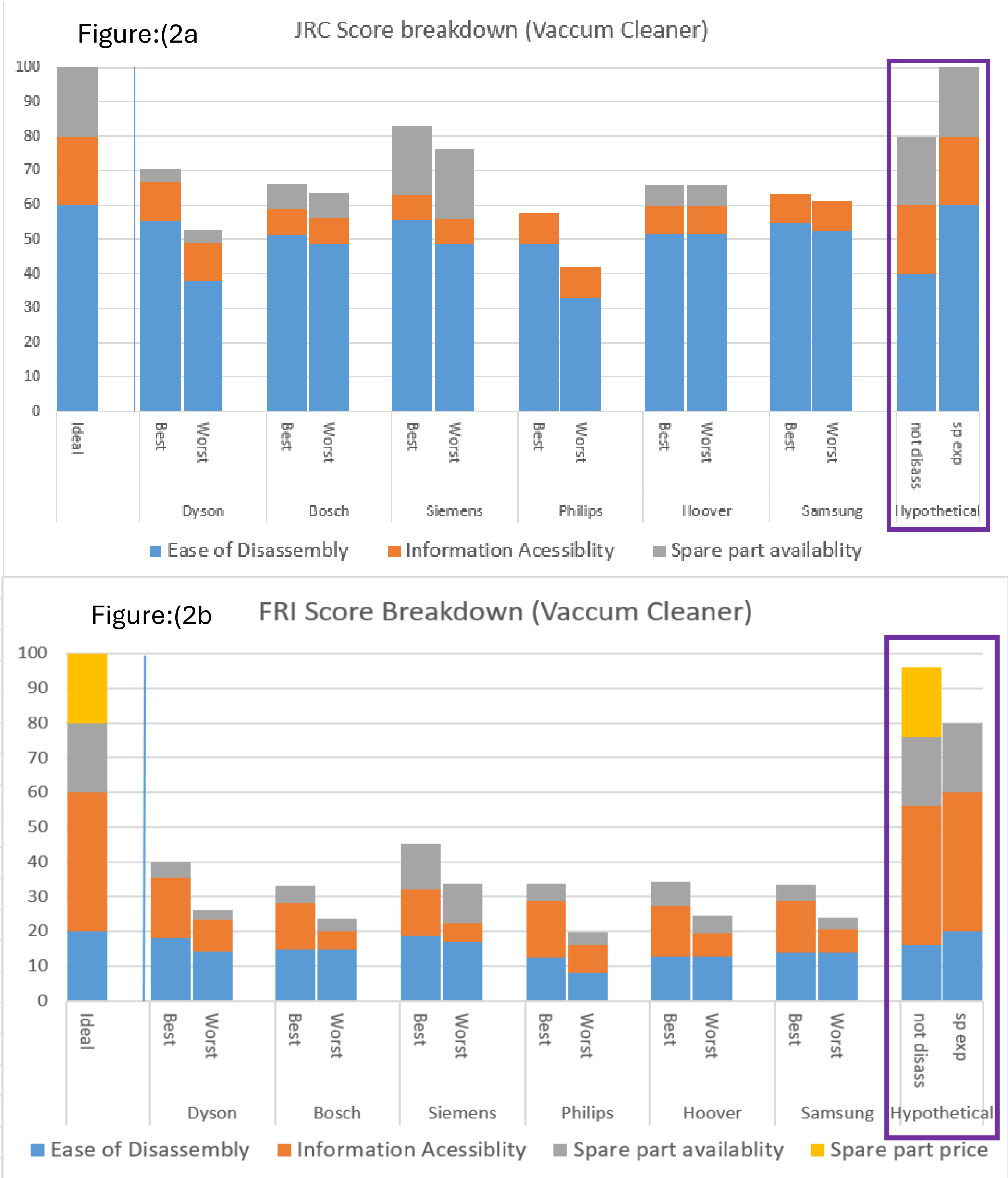
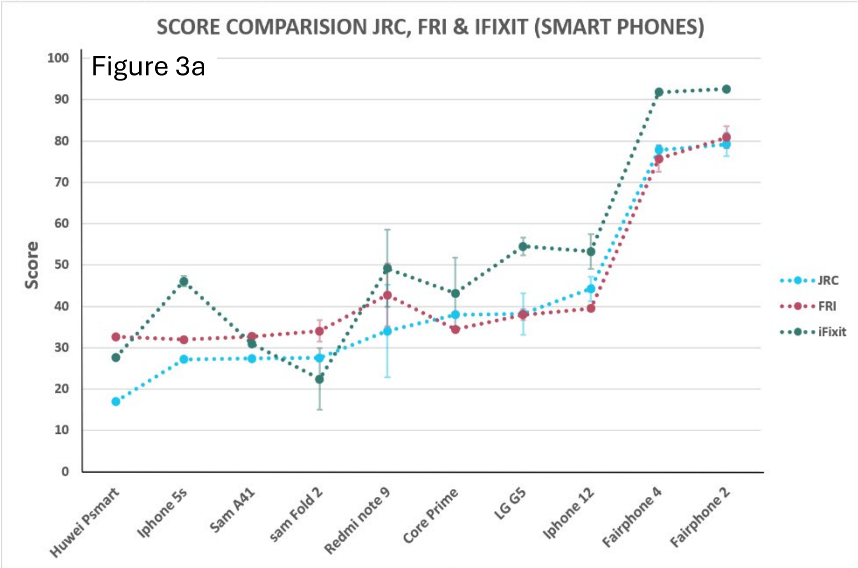


Figure 2: Score breakdown for vacuum cleaners. 2a = JRC Score, 2b = FRI score, "sp exp " = expensive spare part "; not disasss" = a priority part cannot be disassembled.

Results for the ONR system are not shown. ONR has 11 must-have criteria, for which none of the assessed vacuum cleaners passed. Essentially, the overall score of ONR for all vacuum cleaners was 0. Furthermore, scoring of vacuum cleaners by ONR turned out to be highly subjective. This subjectiveness arises because ONR frequently provides 0-10 score levels but does not provide instructions on how each level should be scored. For example, one of the criteria states, "The appliances should be mostly reducible to individual components, which should also be available as spare parts," with scoring ranging from 1 to 10. However, terms like "mostly reducible" and "individual components" are open to interpretation. Additionally, there are no instructions on how it should be scored if the appliance is reducible to individual components, but spare parts are not available. This subjectivity was also observed in previous research [4], [26].



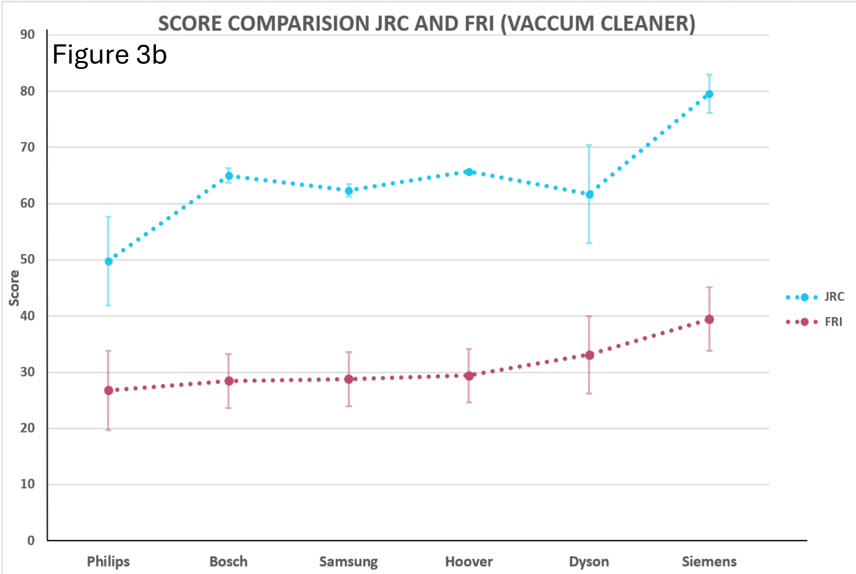


Figure 3: Score comparison for the different scoring systems and their uncertainty range. Bars show the extent of best- and worst-case interpretations. 3a: FRI, iFixit and JRC score for Smartphones. 3b: JRC and FRI scores.

