FAULT DIAGNOSIS IN HOUSEHOLD APPLIANCES: A DESIGN PERSPECTIVE

Beatriz POZO ARCOS

Sustainable Design Engineering

TU Delft

Beatriz POZO ARCOS

Fault Diagnosis in Household Appliances: A Design Perspective

FAULT DIAGNOSIS IN HOUSEHOLD APPLIANCES: A DESIGN PERSPECTIVE

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
Friday 28th, January 2022 at 10:00 o'clock

by

Beatriz POZO ARCOS

Master of Science in Industrial Engineering
Universidad de Castilla-La Mancha, Spain
born in Ciudad Real, Spain

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	Chairperson
Prof.dr.ir. C.A. Bakker	Delft University of Technology, promotor
Prof.dr. A.R. Balkenende	Delft University of Technology, promotor

Independent members:

Prof.dr.ir. P. Zwolinski	University Grenoble Alpes, France
Dr.-ing. N.F. Nissen	TU. Berlin, Germany
Prof.dr.ir. R. Mugge	Delft University of Technology
Prof.dr.ir. R. Wever	Linköping University, Sweden
Prof.dr.ir. J.M.L. Van Engelen	Delft University of Technology, reserve member

The works in this dissertation have been funded by the European Commission under the Horizon 2020 Marie Skłodowska Curie Action 2016 (Grant Agreement number 721909)

ISBN 978-94-6384-292-1

Cover: “People repairing an appliance at a Repair Café, November 2019”. by Beatriz Pozo Arcos
Layout: Beatriz Pozo Arcos

“Whatever you are not changing,
you are choosing”

Acknowledgements

This thesis is my humble contribution to move towards more sustainable ways of production and consumption. Designing products with multiple lifecycles in mind is a way forward towards a better use of our limited planet resources. In this short section, I acknowledge and thank the people that have made this contribution possible.

First, I would like to thank my supervisors Conny and Ruud for accepting me with open arms in their research team, for their constant support and dedication, for their valuable feedback. Overall, I would like to thank them for helping me become the professional I am today. We make a team 1+2 = 4

I would like to thank my family and friends for the love, continuous support, and understanding. You are the north that keeps the needle pointing firmly in my compass.

I would like to thank colleagues from the 4th floor and from the Circ€uit research group for making this research process one of fun times and togetherness.

I would like to thank mentors like Andreas W., Maria W., and Naama ben M. for encouraging me to take this position and make the most out of this project.

I would like to thank disrupters and critics for respectfully challenging my ideas and therefore, contributing to advance the knowledge presented in this thesis.

I would like to thank all people who are putting passion into seeking for a better world for future generations. Keep on going! The movement is slow but the impact will be worth it.

Finally, I would like to thank the doctoral committee members for accepting the invitation to my defence and contributing to the improvement of this thesis.

Table of contents

Summary I

Samenvatting VII

Chapter 1 Introduction 1

1.1 The circular economy for a sustainable development 4

1.2 Design for a circular economy and repair 4

1.3 The process of fault diagnosis and its importance for product repair 6

1.4 Scope 8

1.5 Research objective, research questions and research design 8

1.6 Relevant terms and definitions 9

1.7 Thesis outline 10

Reference 13

Chapter 2 Product Design for a Circular Economy: Functional Recovery on Focus 19

2.1. Introduction 21

2.2. Methodology 22

2.3. Results and Discussion 23

- 2.3.1. Scientific Papers related to Product Design and Circular Economy 23
- 2.3.2. How can product design improve functional recovery from products? 24

2.4. Conclusions 35

2.5. Limitations 36

References 37

Chapter 3 Practices of Fault Diagnosis in Household Appliances: Insights for Design 41

3.1. Introduction 43
3.2. Theoretical framework 44
3.3. Designing for fault diagnosis 47
3.4. Method 49
    3.4.1. Source selection 49
    3.4.2. Product case selection 50
    3.4.3. Content selection 50
    3.4.4. Content analysis 50
3.5. Results - Product case studies at iFixit 52
    3.5.1. Fault diagnosis of blenders 52
    3.5.2. Fault diagnosis of vacuum cleaners 54
    3.5.3. Fault diagnosis of refrigerators 56
    3.5.4. Summary of results 59
3.6. Discussion 61
3.7. Conclusions 65
Acknowledgements 65
References 66

Chapter 4 Faults in consumer products are difficult to diagnose, and design is to blame: a user observation study 71

4.1. Introduction 73
4.2. Fault Diagnosis Model and Analysis Framework 75
    4.2.1. The Diagnosis Process 75
    4.2.2. Strategies for Fault Diagnosis of Consumer Products 76

4.3. Method 77
    4.3.1. The think aloud method 77
    4.3.2. The participants 77
    4.3.3. The products and the faults 78
    4.3.4. Procedure of observations 81
    4.3.5. Data Analysis 83
4.4. Results 88
    4.4.1. Diagnosis Process and Strategies 88
    4.4.2. Influential Factors for the Diagnosis Process 92
    4.4.3. Summary of results 97
4.5. Discussion 97
    4.5.1. About the process of fault diagnosis 97
    4.5.2. About influential factors for fault diagnosis 98
    4.5.3. Initial Design Guidelines to Facilitate Fault Diagnosis 99
4.6. Limitations and recommendations for further study 102
4.7. Conclusion 102
Acknowledgements 103
References 103

Chapter 5 How User Manuals Support the Diagnosis of Common Faults in Household Appliances: An Analysis of 150 manuals 109

5.1. Introduction 112
5.2. Fault Diagnosis Process by End Users 114
5.3. Method 115
    5.3.1. Selection of the manuals 116
    5.3.2 Analysis of the user manuals 117

5.4. Results 120
    5.4.1. Single Dose Coffee Makers 120
    5.4.2. Cylinder Vacuum Cleaners 121
    5.4.3. Washing machines 123
    5.4.4. Fridge – Freezers 125
    5.4.5. Summary of Results 127
5.5. Discussion 127
5.6. Conclusions 133
Declarations 134
References 134

Chapter 6 Discussion and Conclusions 137

6.1. Summary of Findings 138
6.2. Fault diagnosis of household appliances by end users 140
6.3. The influence of product design on the process of fault diagnosis 143
6.4. Fault diagnosis for stimulating repairs 147
6.5. Contribution to scientific knowledge 150
6.6. Implications for design practice 150
6.7. Implication for policy 151
6.8. Future studies and recommendations 152
References 154

About the author 158

Summary

Today's industrialized societies face the challenge of integrating economic activity with sustainable consumption. Prosperity has come hand in hand with environmental damage. Product lifetimes are decreasing and there is a rising demand for high-tech products for which no effective recycling is in place. Hence, the value from products is lost to waste. The current use and management of the Earth's resources is unsustainable.

The circular economy (CE) aims at slowing, closing, and regenerating the flow of goods and materials that enter the economic system. It posits retaining the value from products and encourages a shift to renewable energy resources. In this way, the CE will help reduce our current accelerated resource depletion. In particular, product repairs can help slow down the flow of goods. Repairing products provides an alternative to premature product replacement, and contributes to a significant reduction of waste.

In this thesis, I look in detail at the process of fault diagnosis, one of the initial steps to be taken when repairing products. Fault diagnosis identifies the faulty component(s) or cause of failure in a malfunctioning appliance and is therefore essential for efficiently repair. It enables the time, cost, and skills required for the component repair to be established.

At the start of this PhD, literature had not addressed how end users went through the fault diagnosis process. Neither had it addressed how design could affect this process. However, gaining a complete understanding of the diagnosis process is important to stimulate repair. To this end, in this thesis I address the following two main research questions:

(1) How do end users, with limited repair experience, diagnose faults in household appliances?

(2) How does the design of a household appliance influence the fault diagnosis process?