Performance of hypothetical scenarios

For the hypothetical scenario, for both smartphones and vacuum cleaners, in which one spare part is prohibitively expensive in a further ideally repairable product, high scores were obtained. JRC and iFixit scored up to 100% (Figure 1a, 1c, 2a & 2b) while FRI scored up to 80% (Figure 1b & 2b). Similarly, for the hypothetical scenario, in which a single priority part cannot be disassembled, FRI and JRC exceeded 80%, and iFixit scored 68%.

Comparison of scoring systems

For smartphones, regression analysis showed that JRC, iFixit and FRI scores were highly correlated (R2 = 0.98). However, this correlation doesn't extend to the criteria level, where a lower score in one criterion is often offset by a higher score in another. FRI has higher scores in disassembly ease compared to JRC due to its emphasis on fewer priority parts (4 for FRI versus 8 of JRC) and less stringent disassembly steps (for example for the disassembly of the display, JRC requires less than 3 steps for the highest score, whereas the FRI requires less than 7 steps). Additionally, FRI scores high to criteria such as software reset, update information, and remote assistance availability, which are not considered in the JRC system. However, FRI includes spare part price, and this results in lower scores for most smartphones since most (8/10) score 0 in this criterion. JRC scoring system, despite having stricter disassembly criteria, tends to lean towards higher scores due to the significant weight given to the ease of disassembly (55% for JRC versus 20% for FRI). iFixit scores are higher than both JRC and FRI as it focuses on two easily removable key parts (battery and screen), has highest weight in ease of disassembly (58%), and factors in the availability of third-party spare parts, which are usually easy to acquire.

For vacuum cleaners, regression analysis showed a low correlation (R2 = 0.59). Wilcoxon signed-rank test confirmed that the FRI score of vacuum cleaners is significantly lower than the score of JRC ($P < 0.0001$). In the case of vacuum cleaners, the significantly lower score on FRI than JRC can be attributed to three major factors. The primary factor is the high weight assigned to JRC's disassembly criteria (60%) in contrast to FRI's disassembly criteria (20%). The JRC-score for disassembly only exceeds for all products the total FRI-score. Further, in the JRC system, spare part availability distinguishes between "available", 5 years, and 8 years, whereas FRI distinguishes between 9, 11, and 13 years. As a result, nearly all vacuum cleaners (5 out of 6) receive poor scores for spare part availability in the FRI system. Finally, JRC does not consider the price of spare parts as a criterion, while all vacuum cleaners score 0 in the FRI system in this respect.

Best- and worst-case interpretations

As presented from Figure 1 and Figure 2, and based on Wilcoxon signed-rank test, significant difference between worst- and best-case interpretations are observed in both vacuum cleaners ($P<0.001$) and smartphones ($P<0.004$). This means that the variance from best-case to worst-case within the same product is higher than the difference between product scores, especially for vacuum cleaners. The main reasons for the observed differences are listed in Table 2. These differences arise from unclarity related to bundling, breakable fasteners, adhesive removal, spare part price, spare part availability, and access to repair information.

Table 2: Main reason for difference in score due to difference in interpretation and its explanation.

Design aspect	Interpretation issue in scoring	Possible scoring decisions	Advantage	Disadvantage	Affected scoring system
Bundling	Unclarity on how bundling should be addressed.	Bundled components are considered not removable	Bundling is penalised	Does not consider small elements bundled together	FRI, JRC, IFIXIT
		Consider the entire bundle removable	Considers small elements bundled together	Could promote bundling of large modules	
		Remove the part destructively		Promotes designs requiring destructive disassembly	
Breakable fasteners	Fasteners (e.g., snap fits) that may break during disassembly/reassembly is difficult to consider.	Consider not removable	Promotes fastener that do not break during disassembly	Products may be harshly scored since it's only a chance.	FRI, JRC, IFIXIT
		Consider removable	Conforms to what is currently done in general for FRI	Promotes fastener that break during disassembly	
Adhesive removal process	Multiple tools and techniques may be required, making it difficult to determine the best way to represent the adhesive removal process	Count each and every tool changed by assessor	Can address differences in difficulties of models	Is subjective	FRI, JRC, IFIXIT
		determine and consider standard amount of tool change	Provides consistent and objective assessment for adhesive removal	Database and further research are required	
	Components are generally glued in thin lines, therefore unclear how to check glued surfaces	Assess entre surface that is attached	Easier to test	Less accurate on representation on the ease	iFixit
		Assess only surfaces where glue is present	More difficult to test	More accurate on representation on the ease	
Spare part availability	Unclear how "out of stock" spare parts should be handled	consider not available	Easier to test	Do not account for temporary out of stock parts	FRI, JRC, IFIXIT
		Contact manufacturer when it will be in stock	More representative of real case	difficult to get answers from Manufacturer	
Repair information	Unclear the extent of information required for a "pass" criterion.	Thorough step by step information for diagnosis and repair on each failure mode is required	More accurate representation of information availability	Maybe too strict and currently none of the products will pass. Do not consider partial information	JRC, FRI, iFixit
		Partial guidance on general failure mode may suffice	Points are provided	Less strict and can be easily bypassed without giving clear guidance to user	

5.4. Assessment of ease of disassembly

Figure 4 presents the number of disassembly steps and the calculated DaRT proxy time compared to the actual recorded time in professional disassembly. Based on the overall data set, step values were multiplied by 26.3 s/step (actual time mean/average steps mean) to obtain the best fit trendline with actual time.