We investigated both questions by taking a mixed methods approach. We applied both qualitative and quantitative research and analysis techniques including: literature reviews (chapters 2, 3, and 4), content analyses (chapters 3 and 5), and a user observational study (chapter 4).

The first main research question: *How do end users, with limited repair experience, diagnose faults in household appliances?* was addressed in chapters 3, 4, and 5. From these three studies, we derived a framework that describes the processes users follow to diagnose a fault in household appliances (see figure 1).

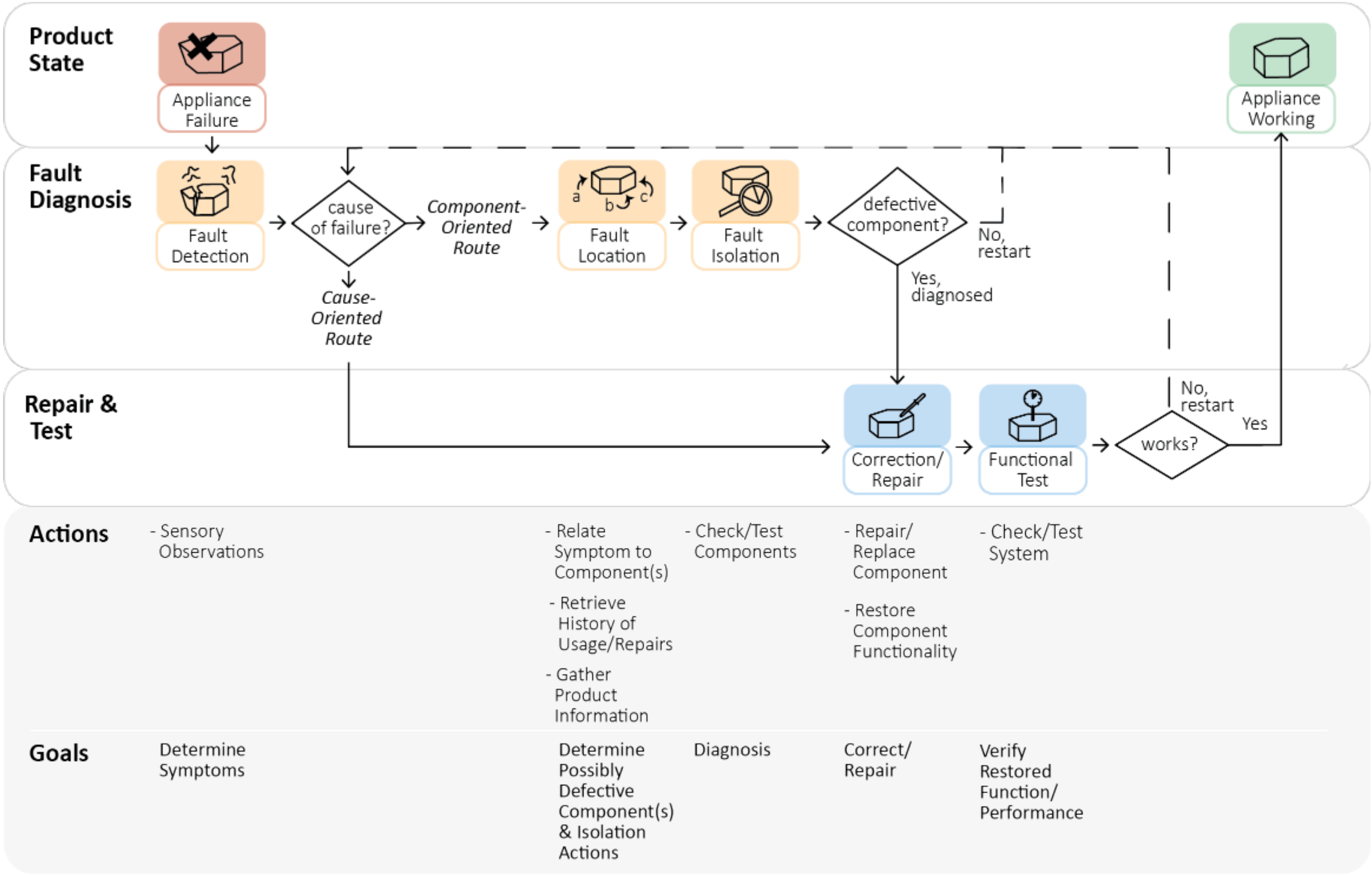


Figure 1. Framework of the Process of Fault Diagnosis by End Users

We distinguish between two main routes to diagnose a fault. The first is the component-oriented route. This consists of the steps of fault detection, fault location, and fault isolation. It identifies and pinpoints the faulty component. The second is the cause-oriented route. This consists of the steps of fault detection and direct remediation. This latter route aims to directly restore the appliance's functionality, avoiding inspection.

The most adequate route for diagnosis depends on the nature of the fault. The component-oriented route is recommended for faults in the components for which there is not a strong coupling between symptom and fault, such as defects. The cause-oriented route is generally recommended for faults caused by common causes of failure. For example, faults due to overdue maintenance or internal error state (for electronics). The symptoms are often well-known and strongly coupled to the causes of failure. A cheap and fast solution is available.

In our studies, end users generally needed expert guidance to successfully diagnose common faults in the selected appliances. At iFixit, a wiki-based self-repair platform, end users asked experts for help to locate the faults in their appliances (chapter 3). In our observational study (chapter 4), participants needed hints to be able to disassemble the appliance. Without those hints, they would not have continued the diagnosis. Lastly, in Chapter 5, we show that manuals generally advise a cause-oriented route to diagnosis rather than a component-oriented route. Thus, the support provided for end users is generally limited to the diagnosis of overdue maintenance faults.

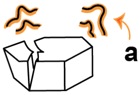
The second main research question we addressed is: How does the design of a household appliance influence the fault diagnosis process? Chapters 2, 3, and 4 address this question. The results show that design affects the diagnosis process in two ways. It can (1) affect the feasibility of the diagnosis steps, and (2) provide guiding cues for end users.

In our studies, the appliances' design generally hindered the diagnosis process. Lack of visual and manual access to the components hampered fault location and fault isolation (chapter 3). In chapter 4, we saw that a difficult disassembly process hinders both fault location and isolation. However, we also show that design cues can guide end users through the diagnosis steps (chapter 4). Textual signals or the arrangement of components can provide cues for users to continue the diagnosis. Based on these insights, in chapter 4, we proposed a set of preliminary guidelines. These were expanded

in Chapter 6 to include the insights from previous studies. These new guidelines are depicted in figure 2.

My thesis makes two main contributions to supporting CE development. First, it provides an original framework of the diagnosis process by end users, and second, it contributes a set of design guidelines to facilitate diagnosis. Further testing of these guidelines is needed, but we anticipate that both the framework and the guidelines will be valuable for design practice to design easy-to-diagnose appliances. Moreover, the empirical evidence provided on the product-user interaction advances knowledge on how end users go through the diagnosis process, which in turn is relevant to further understand current repair practices.

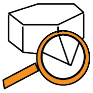
1



FACILITATE FAULT DETECTION AND SYMPTOM-TO-CAUSE DEDUCTION BY GIVING TIMELY AND UNDERSTANDABLE FEEDBACK

Designers can ease fault detection and symptom-to-cause deduction by providing audio and textual cues. For instance, designers can guide and educate end users on the sounds the appliances make during a working cycle. Moreover, text signals can communicate the process the appliance is executing, thereby providing guidance and understanding in case of a fault.

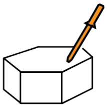
2



FACILITATE INSPECTION OF COMPONENTS WITHOUT THE NEED FOR DISASSEMBLY

Designers can avoid the need to disassemble the appliance by providing lids and doors to access the components. Including testing points in the components can also ease checking their condition. Moreover, making faults visible through the material's casing can also ease inspection without disassembly.