Figure 4a

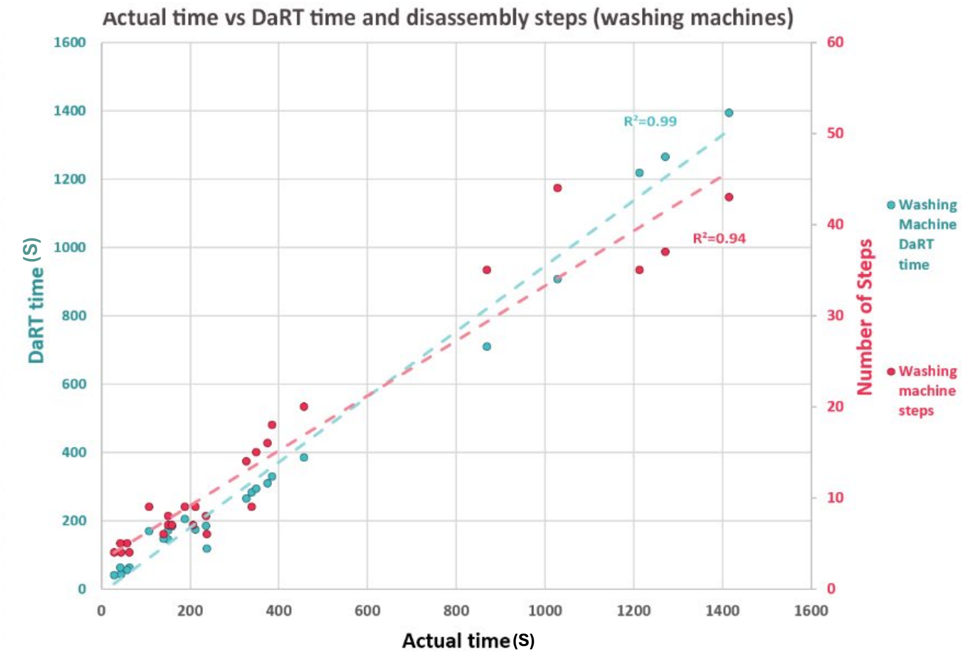


Figure 4b

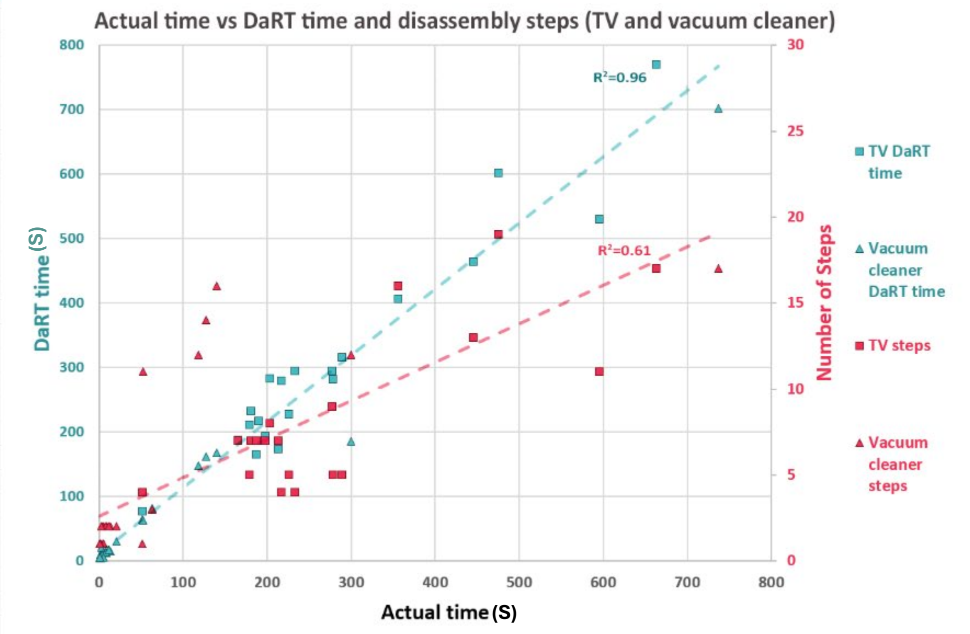


Figure 4: Calculated DaRT times and disassembly steps compared to actual disassembly times. For calculating the correlation coefficients, a step is assumed to take 26.3 s on average. 4a: washing machine data with. 4b: vacuum cleaner and smart TV data.

Considering the data for all three product categories (vacuum cleaner, washing machine, smart TV), a high correlation ($R2 = 0.98$) was observed between DaRT proxy time and actual time, and medium correlation ($R2 = 0.86$) between number of steps and actual time. The R2 relation and trendline for each product is presented in Supplementary material 5.9e. While DaRT proxy time has a high correlation with the actual time for all product categories, the correlation between steps and actual time is quite poor for the TV and vacuum cleaner (see Figure 3b); only its high correlation for washing machines brings up the overall correlation. Furthermore, the intercept of the trendlines for steps deviates significantly from the expected 0 intersection, which is not the case for DaRT proxy time. Finally, the best fit to all data causes the step-based times for vacuum cleaners and washing machines to be significantly overestimated. The step method only provides a reasonable indication of disassembly time for washing machines.

The deviations with the number of steps as a measure for the actual disassembly time are due to two main reasons: a) number of fasteners removed with same tool does not influence the step count, however most of the time the tool has to be changed frequently, and b) some products have many easy to remove small components, resulting in a high disassembly step count, which nevertheless does not take that much time.

In general, DaRT proxy time is slightly higher than the actual time. Upon video observation, the following two main reasons were identified. First, the repairer frequently keeps small tools still in hand while conducting minor disassembly tasks, while DaRT considers every change from tool to hand and vice versa. Second, removal of several components or fasteners is sometimes done at once, whereas in DaRT, each removal of a component or group of fasteners is considered individually.

5.5. Discussion

The validity of scoring systems in hypothetical scenarios, upon comparing different scoring systems and on different disassembly assessment methods is discussed first. Then we discuss the reliability of the scoring systems in best- and worst-case scenarios. In general, all the assessed scoring systems have opportunities for improvement regarding their validity and reliability.

The scoring systems reflected the validity well for products that are known to be highly repairable (such as Fairphone). However, we observed validity problems across all scoring systems in scenarios where repair of a specific priority part was not feasible or affordable. Here, products still scored relatively high, despite the poor repairability. Therefore, in these cases, none of the evaluated scoring systems accurately represent the product's actual repairability. Although these scenarios are not frequent, they do happen regularly, corroborating previous findings [14], [15].

A potential solution to address this issue could involve the implementation of a limiting factor approach [27] for criteria that determine the feasibility of repair. In this approach, if a criterion fails to meet a specified threshold, the overall score would be predominantly determined by this critical criterion, based on how far it falls below the threshold. Other recommended solutions include pass/fail thresholds and increasing assigned weight [15]. However, the limiting factor approach ensures that other criteria are not underestimated in the absence of detrimental features and avoids harsh penalties for products that slightly exceed the threshold value. For instance, if the threshold value is set at 30%, a product with a score of 29% would face severe penalties, while one with a score of 31% would not at all.

This limiting factor approach also allows for balanced distribution of criteria. Currently, The Joint Research Centre (JRC) prioritizes disassembly efficiency, indicating that ease of disassembly enables quicker, safer, and less costly repairs, thereby facilitating better accessibility for both professional and amateur repairers [5]. However, here other critical factors such as spare part availability are given low weight. In contrast, the French Repairability Index (FRI) assigns a lower weight to disassembly and focuses more on factors such as spare part availability and price. These differing weights can lead to scenarios where a high score in one criterion compensates for a poor score in another, undermining the overall goal and validity of assessing repairability. The limiting factor approach prevents this, while ensuring important aspects such as ease of disassembly are not overshadowed.

Currently, only FRI takes spare part price into account (with a weight of 20%), resulting in situations where expensive repairs make repair unfeasible to the customers despite receiving a high score. Spare part price is usually not accounted for because it is hard to assess precisely, as prices fluctuate over time, but such an approach fails to capture critical data, as a result, this is also identified as one of the main issues related to reliability. Possible solutions include using price estimates with large error margins, asking manufacturers to provide information on how spare part prices would change over time, or conducting regular price checks. However, each method has its limitations, and further research may be necessary to effectively tackle this issue.

Software aspects are addressed by two scoring systems (JRC and FRI); for smartphones, software has a weight of 15% and 5%, respectively. For devices centered around software (e.g., smartphones and laptops), long term support of security and software updates are crucial for extended lifetime of the device and could be a deciding factor for users to repair when the product eventually fails [28], [29]. Additionally, software part-pairing, where a part becomes difficult or almost impossible to replace by third party repairers or users, is becoming increasingly prevalent [15]. However, none of the scoring systems take this into account. Thus, while this study did not empirically test software aspects, software update time and part pairing should be investigated to establish if software should be represented with a higher weight or considered as a limiting factor.

To determine priority parts, according to recent research by Bracquene et al. [17], considering either 75% of failures or at least 5 priority parts provides the optimum balance between validity and ease of testing. In situations where the failure rates of priority parts are significantly different (for example, 60% battery, 20% motor for cordless vacuum cleaners), the validity of the scoring system could be improved if individual scores related to priority parts (e.g., ease of disassembly of a priority part, spare part availability) are weighted according to the average failure rate per product category, as done by Bracquene et al. [17]. Given this, the JRC scoring system (with weights based on failure rates) appears to be most valid, followed by FRI. The iFixit scoring system considers only the battery and screen as priority parts, and the combined failure rates for these two are approximately 60% [30]. Thus, the iFixit scoring system could be enhanced by incorporating one or two additional priority parts in the assessment.

Figure 3 shows that the proxy time method provides a better representation of the ease of disassembly than the number of steps. Specifically, DaRT proxy times are valid for a wide range of product categories, as demonstrated by their validity for washing machines, TVs, and vacuum cleaners, while number of steps were only valid for washing machines. This largely extends the validated applicability of proxy times for assessing ease of disassembly. Since ease of disassembly is one of the critical criteria for determination of repairability, a proxy time method is recommended for a higher validity scoring system.

Reliability findings, as presented in Table 2, show that while there is reasonable correlation between scores of the same product across scoring systems, each product's possible variation of score from best to worst was often larger than the differences between products; this is in line with previous research [14], [15]. Thus, scoring systems need clearer and more detailed protocols to minimize subjectivity. One major reliability issue relates to bundling. Here, clearer protocols are required so that designs containing large modules or requiring destructive disassembly are adequately penalized. For example, bundled parts might be considered non-removable. However, it is important to note that the use of bundling can also be beneficial for the ease of disassembly, as well as the product's reliability and cost [26]. Striking the right balance when applying bundling is crucial, and this balance should be reflected in the scoring accordingly. Other reliability issues relate to "repair information" and “diagnosis information” criteria, which are not accurately described by JRC and FRI. The level of detail in diagnosis and repair information should be specified by indicating exact failure modes and parts it addresses steps to diagnose and repair it.

Future opportunities

Validity can be further examined by surveying professional repairers about the product's repairability and evaluating how well their opinions align with the score. Furthermore, comparison of disassembly step numbers and DaRT times versus actual times for glued components should be assessed to provide a complete picture on the validity of each disassembly assessment method.

The reliability of scoring systems can be further improved by engaging a larger number of independent assessors to evaluate the scoring system using the same products. Evaluating more product categories would help to determine the scoring systems' generalizability across different categories.

5.6. Conclusion

This study evaluated the validity and reliability of four prominent repairability scoring systems: the French Repairability index (FRI), Joint Research Centre scoring system (RSS or JRC scoring system), iFixit, and ONR19202. The research aimed to enhance the effectiveness of these systems in promoting more durable and repairable products in alignment with the European Commission's circular economy action plan and the right to repair movement.

While the scoring system provided a valid reflection of products known to be repairable, the analysis also identified several areas that require improvement. Scenarios where repair is deemed infeasible or too expensive demonstrated that the current scoring systems do not accurately represent the actual repairability of products. To address this issue, the study proposed the implementation of a limiting factor approach for criteria that determine the feasibility of repair. This approach ensures that critical criteria play a significant role in determining the score when they fail to meet specified thresholds.

Reliability issues in the scoring systems were also identified. Different interpretations of scoring criteria can change overall product scores significantly, making them score better or worse than other products. The paper recommends a need for a clearer and more detailed protocol to address issues related to bundling, spare part availability and price, and repair and diagnosis information criteria, ensuring that these design aspects are free from subjective interpretations.

Additionally, the study evaluated the accuracy of disassembly assessment methods, specifically the DaRT method based on proxy times (which estimates disassembly times by assigning proxy times to actions) and the step method (which counts the number of disassembly steps), in comparison to actual disassembly time. Results indicated that the DaRT proxy time method gives a better representation of actual disassembly ease than the step method. It accurately assessed washing machines, vacuum cleaners, and TVs, while the steps method was only accurate for washing machines, and even there was less accurate than the DaRT method.

Our findings can help to improve scoring systems, which in turn should improve product design for sustainability. The suggestions presented could serve as resources for designers, repair professionals, consumer organizations, and policymakers, aiding them in promoting more repairable products. For repair scoring systems to be widely adopted in policy or industry, ensuring their validity and reliability is essential to establish trust and credibility.

5.7. Acknowledgements

This work was funded by the European Commission under the Horizon 2020 Premature Obsolescence Multi stakeholder Product Testing Program (PROMPT) (Grant Agreement number 820331).

The research visit of Sonia Sandez was funded by the Consellería de Innovación, Universidades, Ciencia y Sociedad Digital, Program for the promotion of scientific research, technological development and innovation in the Valencian Community. (Spain) (BEFPI-2021) and Generalitat Valenciana (Spain) (ACIF/2020/334)

We would like to sincerely thank Dr. Linda Ritzen for her valuable assistance with the analysis and verification of the DaRT method.

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5.9. Supplementary material

5.9a. Priority parts and relative weight

Table 3: Priority parts for smartphones for each scoring system. For JRC and iFixit, the relative weight given to the priority parts is indicated. Priority parts for FRI are categorized in List 1 and 2. Ease of disassembly, tools required, and spare part price criteria are only applicable for List 2. The indicated relative weights are based on this list.

Priority part (Smartphones)	Relative Weight			
	FRI	JRC (non-foldable)	JRC (foldable)	iFixit
Display assembly	16.8%	30%	25%	50%
Battery	16.8%	30%	25%	50%
Back cover	N/A	10%	9%	N/A
Front camera	16.8%	5%	4%	N/A
Back camera	16.8%	5%	4%	N/A
Connectors	2.6%	5%	4%	N/A
Charging connector	2.6%	N/A	N/A	N/A
Motherboard	2.6%	N/A	N/A	N/A
Buttons	2.6%	5%	4%	N/A
Microphones	2.6%	5%	4%	N/A
Speakers	2.6%	5%	4%	N/A
Hinge assembly	N/A	N/A	17%	N/A
Roll mechanism	N/A	N/A	17%	N/A
Charger	16.8%	N/A	N/A	N/A

Table 4: Priority parts for vacuum cleaner. For JRC and iFixit, the relative weight given to the priority parts is indicated. Priority parts for FRI are categorized in List 1 and 2. Ease of disassembly, tools required, and spare part price criteria are only applicable for List 2. The indicated relative weights are based on this list.

Priority part (Vacuum Cleaner)	Relative Weight		
	JRC	FRI (corded)	FRI (cordless)
Motor	14%	21%	17%
Motor Brushes	14%	N/A	N/A
Filters	14%	1.6%	2.0%
Hose/Wand	14%	21%	2.0%
Battery	14%	N/A	17%
Power cable	14%	N/A	N/A
Drive belt	5%	N/A	N/A
Wheels	5%	1.6%	2.0%
Battery	5%	N/A	N/A
Brushes/Nozzles	5%	21%	17%
Cable rewind	N/A	1.6%	N/A
on/off buttons	N/A	21%	N/A
Power electronics	N/A	1.6%	2.0%
Electronic control board	N/A	1.6%	2.0%
Display unit	N/A	1.6%	2.0%
Power switch control	N/A	1.6%	2.0%
Handle	N/A	1.6%	2.0%
Dust collectors	N/A	1.6%	17%
Cable winder button	N/A	1.6%	N/A
Charger	N/A	N/A	17%

5.9b. Disassembly setup

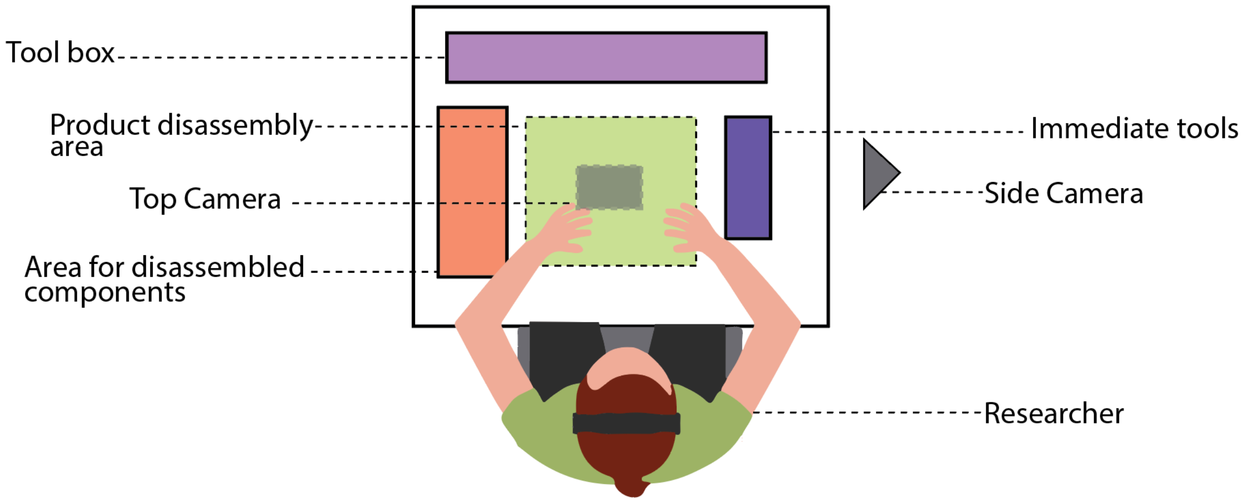

Figure 5: Setup to video record disassembly (top view).

5.9c: Detailed Calculation of FRI, JRC and iFixit scores

Table 5: Calculated FRI, JRC and iFixit scores for smartphones.