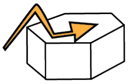
3



FACILITATE DISASSEMBLY AND REASSEMBLY IF NEEDED FOR INSPECTION

Designers can ease disassembly and reassembly by considering the fastener types and their access. For instance, fasteners would be preferable to adhesives. Fasteners prone to damage and breakage during removal should also be avoided (Pozo Arcos et al., 2018).

4



FACILITATE NAVIGATION OF THE PRODUCT’S CONSTRUCTION

Designers can help users navigate the appliance. In particular, the arrangement of components can guide users through different paths. For example, if components that are likely to fail are located on the surface, they can be quickly identified. Another possible arrangement could be one that guides the user through the input-output flow of materials. This would communicate existing relationship between components.

Figure 2 - Design Guidelines for Fault Diagnosis

Samenvatting

De geïndustrialiseerde samenlevingen van vandaag staan voor de uitdaging om economische bedrijvigheid te integreren met duurzame consumptie. De welvaart is gepaard gegaan met milieuschade. Producten gaan steeds minder lang mee en de vraag naar hightechproducten waarvan geen effectieve recycling mogelijk is neemt toe. De waarde van producten gaat verloren in afval. Als gevolg daarvan zijn het huidige gebruik en beheer van de natuurlijke rijkdommen van de aarde niet houdbaar.

De circulaire economie (CE) is erop gericht de stroom aan goederen en materialen die het economische systeem binnenkomt te vertragen, te sluiten en te regenereren. Daardoor blijft de waarde van producten behouden en wordt de overstap naar hernieuwbare energiebronnen gestimuleerd. Zo levert de CE een bijdrage aan het terugdringen van onze huidige versnelde uitputting van bronnen. Met name het repareren van producten kan de goederenstroom vertragen. Producten repareren biedt een alternatief voor de voortijdige vervanging van producten en draagt bij aan een significante vermindering van de hoeveelheid afval.

In dit proefschrift kijk ik in detail naar het proces van storingsdiagnose, een van de eerste stappen die moeten worden genomen wanneer een product wordt gerepareerd. Bij een storingsdiagnose worden het defecte onderdeel (of onderdelen) of de oorzaak van een storing bij een defect apparaat vastgesteld, wat deze onmisbaar maakt voor een efficiënte reparatie. Daarnaast kunnen hiermee de tijd, kosten en vaardigheden die nodig zijn om het onderdeel te repareren worden vastgesteld.

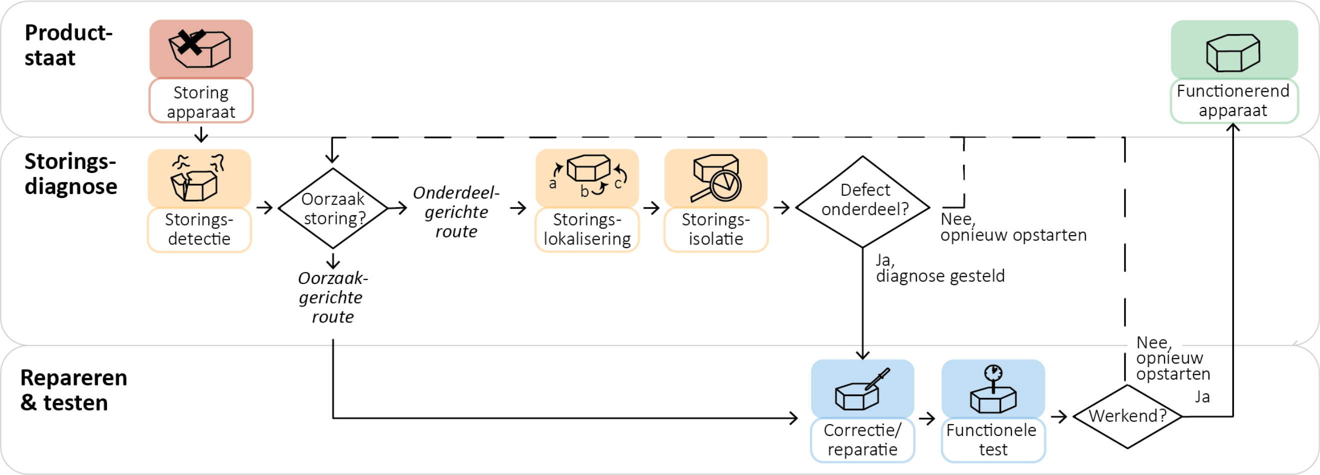
Bij aanvang van dit promotieonderzoek was er in de literatuur nog geen aandacht besteed aan de manier waarop eindgebruikers het proces van storingsdiagnose doorlopen. Ook de potentiële invloed van het ontwerp op dit proces was nog niet onderzocht. Niettemin is het verkrijgen van volledig inzicht in het diagnoseproces belangrijk om reparaties te bevorderen. Daarom beantwoord ik in dit proefschrift de volgende twee hoofdonderzoeksvragen:

(1) Hoe diagnosticeren eindgebruikers, die beperkte ervaring met repareren hebben, storingen in huishoudelijke apparaten?

(2) Welke invloed heeft het ontwerp van een huishoudelijk apparaat op het storingsdiagnoseproces?

We hebben beide vragen onderzocht op basis van een combinatie van methodes. We hebben zowel kwalitatief als kwantitatief onderzoek gedaan, en tot de gebruikte analysetechnieken behoren literatuuronderzoek (hoofdstuk 2, 3 en 4), content-analyse (hoofdstuk 3 en 5) en onderzoek op basis van gebruikersobservatie (hoofdstuk 4).

De eerste hoofdonderzoeksvraag – *hoe diagnosticeren eindgebruikers, die beperkte ervaring met repareren hebben, storingen in huishoudelijke apparaten?* – komt aan bod in hoofdstuk 3, 4 en 5. Uit deze drie onderzoeken hebben we een schema afgeleid dat de processen beschrijft die gebruikers volgen om een storing in een huishoudelijk apparaat te diagnosticeren (zie figuur 1).



Acties	- Zintuiglijke observaties	- Verband leggen tussen symptoom en onderde(e)l(en) - Gebruiks-/reparatiegeschiedenis opvragen - Productinformatie verzamelen	- Onderdelen controleren/ testen	- Onderdeel repareren/ vervangen - Functionaliteit onderdeel herstellen	- Systeem controleren/ vtesten
Doelen	Symptomen vaststellen	Eventueel defecte onderde(e)l(en) & isolatie-acties vaststellen	Diagnose	Corrigeren/ repareren	Herstelde functie/ prestatie verifiëren

Figuur 1. Schema van het proces van storingsdiagnose door eindgebruikers

We onderscheiden twee hoofdroutes voor de diagnose van een storing. De eerste is de onderdeelgerichte route. Deze bestaat uit de stappen storingsdetectie, storingslocatie en storingsisolatie. Het defecte onderdeel wordt hierbij vastgesteld en gelokaliseerd. De tweede is de oorzaakgerichte route. Deze bestaat uit de stappen storingsdetectie en directe remediëring. De tweede route is gericht op het direct herstellen van de functionaliteit van het apparaat, waarbij inspectie wordt overgeslagen.

Wat de meest adequate route voor de diagnose is, is afhankelijk van de aard van de storing. De onderdeelgerichte route wordt aanbevolen voor storingen in onderdelen waarbij geen sterk verband bestaat tussen het symptoom en de storing, zoals bij defecten. De oorzaakgerichte route wordt over het algemeen aanbevolen bij storingen die worden veroorzaakt door veel voorkomende storingsoorzaken, bijvoorbeeld storingen die het gevolg zijn van achterstallig onderhoud of een interne foutstatus (bij elektronica). De symptomen zijn vaak welbekend en sterk gelinkt aan de oorzaken van de storing. Vaak is er een goedkope, snelle oplossing voorhanden.