		FRI																			
Product		Sam A41		sam Fold 2		Core Prime		Redmi note 9		Huwei Psmart		Iphone 5s		Iphone 12		Fairphone 4		Fairphone 2		LG G5	
Criteria	**Weight (%)**	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst
Ease of Disassembly	**20**	12.5	12.5	11.7	11.7	14.2	14.2	17.9	15.4	10.8	10.8	11.6	11.8	10.0	10.0	20.0	15.3	19.8	15.9	18.4	17.3
Information Acessiblity	**20**	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	5.4	5.4	3.8	3.8	13.1	13.1	13.1	13.1	13.1	13.1	4.1	3.8
Spare part availablity	**20**	2.4	2.4	6.7	2.4	2.4	2.4	14.2	2.4	2.4	2.4	2.4	2.4	2.4	2.4	18.3	16.7	18.3	16.7	2.4	2.0
Spare part price	**20**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	10.0	15.0	15.0	0.0	0.0
Software aspects	**20**	14.5	13.5	14.5	13.5	14.5	13.5	14.5	13.5	14.5	13.5	14.5	13.5	14.5	13.5	17.5	17.5	17.5	17.5	14.5	13.5
Health and saftey	**0**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Repair endorsment	**0**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
OVERALL SCORE		**33.2**	**32.2**	**36.7**	**31.4**	**35.0**	**34.0**	**50.4**	**35.1**	**33.1**	**32.1**	**32.3**	**31.6**	**40.0**	**39.0**	**78.9**	**72.5**	**83.7**	**78.2**	**39.3**	**36.6**
		JRC																			
Ease of Disassembly	**55**	18.5	18.3	18.5	18.5	29.0	29.0	30.3	22.9	17.0	17.0	15.2	15.2	14.3	14.3	43.1	40.7	46.1	40.3	37.3	30.1
Information Acessiblity	**15**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0	15.0	15.0	15.0	15.0	15.0	3.0	0.0
Spare part availablity	**15**	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	12.0	12.0	12.0	12.0	3.0	3.0
Spare part price	**0**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Software aspects	**15**	9.0	9.0	9.0	9.0	9.0	9.0	9.0	0.0	0.0	0.0	12.0	12.0	12.0	12.0	9.0	9.0	9.0	9.0	0.0	0.0
Health and saftey	**0**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Repair endorsment	**0**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
OVERALL SCORE		**27.5**	**27.3**	**27.5**	**27.5**	**38.0**	**38.0**	**45.3**	**22.9**	**17.0**	**17.0**	**27.2**	**27.2**	**47.3**	**41.3**	**79.1**	**76.7**	**82.1**	**76.3**	**43.3**	**33.1**
		Ifixit																			
Ease of Disassembly	**58.33**	20.5	16.8	16.7	8.7	39.6	18.6	36.1	23.6	18.3	14.6	35.4	30.7	23.5	19.6	55.9	55.9	57.0	57.0	43.6	39.9
Information Acessiblity	**12.5**	0.6	0.6	0.6	0.6	0.6	0.6	1.3	0.6	0.6	0.6	0.6	0.6	7.5	7.5	11.6	11.6	11.6	11.6	3.8	0.6
Spare part availablity	**20.83**	5.2	5.2	8.9	1.5	5.2	5.2	17.9	5.2	5.2	5.2	5.2	5.2	16.4	12.6	16.4	16.4	16.4	16.4	5.2	5.2
Spare part price	**0**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Software aspects	**0**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Health and saftey	**4.17**	1.4	1.0	1.4	1.0	3.5	3.5	1.7	1.7	1.0	1.0	1.6	1.6	1.7	1.4	4.0	4.0	4.0	4.2	3.5	3.5
Repair endorsment	**4.17**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	4.2	1.0	4.2	4.2	4.2	4.2	1.0	1.0
OVERALL SCORE		**28.7**	**24.8**	**28.6**	**12.9**	**49.9**	**28.9**	**58.0**	**32.2**	**26.2**	**22.6**	**43.8**	**39.1**	**53.3**	**42.2**	**92.0**	**92.0**	**93.1**	**93.2**	**57.1**	**50.3**

Table 6: Calculated JRC and FRI scores for vacuum cleaners.

		JRC											
Product		Dyson		Bosch		Siemens		Philips		Hoover		Samsung	
Criteria	Weight %	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst
Ease of Disassembly	60	55.2778	37.7778	51.25	48.75	55.5263	48.6842	48.9474	33.1579	51.3889	51.3889	54.7222	52.5
Information Acessiblity	20	11.25	11.25	7.5	7.5	7.5	7.5	8.75	8.75	8.23529	8.23529	8.75	8.75
Spare part availablity	20	3.88889	3.88889	7.5	7.5	20	20	0	0	6.11111	6.11111	0	0
Spare part price	0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
OVERALL SCORE		70.4167	52.9167	66.25	63.75	83.0263	76.1842	57.6974	41.9079	65.7353	65.7353	63.4722	61.25
		FRI											
Ease of Disassembly	20	18.1746	14.0595	14.8413	14.8413	18.6667	17	12.619	8.11905	12.7778	12.7778	14	14
Information Accessiblity	40	17.3333	9.33333	13.3333	5.33333	13.3333	5.33333	16	8	14.6667	6.66667	14.6667	6.66667
Spare part availablity	20	4.44444	2.84444	5.07407	3.47407	13.0949	11.4949	5.22222	3.62222	6.75128	5.15128	4.93333	3.33333
Spare part price	20	0	0	0	0	0	0	0	0	0	0	0	0
OVERALL SCORE		39.9524	26.2373	33.2487	23.6487	45.0949	33.8282	33.8413	19.7413	34.1957	24.5957	33.6	24

5.9d: DaRT timings for each action

*Table 7: DaRT Timings. Assumptions: a) Basic tools are used, no power tools, b) The disassembly sequence product is known, c) Disassembly is done by Professional repairer. * =Disassembly action could be performed in reassembly and vice versa. a = For large items (such as washing machines) 1.3 factor is applied. b = This time is added to the action. Green cells = Disassembly and reassembly times are different, Disass = Disassembly, Reass = Reassembly.*

Action (Disass)	Disass Dart Time (s)	Action (Reassembly)	Reass Dart Time (s)
Tool Change	2.97	Tool Change	2.97
Hinge (open)*	2.10	Hinge (close)*	2.10
Loosen (friction fit)	3.30	Attach	5.47
Pry (snap fit)	4.45	Attach	4.45
Pull	2.10	Push	2.10
Remove and pace component away	2.40	Grab and place component in position	7.67
Remove and place screw away	1.87	Grab and place screw in position	3.30
Tilt* (>150N)	6.05	Un-tilt*	3.92
Tool positioning [a]	1.83	Tool positioning [a]	1.83
Turn product with two hands	3.23	Turn product with two hands	3.23
unplug (hose)	2.70	Plug (hose)	5.87
unplug (wires)	3.83	Plug (wires)	3.83
Unroute (cables)	4.13	Route (cables)	8.30
Unscrew Crank Small-medium	9.73	Screw Crank small-medium	9.73
Unscrew Turn Small-medium	6.00	Screw Turn small-medium	6.00
Cut*	1.96	Cut*	N/A
Pry Circumference	3.00	Attach pried circumference	N/A
Pry Glued Circumference (/5cm)	21.00	Attach glued circumference	N/A
Unscrew Turn High	18.20	Screw Turn High	N/A
Unscrew Crank High	14.90	Screw Crank High	N/A
Pry (snap fit) High	12.7	Attach	N/A
Loosen (friction fit) High	12.1	Attach	N/A
Dismantle	7.62	Assemble	9.52
Adhesive heat (plate)	128	N/A	N/A
Accessibility penalty [b]	14	Low Accessibility [b]	11.11

5.9e: Correlation coefficient and trendline for DaRT proxy times

*Table 8: Correlation coefficient and trendline for DaRT proxy times and steps as a function of actual disassembly time. *To provide appropriate time-based comparison, steps values are multiplied by 26.3 for the trendline.*

Products	R^2 Relation to Actual Time		Trendline	
	DaRT	Steps	DaRT	Steps*
Washing Machine	0.99	0.94	1.06x +14.21	0.81x +83.31
TV	0.93	0.61	0.96x -12.33	0.68x +76.93
Vacuum Cleaner	0.97	0.54	0.91x +9.20	0.62x +49.77
Overall	**0.98**	**0.86**	**0.95x +10.32**	**0.79x +58.60**

6.
Discussion and Conclusion

This dissertation investigated multiple dimensions of repairability - spanning product design, fault diagnosis, disassembly and reassembly, and evaluation methods. Throughout this work, we examined how product design features influence the ease and effectiveness of fault diagnosis (Chapter 2), the development of more accurate yet practical models for assessing disassembly and reassembly times (Chapter 3), objectivity and completeness in repairability scoring systems (Chapter 4), and the validity (accurately and comprehensively measure what it is intended to measure) and reliability (consistently and objectivity measure the scores) of currently available scoring systems (Chapter 5).

In exploring these areas, the dissertation expanded upon traditional notions of “design for repair” by integrating user-centric considerations, such as the end-user’s ability to locate, isolate, and interpret faults (Chapter 2). It moved beyond a narrow emphasis on disassembly and maintenance actions to incorporate the under-addressed dimension of design for diagnosis. Further, it recognized that existing evaluation methods, including the commonly used step counting for disassembly, may be less reliable indicators of ease of repair than time-based approaches like the DaRT (Disassembly and Reassembly Time) model (Chapter 3). Finally, through an in-depth analysis of repairability scoring systems, it identified gaps in its validity and reliability, shedding light on the need for robust criteria that accurately capture a product’s repairability potential (Chapters 4 and 5).

Together, these areas show that making products easier to repair requires aligning design strategies with strong evaluation methods. By placing repair at the intersection of user needs, design, and assessment, this dissertation emphasizes that repairability is complex and that holistic approaches are key to supporting the circular economy and the right to repair.

6.1. Overall Outcomes

Building on a thorough examination of consumer-product repair processes, this concluding section highlights how design features, user fault diagnosis, disassembly, and repair information converge to influence real-world repair outcomes. Overall, the dissertation demonstrates that consumer product repairability arises from the intricate interplay of multiple interdependent elements, including product design, user fault diagnosis, disassembly complexity, spare part availability, spare part price, and the availability of repair information, and that valid and reliable assessment of these factors is essential for improving real-world repair outcomes

We observed that product design heavily influences a user's ability to diagnose faults, more than their repair expertise (Chapter 2). Users tend to follow different strategies depending on the design of the product: a "pinpointed strategy", which is a strategy that led the user directly to the fault, was often the outcome of design features that provided clear feedback to the user. A "systematic strategy", which is based on deducing the problem in structured iterative steps was followed by the users when there were design features that facilitated disassembly of the product. In contrast, if disassembly is not facilitated or is even hindered (e.g. due to hidden and high force fasteners), users would often follow an "unstructured strategy" and give up.

As disassembly is a key principle in repairability, we provided methodological improvements in assessing disassembly and reassembly times, most notably by developing the DaRT model (Chapter 3). This model uses proxy time based on over 10,000 datapoints of actual repair actions on different types of smart phones, smart TVs, vacuum cleaners, and washing machines. The model was able to predict disassembly times for household appliances with a high level of accuracy while being easier to apply than more complex models such as eDIM. Notably, DaRT's inclusion of reassembly times represents an advance over other existing approaches, enabling a more comprehensive assessment. In addition, this model accommodates a wide range of products, thus broadening its applicability. Its balance of simplicity and accuracy holds significant promise for enhancing scoring systems that measure physical repairability, ultimately supporting manufacturers and repairers in developing and accessing sustainable product designs.

The analysis of various repairability scoring systems revealed that most scoring systems tend to perform well in evaluating specific design factors, particularly fastener reusability and ease of disassembly. However, while they are instrumental for policymaking, consumer guidance, and market surveillance, they are often insufficiently objective and complete (Chapter 4). All of the evaluated scoring systems could be improved to more objectively assess design aspects such as fault diagnosis, health and safety criteria, and software restrictions. In addition, most systems would be strengthened by including criteria such as repair safety, diagnosis and software restrictions.

The reliability and validity of repair scoring systems depend on their ability to consistently and accurately reflect real-world repair scenarios across diverse product contexts. While the scoring systems showed a similar trend for the products studied, they fail to accurately represent scenarios where repair is unrealistic or prohibitively expensive (Chapter 5). This is related to the fixed weights that are attributed to the different aspects that determine repairability. To address this, the dissertation proposes a limiting factor approach, which ensures that critical criteria significantly impact the overall score when their thresholds are not met. We also identified that ambiguous interpretation of criteria can cause substantial variations in scores. Here we provide several recommendations addressing ambiguities related to bundling of parts into sub-assemblies, spare part availability, spare part pricing, and provision of repair and diagnosis information, ensuring these aspects are assessed consistently and objectively.

6.2. Integrated Perspectives on Repairability: Synthesizing Design, User, Manufacturing, and Policy Insights to Advance Circular Strategies

Adopting different perspectives is essential for understanding how design, user behavior, manufacturing decisions, and policy frameworks collectively shape real-world repair outcomes. This chapter synthesizes insights from these perspectives, illustrating how integrated efforts can enhance repair feasibility, empower users to engage in repair, and inform policy actions that foster a more sustainable, circular economy.

Design Perspective

Design guidelines for ease of repair have been extracted from this research building upon findings from literature research (Chapter 2, Chapter 4), examining how various design features and actions influence disassembly and reassembly (Chapter 3), analyzing how design features influence fault diagnosis by users (Chapter 1), and evaluating different scoring systems (Chapter 4, Chapter 5). Table 1 summarizes the design guidelines for repair synthesized from this research.

Table 14: Design guidelines for repair. Priority parts are parts with a relatively high likelihood of failure that are essential for products function. The numbers in brackets next to design guidelines indicate the chapter this guideline is derived from.

Design Guideline	Explanation / Example
Facilitate diagnosis through clear symptom-to-cause fault indication. (2)	Clear fault indication, e.g., explicit messages such as “battery failure” or “replace battery”, enables the user or technician to directly identify the faulty component without extensive investigation.
Minimize the need to disassemble the product for fault diagnosis. (2)	• Provide easily accessible test points for electrical diagnostics. • Provide easily accessible diagnostic doors or panels to inspect priority components (e.g., battery compartment). • Provide transparent or clear housing to quickly verify internal conditions visually.
Use fasteners that are easy to remove and reassemble. (2,3,4,5)	• Minimize high force snap fits (>20N removal force) to reduce effort and avoid damage. • Avoid adhesives and hidden or non-standard fasteners to simplify access. • Utilize reusable fasteners (e.g., screws) for ease of reassembly.
Position priority parts such that fewer components need to be removed before reaching them. Decrease the number of actions required to reach the priority part. (3,4,5)	Design products so non-priority parts are clustered into removable sub-assemblies, enabling priority parts to be accessed independently. Alternatively, relocate priority components toward shorter disassembly pathways.
Provide disassembly and reassembly guidance. (2,4,5)	Disassembly and reassembly cues facilitate correct and safe maintenance procedures, reducing user error: • Clearly visible and labelled fasteners;

	• Color-coded wiring or connectors; • Visual assembly/disassembly diagrams or icons.
Provide comprehensive repair information. (2,4,5)	Detailed information regarding failure diagnosis, user-friendly repair guides, professional repair options, spare parts availability, and associated repair costs helps empower consumers, enabling informed repair decisions.
Avoid bundling priority parts with other components using non-removable fasteners. (3,4,5)	Priority parts should be individually accessible and removable without damaging adjacent components. Bundling with non-removable fasteners to other components increases spare part cost.
Standardize components and interfaces. (4,5)	Standardizing parts and interfaces across multiple products that perform identical or similar functions (e.g., motors and batteries) improves spare parts availability, reduces costs, and thus significantly enhances product repairability.

These design guidelines provide manufacturers and designers with a set of criteria and considerations that can be integrated early in the product development process to systematically improve the repairability of household appliances.

Design for repair is, however, just one step in circular design, and designing for other circular strategies, such as durability or recyclability, might lead to complementary and sometimes contradictory guidelines due to the inherent trade-offs between extending product lifetimes and facilitating efficient material recovery at end-of-life. Such interactions and tensions among these strategies will be discussed in section 2.3.

User Perspective

Design for repair and user behavior are connected. Design choices affect how users perceive and approach repairs, and effective design must also tackle psychological and social barriers. User willingness to repair depends not only on technical feasibility but also on perceived ease, access to information, and confidence in the process [1]. Many users still hesitate to repair due to fears of breaking the product further, doubts about their skills, or the belief that repair is inconvenient [2], [3]. Our findings show that intuitive design elements like clear fault indication, visible disassembly paths, and modular components simplify repairs and empower users to engage with repair and bridge the gap between a product's technical repairability and adoption of repair by users. These findings echo broader studies, which argue that user-centered design should account for both the practical and psychological needs of repairers [2].

However, product appeal and the stigma of repaired goods could discourage these efforts. Addressing these challenges involves creating designs that empower users while promoting repair as both environmentally and economically valuable. The rise of repair cafes and do-it-yourself repair communities shows that users respond positively to repair when the process is accessible and rewarding [4]. By aligning product design with these values, repair can become a key driver of circular economic goals.