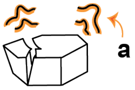
Bij onze onderzoeken hadden eindgebruikers meestal begeleiding van experts nodig om veelvoorkomende storingen in de geselecteerde apparaten met succes te diagnosticeren. Op iFixit, een wikiplatform voor het zelf uitvoeren van reparaties, vroegen eindgebruikers experts om assistentie bij het lokaliseren van de storingen in hun apparaten (hoofdstuk 3). Tijdens ons observatieonderzoek (hoofdstuk 4) hadden deelnemers aanwijzingen nodig om het apparaat te kunnen demonteren. Zonder die aanwijzingen hadden zij de diagnose niet kunnen voortzetten. Ten slotte laten we in hoofdstuk 5 zien dat in handleidingen over het algemeen een oorzaakgerichte diagnoseroute wordt geadviseerd in plaats van een onderdeelgerichte. Als gevolg daarvan is de steun die aan eindgebruikers wordt geboden over het algemeen beperkt tot het diagnosticeren van storingen die het gevolg zijn van achterstallig onderhoud.

Onze tweede hoofdonderzoeksvraag was: *welke invloed heeft het ontwerp van een huishoudelijk apparaat op het storingsdiagnoseproces?* Deze vraag komt in hoofdstuk 2, 3 en 4 aan bod. Uit de resultaten blijkt dat ontwerp het diagnoseproces op twee manieren beïnvloedt. Het kan: (1) de uitvoerbaarheid van de diagnosestappen beïnvloeden en (2) eindgebruikers sturende signalen bieden.

Bij onze onderzoekers hinderde het ontwerp van de apparaten het diagnoseproces veelal. Een gebrek aan visuele en manuele toegang tot de onderdelen belemmerde de storingslokalisering en -isolatie (hoofdstuk 3). In hoofdstuk 4 zien we dat een lastig demontageproces zowel storingslokalisering als storingsisolatie belemmert. Maar we laten ook zien dat ontwerpsignalen eindgebruikers door de stappen van de diagnose kunnen leiden (hoofdstuk 4). Tekstuele signalen of de indeling van onderdelen kunnen gebruikers begeleiding bieden voor het voortzetten van de diagnose. Op basis van deze inzichten stellen we in hoofdstuk 4 een set voorlopige richtlijnen voor. Deze worden in hoofdstuk 6 uitgebreid om de inzichten uit eerdere onderzoeken mee te nemen. Deze nieuwe richtlijnen worden weergegeven in figuur 2.

Mijn proefschrift levert twee hoofdbijdragen aan het ondersteunen van de ontwikkeling van de CE. Ten eerste wordt er een oorspronkelijk schema geboden van het diagnoseproces van eindgebruikers en ten tweede wordt er een set ontwerprichtlijnen voorgesteld om diagnose te vergemakkelijken. Deze richtlijnen zullen verder moeten worden getest, maar wij verwachten dat zowel het schema als de richtlijnen in de ontwerppraktijk waardevol zullen zijn voor het ontwerpen van gemakkelijk te diagnosticeren apparaten. Daarnaast vergroot het vergaarde empirische bewijs over de interactie tussen gebruikers en apparaten de kennis over de manier waarop eindgebruikers het diagnoseproces doorlopen, wat op zijn beurt relevant is voor meer inzicht in huidige reparatiepraktijken.

1



FACILITEER STORINGSDETECTIE EN DE DEDUCTIE VAN SYMPTOOM NAAR OORZAAK DOOR TIJDIGE EN BEGRIJPELIJKE FEEDBACK TE GEVEN

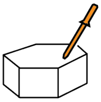
Ontwerpers kunnen storingsdetectie en de deductie van symptoom naar oorzaak vergemakkelijken door middel van geluidssignalen en tekst. Zo kunnen ontwerpers eindgebruikers bijvoorbeeld richtlijnen en voorlichting bieden over de geluiden die een apparaat produceert tijdens een operationele cyclus. Daarnaast kunnen tekstuele signalen communiceren welk proces het apparaat aan het uitvoeren is, om richting en inzicht te geven in geval van een storing.

2

FACILITEER DE INSPECTIE VAN ONDERDELEN ZONDER DAT DAARVOOR DEMONTAGE VEREIST IS

Ontwerpers kunnen de noodzaak om een apparaat te demonteren wegnemen door met deksels en kleppen toegang te geven tot de onderdelen. Het opnemen van testpunten in de onderdelen kan het controleren van de toestand daarvan eveneens vergemakkelijken. Inspectie zonder demontage kan bovendien worden vergemakkelijkt door storingen zichtbaar te maken door de behuizing van het product heen.

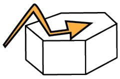
3



FACILITEER DEMONTAGE EN HERMONTAGE ALS DIE NOODZAKELIJK ZIJN VOOR DE INSPECTIE

Ontwerpers kunnen demontage en hermontage vergemakkelijken door aandacht te besteden aan de soorten bevestigingen en de toegankelijkheid daarvan. Zo hebben mechanische bevestigingen de voorkeur boven kleefstoffen. Bevestigingen die tijdens het verwijderen kunnen worden beschadigd of breken moeten eveneens worden vermeden (Pozo Arcos et al., 2018).

4



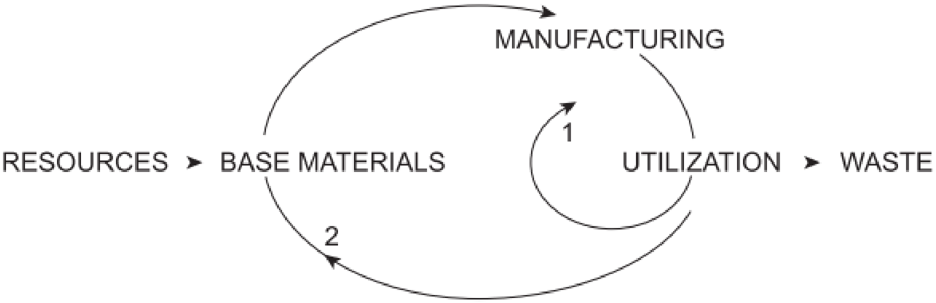
FACILITEER DE NAVIGATIE VAN DE CONSTRUCTIE VAN HET PRODUCT

Ontwerpers kunnen gebruikers helpen bij het navigeren van het apparaat. Met name de indeling van onderdelen kan gebruikers door verschillende trajecten leiden. Als bijvoorbeeld onderdelen die snel storingen vertonen zich aan het oppervlak bevinden, kunnen deze snel worden geïdentificeerd. Een andere mogelijke indeling is er een die de gebruiker door het invoer-uitvoertraject van materialen leidt. Dat zou de relatie tussen onderdelen communiceren.

Figuur 2. Ontwerprichtlijnen voor storingsdiagnose

CHAPTER 1

INTRODUCTION



Closed loop economy (Stahel, 2006) pg. 193

One of today's challenges for industrialized societies is how to integrate economic activity with an efficient and sustainable use of the planet's limited resources (Stahel, 2013). Prosperity now comes hand in hand with environmental damage. The earth's limited resources are depleting at a fast pace. Product lifetimes in consumer products have been declining (Bakker et al., 2014; Stamminger and Hennies, 2016). Moreover, there is a high demand for short-lived high-tech consumer products for which no effective recycling and material recovery infrastructures are in place (Tansel, 2020). Hence, the value from products is lost to waste. The current use and management of the Earth's resources is unsustainable (ibid).