Repair labels as an outcome of assessment have the potential to guide consumer or institutional purchasing decisions by clearly communicating product repair. However, the effectiveness of these labels critically depends on how reliably and validly the information is presented to consumers, highlighting the need for transparent and credible communication [5]. Existing repairability labelling frameworks, such as the French Repairability Index (FRI), explicitly incorporate user-centric aspects such as ease of disassembly and information accessibility, which directly impact consumers' perceptions of repairability. However, we identified that many scoring systems fail to consider scenarios in which a product can still receive high overall scores despite low ratings on critical repairability factors such as spare parts pricing and availability, which are crucial for influencing users' decisions to repair rather than replace. Consequently, this shortcoming diminishes the validity of these scoring systems.

Regardless, merely presenting repair-related information on labels may inadvertently reinforce consumers' doubts about product quality and longevity [6]. Therefore, successful labelling requires not only technical validity but also strategic integration of psychological and social considerations. In these scenarios, work focusing on the user perspective, such as that of van den Berge [5] complements this dissertation in bridging the gap between technical repairability and consumer adoption of repair practices.

Manufacturer Perspective

Manufacturers generally balance trade-offs during design decisions. For instance, bundling multiple functions into a single component may lower production costs and enhance performance, yet it can complicate fault isolation, make disassembly and reassembly impossible, and create expensive spare parts. Similarly, strong adhesives might deliver improved waterproofing but hamper disassembly [7]. As a result, manufacturers often neglect repairability, perceiving it as a cost-increasing factor. However, designing for disassembly can also improve design for assembly, ultimately reducing manufacturing costs. For example, in designing the Mirra chair for disassembly, Herman Miller reduced the number of fasteners and simplified the assembly process, leading to shorter assembly times and lower manufacturing costs [8].

Additionally, redesigning products for easier repair can yield long-term returns through better customer loyalty and brand differentiation in markets that value sustainability [9]. By embedding repairability into the core product strategy, firms can, for example, transition from purely sales-driven models to service-oriented approaches, where revenue emerges from offering maintenance packages, repair services, and ongoing product upgrades. This shift encourages deeper consumer loyalty by demonstrating a genuine commitment to extended product lifespans and responsible resource usage [10]. Furthermore, emphasizing repairability bolsters brand reputation among environmentally conscious consumers, reinforcing perceptions of quality and ethical stewardship [11]. Over time, such strategies can generate cost savings in material consumption, establish stronger post-purchase relationships, and enable companies to stand out in a market increasingly attuned to circular economy practices. Ultimately, prioritizing repairable designs offers both economic resilience and environmental credibility.

Design decisions for repair do not necessarily have to come with significant tradeoffs. Design details such as hidden cable routes or fastener type can significantly raise repair complexity and can be easily avoided. Employing strategies like labeled wiring, user-friendly fasteners, and moving priority parts up the disassembly pathway can reduce the skill and time required for successful diagnosis and repair. These often-minor design decisions can form a decisive factor in whether a product is ultimately repaired or replaced.

Additionally, manufacturers are able to utilize the scoring systems to assess their products and guide decisions that favor repairability. When it comes to repairing, the ability to predict the time it takes to repair the product becomes important. A tool such as DaRT could be an asset in predicting repair times.

Policy Perspective

Policy interventions have increasingly recognized repair as a key strategy to extend product lifetime and reduce waste, notably through initiatives such as the Right to Repair directive [12]. These regulations foster legislative frameworks that call for mandatory repairability indicators and product design requirements. Our research informs these efforts by providing evidence on how poor design can hamper disassembly and prohibitively expensive or unavailable spare parts can nullify the intended environmental benefits of repair. For instance, our findings show that even if a product scores well on some criteria, leading to a relatively high overall score, a single non-removable or unreasonably expensive part may render repair practically infeasible. Addressing such pitfalls could benefit from a "limiting factor" approach. In this approach, if a criterion fails to meet a specified threshold, the overall score would be predominantly determined by this critical criterion, based on how far it falls below the threshold. This approach prevents low scores in critical criteria from being offset by high scores elsewhere.

Moreover, our comparative analysis of repairability scoring systems (JRC, iFixit, FRI, and ONR) points to the need for more precise policies that account for actual disassembly complexity rather than mere theoretical criteria like the number of steps. By incorporating proxy-time approaches (DaRT) and properly weighing the different aspects of repairability, policy instruments can better capture genuine repair feasibility, thus spurring design improvements. Our research highlights the importance of robust, detailed policy guidelines which encourage specifying criteria such as availability of diagnostic information, reassembly feasibility, and realistic cost thresholds to ensure that legislative measures genuinely promote a culture of repairing over discarding. Such insights have already proven valuable for guiding future regulatory pathways, as evidenced by our contributions to a JRC policy report [13], which demonstrates this dissertation's broader outreach and influence on the development of future regulations.

6.3. Relations to other circular strategies

Repair-centered strategies and guidelines are intricately interwoven with other core principles of the circular economy, such as product durability (product's ability to function reliably under diverse operational conditions across its intended service life), remanufacturing, and recycling [14], [15], [16], [17], [18]. While on the one hand there are synergies between different strategies (such as repair and remanufacturing), on the other hand tensions also exist, particularly around aspects of repair and durability or repair and recyclability. As a result, design decisions must strike a balance between the relevant circular strategies in order to optimize the overall circularity of the product.

Design for remanufacturing rests on core design principles including modular architecture, standardized interfaces, and straightforward component separation that both simplify and accelerate the remanufacturing process [19]. Facilitating disassembly and reassembly not only helps with individual repairs but also enhances batch-level operations in remanufacturing, where restoring multiple units to a near-new condition hinges on quick disassembly and the reliable reassembly of refurbished or replacement modules. As a result, design for remanufacturing has a stronger interest in disassembly methods that can be automated compared to design for repair. Moreover, robust component design capable of enduring repeated disassembly, minimizes the risk of breakage and thereby increases the likelihood of multiple lifecycles. Overall, design for remanufacture and design for repair have much in common, however design for remanufacture will benefit from a stronger focus on automated repair in contrast to manual disassembly for repair.

While repairability assessment can be predicted based on the product architecture, robustness cannot be easily determined. Assessing robustness typically requires accelerated testing and stress tests, as breakdown of components can be due to many different loads (mechanical, electrical, thermal, chemical, physical) and is often dependent on the complex interplay of multiple components [20]. Measures that advance repairability, like particular types of connectors, might simultaneously reduce robustness. Examples are parts being integrated into large modules, or being glued together for water and dust resistance, both of which could reduce repairability of the product. In such cases repair is not just made easier, but also may need to be performed more often, likely at the cost of an increased environmental impact [3], [20]. Ultimately, durability must be considered integral parts of design for repair if we wish to promote a culture of extended product lifetime.

Design for recycling may benefit from principles such as design for disassembly when specific components need to be manually extracted (e.g., batteries) before further processing [21]. However, manual disassembly during recycling is largely limited to depollution, and recycling takes usually place in a destructive mechanical step (shredding). Some connections are unfavorable in both repair and recycling, e.g. adhesives. Unfortunately, some design features that promote repair, such as screws, often fail to disconnect during shredding, thus hampering recycling [22]. This issue illustrates a potential trade-off: ease of reversible manual disassembly, which is beneficial to repair, may adversely affect recycling yield. Consequently, achieving optimal product circularity requires a nuanced understanding of these competing design strategies, emphasizing the need for context-specific analysis to balance repairability and recyclability objectives.

6.4. Contribution to Science

This dissertation advances scientific understanding of repairability by exploring dimensions of product design, user interaction, and evaluation criteria that had previously received limited attention. While existing literature has examined disassembly and maintenance, this research expands the scope to emphasize fault diagnosis as a critical precursor to effective repair, emphasizing its role in bridging technical design and user interaction. This approach extends beyond traditional studies centered solely on mechanical ease of repair, introducing a more holistic view of how diagnostic design elements interact with user cognition and behavior.

In addition, the studies here challenge and refine existing frameworks for repairability assessment. Through a rigorous comparison of scoring systems against established design principles and empirical tests, this dissertation not only identified shortcomings in current methodologies (such as their incomplete coverage of diagnosis aids and inconsistent weighting of key criteria) but also provides recommendations such as introducing limiting factors for critical repairability criteria and providing more details to enhance their validity and reliability. This contributes to the broader body of knowledge on product assessment and standardization, offering researchers a more nuanced understanding of what constitutes a truly repairable product.

In our study on disassembly and reassembly times we established that for most operations disassembly and reassembly require a similar time, something that was tacitly assumed in other studies. However, we established that especially in the case of actions that require positioning, reassembly often takes more time than disassembly. Further, the development and validation of the DaRT proxy time model provides deeper insight into disassembly and reassembly among a wider range of product architectures than studied before. By demonstrating its simplicity and accuracy over diverse product categories, this research established a practical, time-based alternative to complex metrics like eDiM, offering an adaptable approach for future studies.

6.5. Contribution to Society and Environment

The insights and methodologies developed in this dissertation have clear societal and environmental relevance. By highlighting how product design can empower users to diagnose and fix their own devices, the research supports the "right to repair" movement, further enabling individuals and communities to reduce unnecessary waste and consumption. When end-users feel more confident in repairing products, it diminishes the steady stream of discarded electronics, ultimately decreasing the burden on waste management systems and the environmental footprint associated with manufacturing new goods. Additionally, reliable scoring systems enable users to better consider repairability in their buying decisions. Furthermore, the DaRT tool developed in this dissertation enables companies and policymakers to evaluate a product's physical repairability, allowing both producers and repairers to more accurately calculate the resources needed for repair services, promote the design of more repairable products, and ensure compliance with relevant policies.

From a policy perspective, more accurate and objective repairability scoring systems can guide legislators and market surveillance authorities toward more informed decision-making, ensuring that future regulations better reflect genuine repairability potential rather than superficial product claims. A higher standard of repairability not only enhances users' trust in sustainable products but also encourages manufacturers to invest in more robust designs. Such a shift in industry practices can help conserve precious raw materials and curb greenhouse gas emissions, aligning with global ambitions to mitigate climate change and foster a more resource-efficient, circular economy.

6.6. Limitations and future research

This section addresses the limitations identified in the research and provides recommendations for future studies to enhance the understanding and application of repairability in design, disassembly assessment, and scoring systems. While significant progress has been made in these areas, some gaps remain.

Future studies on design for repairability and diagnosis could expand the scope to include a broader range of consumer products, as the current research focused on a limited subset, such as small household appliances and ICT devices. A more diverse product pool would enable the identification of additional design features that influence fault diagnosis and repairability across a wider range of product categories. Additionally, while the proposed design guidelines highlight principles like accessibility, modularity, and feedback, their practical implementation in real-world product development remains underexplored. This shows a need for further empirical studies to investigate how these guidelines influence product design, user interactions, and repair practices. Moreover, examining ways to effectively integrate these guidelines into existing design workflows, such as through design tools or training programs for designers, could bridge the gap between theoretical recommendations and practical application.

Despite significant progress made with tools such as the DaRT model, disassembly assessment still faces some limitations. For instance, actions such as loosening and prying demonstrate exceptionally broad time distributions, making it difficult to accurately capture the variability in real-world scenarios. Further research is needed to explore the underlying factors influencing these variations, such as material properties and design choices. Additionally, while DaRT proxy times provide robust estimates for many actions, their applicability to other product categories, like furniture or automotive components, remains untested. Expanding DaRT's dataset to encompass a wider range of products could enhance its generalizability. Moreover, insufficient data on actions such as desoldering and certain reassembly tasks limit the completeness of the model. Gathering empirical data for these underrepresented actions would refine the model and improve its predictive accuracy, enabling more reliable repairability assessments across diverse products.

Current repairability scoring systems, while valuable, lack sufficient focus on underexplored criteria such as health and safety, diagnostic capabilities, and software pairing, which relates to the inability to use the same parts that have not been directly authorized by the manufacturer. These gaps limit the comprehensiveness of the assessments. For example, the health and safety criteria remain largely subjective, with unclear definitions of the levels and their testing methods, limiting the consistency and applicability of scores. Similarly, diagnostic aspects are often reduced to the presence of error codes or simple fault indicators, overlooking the role of physical design features like accessibility to testing points and visibility of components. Future research should explore these criteria in greater detail, developing objective metrics that capture their influence on real-world repair scenarios. These enhancements could significantly improve the validity of the scoring systems.

Additionally, tensions and synergies with other circular strategies, particularly durability and recycling, have not been examined in depth within this dissertation. Future research could more systematically investigate how these strategies interact, thereby yielding robust insights into the complexities and opportunities that arise from implementing and assessing multiple circular measures concurrently. By exploring these potential trade-offs and complementarities, policymakers and designers can make informed decisions that maximize resource efficiency, minimize environmental impacts, and promote sustainable practices.

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About the author

Sagar Dangal was born on September 22, 1991, in Chautara, Nepal. He completed his master’s degree in integrated Product Design, graduating Cum Laude from Delft University of Technology in December 2018. His master's research focused on ergonomics and generative design, successfully reducing aircraft seat weight by 20% and significantly enhancing passenger comfort, a contribution documented in a published scientific paper.

Following his graduation, Sagar served as an R&D Product Design Engineer at Vanema, where he specialized in designing and prototyping lightweight, ergonomic aircraft seats utilizing innovative spring-foam technology in compliance with FAA and EASA standards.

From 2019 to 2023, Sagar was a PhD researcher and work package leader on repairability at TU Delft, where he developed methods to test premature obsolescence in household electronics. He led a multidisciplinary team to improve product longevity through testing protocols, design guidelines, and contributions to circular economy policies and standards.

Currently, he works as a product research manager and freelance consultant, translating user insights into actionable product strategies. His work bridges design, research and engineering with real-world user needs.

List of Publications

Journal Article

Arcos, B. P., Dangal, S., Bakker, C., Faludi, J., & Balkenende, R. (2021). Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study. *Journal of Cleaner Production*, 319, 128741.

Dangal, S., Faludi, J., & Balkenende, R. (2022). Design Aspects in Repairability Scoring Systems: Comparing Their Objectivity and Completeness. *Sustainability*, 14(14), 8634.

Dangal, S., Martinez, S., Bolanos, J., Faludi, J., & Balkenende, R. (2024). Empirical evaluation of repairability scoring systems for validity and reliability. *Resources, Conservation and Recycling*, 218,108211.

Conference Paper

S. Dangal, R. van den Berge, B. Pozo Arcos, J. Faludi, and R. Balkenende, "Perceived capabilities and barriers for do-it-yourself repair," May, 2021, PLATE Conference. Available: https://ulir.ul.ie/handle/10344/10261.

Acknowledgements

I owe my deepest thanks to my promoter and co-promoter, Ruud and Jeremy. You gave me exactly the right mix of freedom and rigor. Your timely questions, line-by-line comments, and strategic guidance raised the standard of this dissertation and taught me how to design rigorous studies that yield valid insights, argue with precision, write with clarity and brevity, and draw conclusions that are both robust and impactful. Thank you for your patience, and for always making time when it mattered.

Thank you to the doctoral committee for reading, assessing, and providing valuable feedback on this dissertation. I built on the groundworks you laid, and it is a pleasure to have the scholars who defined this terrain on the committee.

To my PhD colleagues: thank you for the daily companionship. Our lunch conversations made the hard days lighter and the good days better. We helped each other debug, rethink, and keep perspective. This mutual support is something I will always value. Our trip to Texel remains one of my most cherished memories.

To the SDE team: thank you for the supportive atmosphere. Conny Bakker and Bas, your doors were always open for support and stimulating conversations; your curiosity turned hallway check-ins into chances to develop new ideas and insights. Ingrid, coaching the student courses with you was a pleasure. Your calm structure and insightful feedback taught me how to coach with clarity and care, and those lessons will shape how I teach long after this thesis.

Dear members of the PROMPT project team: it was wonderful working together in pursuit of longer-lasting products. From workshops and deliverables to timely discussions, your professionalism made collaboration a pleasure. I would specifically like to thank the iFixit team and the RUSZ team for our collaboration within the work package. I greatly valued your openness, the quality of the discussions, and the way the team balanced ambition with pragmatism. Your input greatly strengthened the contents of this dissertation.

Dear Gery, thank you for your continuous support and motivation throughout this journey. You were there for me on the long days and the late nights, with patience and practical help, reminding me to rest and celebrate small wins, you turned a solitary process into a shared endeavor. I could not have done this without you.

And last but not the least, my parents. I am deeply grateful for their continuous support. Your steady encouragement, quiet sacrifices, and insistence on curiosity, integrity, and hard work made this journey possible. Whatever merit this work has, carries your imprint. Any success I have is, in no small part, the consequence of your love and example. I am here because of you.