The circular economy is a means to change these currently unsustainable practices (Stahel, 2006). In particular, repair practices are a strategy that can bring about positive change (Stahel, 2013). Product repairs require little energy and few resources for extending the life of products (Cooper and Gutowski, 2017). They are an effective way of increasing product lifetimes and can slow down the flow of materials, thereby preventing waste. Ramping up repair practices can also result in a reduction of emissions from transportation and production of new products (Stahel, 2006). Moreover, repair practices run on "manpower" and can be done locally. So they can have an added positive socioeconomic impact by creating jobs at home and boosting economic development. The smaller the economic loop, the more profitable and resource efficient it becomes (Stahel, 2006).

In Europe, the repair market of consumer products is in decline due to product, service, and system level barriers (Svensson-Hoglund et al., 2021). Current product design makes repairs difficult (iFixit, 2019; Pamminger et al., 2017; Repair Cafe International Foundation, 2020) as it influences how time-consuming, complicated, and economically viable the repair will be (Imrhan, 1992; Sabbaghi et al., 2017; Wani and Gandhi, 1999). Specifically, the high labour costs hamper its profitability (Allwood et al., 2011). At a system level, repair practices currently face legal and market barriers, e.g. infringement of intellectual property rights and contract agreements, unfavourable consumer and tax laws, and negative consumer perceptions of repaired products (Svensson-Hoglund et al., 2021). Technical, value, and emotional factors influence consumer's decision to repair (Terzioğlu, 2021). Moreover, the infrastructure available is decisive in facilitating repairs (Jaeger-Erben et al., 2021).

Design can help overcome product-level barriers, which, in turn, can reduce some of the abovementioned service and system barriers (Allwood et al., 2011; Dindarian et al., 2012; European Environment Agency, 2017). For instance, changes to the design of a product could translate into a more rapid repair process and lower costs, thereby resulting in better competition against product replacement. However, at the start of this PhD-project, know-how on design for repair neglected the fault diagnosis process. Research on repair practices presented an incomplete picture of the process, which in turn translated into fragmented guidance for designers. Of the main steps involved in the repair process (fault diagnosis, disassembly, repair, and reassembly) (Cuthbert et al., 2016); disassembly had been largely explored (Alonso Movilla et al., 2016; Mathieux et al., 2018); while fault diagnosis had been neglected. Hence, fault diagnosis was selected as the focal area of our study.

A smooth, rapid, and transparent fault diagnosis process can greatly facilitate product repair. It identifies the defective component in a machine (Mahabala et al., 1994) and determines its operational condition (USA Department of Defense, 1988). Fault diagnosis is often considered the most time consuming step in a repair process (Kane, 2016). Hence, when easily performed, overall repair time will be shortened. Moreover, a successful diagnosis process can positively influence the repair-or-replace decision-making process. The time, effort, skills, and knowledge needed to repair a product all influence the user's decision to repair (Terzioğlu, 2021). Hence, a successful diagnosis could potentially ease this decision. However, despite its relevance for repairs, little was known about how end-users address the fault diagnosis process when a failure occurred in their appliances. Instead, the literature addressing this topic mostly described how it was carried out by computers in dynamic systems (Khaksari, 1988; Patton et al., 2000, 1989) and how operators troubleshot automated industrial machinery (Bereiter and Miller, 1990, 1989).

In this thesis, we examine how users carry out the diagnosis process, and how product design affects its execution in household appliances in view of adapting products for life extension. We contribute to the currently available picture of the fault diagnosis process from two previously unexplored perspectives: the end users and the product design of appliances. We provide a clear description of the steps end users take towards a successful diagnosis and, in addition, we provide knowledge for design practitioners aiming to make their products easier to diagnose.

This chapter briefly introduces the knowledge base for the studies presented in this thesis. Section 1.1 summarizes the concept of a circular economy and how it can contribute to sustainable development. Section 1.2 explores how design can contribute to the transition towards a circular economy. In section 1.3 we explain the relevance of the process of fault diagnosis in a circular economy and explore current knowledge on the process of fault diagnosis. Section 1.4 describes the scope of the thesis and in section 1.5 we formulate the research objective, research questions and research design. Section 1.6 introduces relevant terms and definitions used throughout the thesis and finally, section 1.7 outlines the thesis structure.

1.1 The circular economy for a sustainable development

The circular economy is a school of thought originating from sustainable economics and has recently become popular as a means of overcoming current unsustainable practices. It encompasses many known sustainable schools of thought such as industrial ecology, cradle-to-cradle design, and biomimicry (Ellen MacArthur Foundation, 2017). At its core, a circular economy is about stock optimization (Stahel, 2013). It posits reducing waste and boosting socio-economic growth by keeping products valuable, and shifting towards a renewable energy supply (Stahel, 2006). In other words, it aims at slowing, closing, and regenerating the current flow of materials and goods (Bocken et al., 2016).

The circular economy pursues a cradle-to-cradle approach for goods and materials that enter the economic system. To keep a product valuable, its service-life needs to be preserved, optimised and extended instead of it being disposed of (Stahel, 2006). Moreover, supply chains need to form closed loops so that products can be taken back after use, and recovered or recycled. Additionally, the circular economy requires new forms of ‘profit’ that are uncoupled from material consumption (Bocken et al., 2016). From a consumer perspective, a circular economy requires active participation and a change in consumer behaviour (Camacho-Otero et al., 2020).

1.2 Design for a circular economy and repair

Design is one of the enablers that can bring about the systemic change needed to transition to a circular economy (Allwood et al., 2011; Haas et al., 2015). Products, services, systems, and transitions can be designed to adapt to the needs of a circular economy (Ceschin and Gaziulusoy, 2016). The field of design for a circular economy starts from the premise that the flow of materials and goods must change: the flow of resources must be slowed down and closed.

Goods can be designed to be long-lasting by designing for physical and emotional durability (Den Hollander et al., 2017); and/or designed for extending their lifespan through direct reuse, maintenance and repair, refurbishment, remanufacture or technology upgrading. Recent research suggest that an adequate recovery strategy has to consider the product's optimal lifespan (Bakker et al., 2014; Kim and Kwak, 2012). Repair practices are specially recommended for those products for which the environmental impact of replacement is higher than the impact of repair (Bakker et al., 2014; Bovea et al., 2020; Cooper and Gutowski, 2017). This applies for most consumer products that fail before their "optimal lifetime" (Kim and Kwak, 2012). Recycling is seen as a better option for technologically obsolete products or products in a state beyond repair (Stahel, 2006).

The literature notes several approaches to facilitate product repair by design. Some researchers have focused on understanding which design principles facilitate repair, and how these can be implemented in products. For instance, Den Hollander (2018) identifies 16 design principles relevant to design for repair. Asif et al. (2021), and Jose and Tollenaere (2005) explore how to embody modularity, a relevant principle for product repair. Other strands of research have focused on the disassembly step and provide design tools to facilitate it (De Fazio et al., 2021; Vanegas et al., 2018). Another approach has been to analyse how repairable a product is through reparability indicators (Bracquené et al., 2021). The product design, availability of parts, service provided, and available repair information are assessed, which in turn provides relevant insights for the products' redesign. Other approaches have been more general and have analysed relevant properties for the circularity of products (e.g. durability, reparability, reusability, and recyclability) (Shahbazi and Jönbrink, 2020; Tecchio et al., 2016). Lastly, papers analysing the potential for reuse of discarded appliances have also contributed relevant knowledge to improve product repair (Dindarian et al., 2012; Parajuly and Wenzel, 2017).

In many of these studies, fault diagnosis is considered as an important aspect of a repair, but we have not been able to find any studies that analyse it in depth. Moreover, the user's perspective in the repair process is insufficiently represented. Studies on repair practices mostly focus on the attitude of users and their engagement with repair behaviour (Jaeger-Erben et al., 2021; Lefebvre et al., 2018; Terzioğlu, 2021). The difficulties and motivations faced by DIYers and independent repairers have also been studied (Charter and Keiller, 2014; Raihanian Mashhadi et al., 2016). However, there is little knowledge on how consumers (end-users) actually repair their appliances. The product-user interaction from failure to diagnosis had not been extensively investigated.

1.3 The process of fault diagnosis and its importance for product repair

The advent of the circular economy has brought attention to the process of fault diagnosis for recovering consumer products. Cuthbert et al. (2016) considered it a key factor for increasing the reparability of household appliances, and Sabbaghi et al. (2017) concluded that fault diagnosis could influence the profitability of repair practices. Moreover, it is needed to determine the potential for reuse of household products after disposal (Dindarian et al., 2012; Parajuly and Wenzel, 2017).

Early references in the literature to the process of fault diagnosis focus on industrial, complex systems, and military applications. "*Diagnostics, i.e. fault detection, fault location and fault isolation, is the process of detecting, localizing, isolating and fixing the failures in such sophisticated systems*" (Khaksari, 1988). Its importance is related to safety and reliability reasons, and to maintain the operational readiness (availability) of military machinery, industrial plants, and large infrastructures (Fox et al., 1983; Isermann, 2006; Patton et al., 2000; USA Department of Defense, 1988).

Due to the complexity of such systems, operators were not expected to perform the diagnosis process on their own, instead they would be supported by expert systems (Kluge and Termer, 2017). Hence, most of the literature describes the diagnosis process by expert systems -a subfield of artificial intelligence that tries to imitate human expert problem-solving skills (Khaksari, 1988). In these systems, diagnosis consists of providing information to computers either manually or through sensors (Fox et al., 1983), and when using this information, the expert systems embedded in the infrastructure would determine the source of the fault and recommend corrective actions.

Few studies have researched how operators conduct the fault diagnosis process in complex machinery. Morris and Rouse (1985) present an early review on the cognitive process of problem-solving or troubleshooting, and on the skills that make a good troubleshooter. Bereiter and Miller (1990, 1989), through case studies, investigated difficulties encountered by expert maintenance technicians during the fault diagnosis process. They describe three main tasks for diagnosing an automated manufacturing system: information collection, hypothesis testing, and repair attempts. Patrick (1993) describes the fault diagnosis process followed in a steel mill. The process consisted of three main stages or goals: first, the initial symptom identification, second, fault set reduction, and third, fault search within a computer controlled subsystem. Recently, Kluge and Termer (2017) describe the diagnosis followed by maintenance workers for three fault scenarios in a large industrial system. The descriptions of the diagnosis process in these papers are product specific and differ from each other. Nonetheless, a three step approach seems to be a common feature to these reports.

Recent research on the process of fault diagnosis now includes household appliances, although the focus remains on technology. For instance, Baek et al. (2020) investigated how to facilitate the diagnosis of rotary parts of washing machines using a smartphone. Marcu et al. (2017) present a method to detect faults in worn out washing machine brushes using the appliance's power signature. Recent studies also show a similar interest in improving fault detection techniques via sound in common rotary components of household appliances e.g. bearings and induction motors (Glowacz, 2019; Jiang et al., 2018; Malla et al., 2019). Other studies have explored how to connect household appliances to smart networks to facilitate their service by using technology like the internet of things, cloud computing, and machine learning (Ahmad et al., 2014; Bhavana, 2020; Prist, 2020). Yet, none of these papers provides a complete description of the fault diagnosis process in household appliances.

On the other hand, popular sources such as Davidson (2004), Kleinert (2013), and Mostia William L. (2006) do provide descriptions of the steps needed to identify the cause of malfunction in consumer products, although they differ. Kleinert (2013) describes a test-based diagnosis process specific to certain appliances. Mostia William L. (2006) and Davidson (2004) describe different steps with three main common stages: (1) collect information about the malfunction and symptoms the appliance presents; (2) relate symptoms to possible causes using different sources of information, and (3) test the proposed solutions in the components to finally (4) make the repair.

However, in these investigations of the diagnosis process, a general framework of the process is lacking and the end-user perspective as an actor of the diagnosis process is not depicted. Some studies looked into the cognitive aspects of troubleshooting (Jonassen and Hung, 2006), and search strategies and skills needed to troubleshoot by differently skilled participants (Morris and Rouse, 1985). However, how end users with little repair experience would go about the process of diagnosis in household appliances has not been investigated.

1.4 Scope

The studies in this thesis deal with the topic of fault diagnosis of household appliances and their design. We chose to focus on household appliances due to their broad adoption. We selected electromechanical appliances and not electronic products because the former provide a greater variety of design features than the latter. Furthermore, we review the process of fault diagnosis in the context of a repair and the design of a product, meaning its physical design, not the service around it or the system in which it is used.

The subjects of interest in this thesis are end users with relatively low repair skills. It is assumed, due to the complexity of the diagnosis process, that this type of end user will have the most difficulties performing the process of fault diagnosis. Insights into how they go about the diagnosis process are important to stimulate repair.

1.5 Research objective, research questions and research design

In the previous sections, we identify two main gaps of research. First, we were unable to find any studies describing how end users diagnose their products. Second, how the design of a product can affect the process for end-users has also not been studied. Nonetheless we expect that this impacts the time, skills, and costs associated to the diagnosis process, and consequently the repair. Therefore, in this thesis, we aim to understand the steps end-users follow to diagnose a malfunctioning household appliance and how this process might be affected by the design of a product. These aims translated into the following research questions:

1. How do end users with limited repair experience diagnose faults in household appliances?

2. How does the design of a household appliance influence the process of fault diagnosis for end users?

We investigated both questions together in the thesis because the diagnosis process occurs as an interaction between the user and the product. The research follows a mixed methods approach, incorporating both forms of inquiry and data analysis: qualitative and quantitative (Creswell and Creswell, 2018). The research methods employed for the empirical studies include: two qualitative content analyses and an observational study in which the participants thought aloud. These methods allowed us to gain insights from users, with minimum disturbance in their practice. The data analysis is mostly qualitative as the aim of the thesis is to explore and provide an understanding of a topic based on multiple individual experiences of people not previously studied (Creswell and Creswell, 2018). In addition, we performed quantitative analyses to find correlations between factors or provide the count of occurrence of certain parameters relevant for the analysis.

The relevance of this thesis lies in the essential nature of fault diagnosis for product life extension. It contributes by providing a model of how end users go through the fault diagnosis process when diagnosing consumer products. Apart from its scientific contribution, in this thesis we provide recommendations for designers to facilitate the diagnosis process by design. Understanding the process can contribute to facilitating an active role for users in a circular economy and the design of easier-to-diagnose products.

1.6 Relevant terms and definitions

Throughout this thesis, the following terms are frequently used: repair, fault diagnosis, end user, household appliance, and (product) design. This section defines our use of these terms.

The definition of repair is based on the standard ISO 14009:2020, which provides guidelines for "incorporating material circulation in design and development". The Ecodesign Directive 2009/125/EC (European parliament and the Council, 2009) guiding Ecodesign framework for Europe's Circular Economy Action Plan, recommends using the ISO 14000 family of standard to interpret terms throughout the regulation. Based on the standard, repair is the "*process of returning a faulty product to a condition where it can fulfil its intended use*". On the other hand, the definition of maintenance used in this thesis, is the same as one used in a recent thesis on product care: "*Maintenance is* *defined as the process of keeping something in an existing state and preserving it from failure or decline*" (Ackermann, 2020). Thus, this thesis distinguishes between repair and maintenance and assumes that repair occurs when a product malfunctions, and maintenance occurs before product malfunction. All actions that aim at restoring the functionality of a product are considered repairs.

The International Electrotechnical Commission, a source for other definitions in the standard, defines a fault as "*the inability of an item to perform as required, due to an internal state.*" (IEC 192-04-01, 2015) and fault diagnosis as the "*action to identify and characterize the fault. Fault diagnosis may also localize the fault and/or indicate its cause"* (IEC 192-06-20,2015).

The term troubleshooting often appears in the literature to describe a process similar to fault diagnosis. Troubleshooting is equated to fault diagnosis in different scientific and non-scientific publications (Jonassen and Hung, 2006; USA Department of Defense, 1988). Similarly, fault-finding is equated to fault diagnosis (Patrick, 1993).

The studied actors of the diagnosis process in this thesis are the product users, also referred to as end users: "*the ultimate consumer of a finished product*"(Merriam-Webster, 2021). The studied products are household appliances, which are "*machines designed to do a particular task, especially in the home"* (Oxford Dictionary, 2021). Of particular interest are electromechanical appliances commonly found in households. Last, the term design or product design is frequently used through this thesis. Product design refers to the branch of industrial design focused on the development of products. Industrial design is defined as: "*a strategic problem-solving process that drives innovation, builds business success, and leads to a better quality of life through innovative products, systems, services, and experiences*" (World Design Organization, 2021)

1.7 Thesis outline

This is an article-based dissertation. The core consists of four chapters, each of which represents a separate study (either published or under review at the time of writing). Figure 1 presents an overview of the research questions, topics, and methods explored in each of the studies.

Main RQs	RQs addressed per Chapter			
(1) How do **end users** with limited repair experience diagnose faults in appliances?		○	○	○
(2) How does the **design** of an appliance influence the process of fault diagnosis?	○	○	○	
Chapters (Studies)	2 - Product Design in a Circular Economy Funcional Recovery on Focus	3 - Practices of Fault Diagnosis in Household Appliances: Insights for Design	4 - Faults in consumer products are difficult to diagnose, and design is to blame: a user observation study	5 - How user manuals support the diagnosis of common faults in household appliances: an analysis of 150 manuals
Sub RQs	How can product design ease the process of recovering functionality from products?	How do end users diagnose faults in household appliances, and how does product design affect this process?	How do users with different repair skills diagnose faults in consumer products? How does a product's design and user repair skills influence the process?	To what extent do user manuals provide sufficient information to diagnose the most frequent faults in household appliances?
Method	Systematic literature review of product design, EOL* strategies, and CE*.	Literature review of the process of fault diagnosis and content analysis of iFixit's Q&A* forum	Literature review of problem-solving strategies and observational study with 24 participants.	Content analysis of 150 user manuals of common household appliances

EOL* = End-of-Life; CE* = Circular Economy; Q&A*= Questions and Answers

Figure 1- Overview of studies and topics investigated in this thesis. The dots indicate which research questions are addressed per chapter.

As figure 1 shows, the steps end users follow to diagnose an appliance and how the appliance design can influence the process are the two main topics investigated in this thesis. Both topics have been explored through a number of underlying questions in each of the chapters.

The first research question is addressed in Chapter 2: “How can product design facilitate the functional recovery from products?”. Through a systematic literature review on the topics of product design, end-of-life strategies, and circular economy, this chapter positions the process of fault diagnosis in the context of a circular economy. This chapter was published as a conference paper in 2018: Pozo Arcos, B., Balkenende, A.R., Bakker, C.A., Sundin, E., 2018. Product design for a circular economy: functional recovery on focus. pp. 2727–2738. https://doi.org/10.21278/idc.2018.0214.

Subsequent studies focused on addressing both main research questions using different methods. Chapter 3 investigates how end users diagnose faults in household appliances and how a product’s design can affect this process. It qualitatively analyses iFixit’s forum of questions and answers, a wiki page of product repairs, using a framework of the diagnosis process derived from the literature. This chapter was published as an original article in 2020 in the Journal of Cleaner Production: Pozo Arcos, B., Bakker, C., Flipsen, B., Balkenende, R., 2020. Practices of fault diagnosis in household appliances: Insights for design. J. Clean. Prod. 265, 121812. https://doi.org/10.1016/j.jclepro.2020.121812.

Chapter 4 builds on the previous investigation. It asks again how conventional users diagnose faults in consumer products and how this is affected by a product’s design, but takes a different approach. It presents an observational study with 24 participants to understand the diagnosis process they would follow. Participants were given a defective consumer product and were asked to diagnose it while thinking aloud in our lab. This chapter was submitted as an original article to the Journal of Cleaner Production in 2020: Pozo Arcos, B., 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. J. Clean. Prod. 128741. https://doi.org/10.1016/j.jclepro.2021.128741

The final research question addressed in this thesis is: “to what extent does the information provided in user manuals facilitate the diagnosis of common faults in household appliances” (Chapter 5). In this chapter, we complete the depiction of product-user interaction during the diagnosis process. It analyses 150 user manuals using the framework of the diagnosis process developed in Chapter 4 and data on frequently failing components. This chapter was submitted as an original article to the journal Circular Economy and Sustainability in 2021: Pozo Arcos, B., Bakker, C., Balkenende, R., 2021 How user manuals support the diagnosis of common faults in household appliances: an analysis of 150 manuals.

Lastly, chapter 6 discusses and concludes the works in this thesis. First, it presents a summary and discussion of the main findings. Next, the main contributions of this study to scientific knowledge, design practice, and policy are presented. New avenues of research are also proposed.

References

Ackermann, L., 2020. Design for Product Care. TU Delft Univ. https://doi.org/10.4233/uuid:9fe0a3cd-a7f7-4d29-bb44-6dc78575a2e8

Ahmad, W.S., Perinpanayagam, S., Jennions, I., Khan, S., 2014. Study on intermittent faults and electrical continuity. Procedia CIRP 22, 71–75. https://doi.org/10.1016/j.procir.2014.07.015

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Material efficiency: A white paper. Resour. Conserv. Recycl. 55, 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002

Alonso Movilla, N., Zwolinski, P., Dewulf, J., Mathieux, F., 2016. A method for manual disassembly analysis to support the ecodesign of electronic displays. Resour. Conserv. Recycl. 114, 42–58. https://doi.org/10.1016/j.resconrec.2016.06.018

Asif, F.M.A., Roci, M., Lieder, M., Rashid, A., Mihelič, A., Kotnik, S., 2021. A methodological approach to design products for multiple lifecycles in the context of circular manufacturing systems. J. Clean. Prod. 296. https://doi.org/10.1016/j.jclepro.2021.126534

Baek, J.M., Ji, S.H., Koo, J.C., 2020. A cost effective on-site fault diagnosis method for home appliance rotor failures. Microsyst. Technol. 9. https://doi.org/10.1007/s00542-020-04892-9

Bakker, C., Wang, F., Huisman, J., Den Hollander, M., 2014. Products that go round: Exploring product life extension through design. J. Clean. Prod. 69, 10–16. https://doi.org/10.1016/j.jclepro.2014.01.028

Bereiter, S.R., Miller, S.M., 1990. Difficulties in troubleshooting automated manufacturing systems. Int. J. Ind. Ergon. 5, 91–104. https://doi.org/10.1016/0169-8141(90)90031-V

Bereiter, S.R., Miller, S.M., 1989. A Field Based Study of Troubleshooting in Computer-Controlled Manufacturing Systems. IEEE Trans. Syst. Man Cybern. 19, 205–219. https://doi.org/10.1109/21.31027

Bhavana, K., 2020. Internet of Things Enabled Device Fault Prediction System Using Machine Learning.

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bovea, M.D., Ibáñez-Forés, V., Pérez-Belis, V., 2020. Repair vs. replacement: Selection of the best end-of-life scenario for small household electric and electronic equipment based on life cycle assessment. J. Environ. Manage. 254. https://doi.org/10.1016/j.jenvman.2019.109679

Bracquené, E., Peeters, J., Alfieri, F., Sanfélix, J., Duflou, J., Dewulf, W., Cordella, M., 2021. Analysis of evaluation systems for product repairability: A case study for washing machines. J. Clean. Prod. 281. https://doi.org/10.1016/j.jclepro.2020.125122

Camacho-Otero, J., Tunn, V.S.C., Chamberlin, L., Boks, C., 2020. Consumers in the circular economy. Handb. Circ. Econ. 74–87. https://doi.org/10.4337/9781788972727.00014

Ceschin, F., Gaziulusoy, I., 2016. Evolution of design for sustainability: From product design to design for system innovations and transitions. Des. Stud. 47, 118–163. https://doi.org/10.1016/j.destud.2016.09.002

Charter, M., Keiller, S., 2014. Grassroots Innovation and the Circular Economy.

Cooper, D.R., Gutowski, T.G., 2017. The Environmental Impacts of Reuse: A Review. J. Ind. Ecol. 21, 38–56. https://doi.org/10.1111/jiec.12388

Creswell, J.W., Creswell, J.D., 2018. Research design: Qualitative, quantitative and mixed methods approaches, fifth edit. ed. SAGE.

Cuthbert, R., Giannikas, V., McFarlane, D., Srinivasan, R., 2016. Repair Services for Domestic Appliances .., in: Service Orientation in Holonic and Multi-Agent Manufacturing. pp. 31–39.

Davidson, H.L., 2004. Troubleshooting and Repairing Consumer Electronics- 3rd edition. TAB electronics.

De Fazio, F., Bakker, C., Flipsen, B., Balkenende, R., 2021. The Disassembly Map: a new method to enhance design for product repairability. Manuscr. Submitt. Publ.

den Hollander, M.C., 2018. Design for Managing Obsolescence: A Design Methodology for Preserving Product Integrity in a Circular Economy. https://doi.org/10.4233/uuid:3f2b2c52-7774-4384-a2fd-. TU Delft Univ. https://doi.org/10.4233/uuid:3f2b2c52-7774-4384-a2fd-7201688237af

den Hollander, M.C., Bakker, C.A., Hultink, E.J., 2017. Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. J. Ind. Ecol. 21, 517–525.

https://doi.org/10.1111/jiec.12610

Dindarian, A., Gibson, A.A.P., Quariguasi-Frota-Neto, J., 2012. Electronic product returns and potential reuse opportunities: A microwave case study in the United Kingdom. J. Clean. Prod. 32, 22–31. https://doi.org/10.1016/j.jclepro.2012.03.015

Ellen MacArthur Foundation, 2017. Concept: What is a circular economy? A framework for an economy that is restorative and regenerative by design [WWW Document]. URL https://www.ellenmacarthurfoundation.org/circular-economy/concept (accessed 6.22.21).

European Environment Agency, 2017. Circular by design: Products in the circular economy, EEA Report No 6/2017. https://doi.org/10.2800/860754

European parliament and the Council, 2009. DIRECTIVE 2009/125/EC establishing a framework for the setting of ecodesign requirements for energy-related products. Off. J. Eur. Union 10–35.

Fox, M.S., Lowenfeld, S., Kleinosky, P., 1983. Techniques for Sensor-Based Diagnosis, in: Proceedings of the International Joint Conference on Artificial Intelligence.

Glowacz, A., 2019. Fault diagnosis of single-phase induction motor based on acoustic signals. Mech. Syst. Signal Process. 117, 65–80. https://doi.org/10.1016/j.ymssp.2018.07.044

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. J. Ind. Ecol. 19, 765–777. https://doi.org/10.1111/jiec.12244

iFixit, 2019. Repair Market Observations: iFixit's testimony to the FTC.

Imrhan, S.N., 1992. Equipment design for maintenance: Part II – The scientific basis for the guide. Int. J. Ind. Ergon. 10, 45–52. https://doi.org/10.1016/S1572-347X(00)80019-1

Isermann, R., 2006. Fault-Diagnosis Systems, Fault-Diagnosis Systems: An Introduction from Fault Detection to Fault Tolerance. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/3-540-30368-5

Jaeger-Erben, M., Frick, V., Hipp, T., 2021. Why do users (not) repair their devices? A study of the predictors of repair practices. J. Clean. Prod. 286, 125382. https://doi.org/10.1016/j.jclepro.2020.125382

Jiang, Y., Li, C., Li, N., Feng, T., Liu, M., 2018. HAASD: A dataset of household appliances abnormal sound detection. ACM Int. Conf. Proceeding Ser. 6–10. https://doi.org/10.1145/3297156.3297186

Jonassen, D.H., Hung, W., 2006. Learning to troubleshoot: A new theory-based design architecture. Educ. Psychol. Rev. 18, 77–114. https://doi.org/10.1007/s10648-006-9001-8

Jose, A., Tollenaere, M., 2005. Modular and platform methods for product family design: Literature analysis. J. Intell. Manuf. 16, 371–390. https://doi.org/10.1007/s10845-005-7030-7

Kane, G.M., 2016. Designing a product-service for repair & maintenance of medical imaging equipment in Africa. TU Delft.

Khaksari, G., 1988. Expert Diagnosis System, in: First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems. pp. 43–53.

Kim, H.M., Kwak, M., 2012. To extend, or to shorten: Optimal lifetime planning, in: Proceedings of the ASME Design Engineering Technical Conference. ASME 2012, pp. 1329–1337. https://doi.org/10.1115/DETC2012-70546

Kleinert, E.T.A.-T.T.-, 2013. Troubleshooting and repairing major appliances, Third edit. ed. McGraw-Hill, New York.

Kluge, A., Termer, A., 2017. Human-centered design (HCD) of a fault-finding application for mobile devices and its impact on the reduction of time in fault diagnosis in the manufacturing industry. Appl. Ergon. 59, 170–181. https://doi.org/10.1016/j.apergo.2016.08.030

Lefebvre, M., Lofthouse, V., Wilson, G., 2018. Towards a Circular Economy: exploring factors to repair broken electrical and electronics products by users with pro-environmental inclination. DRS2018 Catal. 5. https://doi.org/10.21606/drs.2018.556

Mahabala, H.N., Arun Kumar, A.T., Kurup, R.R., Prakash, G.R., 1994. Fault diagnosis of machines. Sadhana 19, 23–50. https://doi.org/10.1007/BF02760389

Malla, C., Rai, A., Kaul, V., Panigrahi, I., 2019. Rolling element bearing fault detection based on the complex Morlet wavelet transform and performance evaluation using artificial neural network and support vector machine. Noise Vib. Worldw. 50, 313–327. https://doi.org/10.1177/0957456519883280

Marcu, M., Darie, M., Cernazanu-Glavan, C., 2017. Component level energy accounting and fault detection on electrical devices using power signatures. I2MTC 2017 - 2017 IEEE Int. Instrum. Meas. Technol. Conf. Proc. 4–9. https://doi.org/10.1109/I2MTC.2017.7969888

Mathieux, F., Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., Dewulf, W., Duflou, J.R., 2018. Ease of disassembly of products to support circular economy strategies. Resour. Conserv. Recycl. 135, 323–334. https://doi.org/10.1016/j.resconrec.2017.06.022

Merriam-Webster, 2021. End user. In Merriam-Webster.com dictionary. [WWW Document]. URL https://www.merriam-webster.com/dictionary/end user (accessed 6.24.21).

Morris, N.M., Rouse, W.B., 1985. Review and Evaluation of empirical research in troubleshooting. J. Hum. Factors Soc. 27.

Mostia William L., J., 2006. Troubleshooting - A Technician's Guide (2nd Edition). ISA.

Oxford Dictionary, 2021. Appliance [WWW Document]. URL https://www.oxfordlearnersdictionaries.com/definition/english/appliance

Pamminger, R., Kuso, S., Wimmer, W., Podhardsky, G., 2017. Re-design of a digital voice recorder to meet the needs of circular economy-Status analysis, in: 2016 Electronics Goes Green 2016+, EGG 2016. Fraunhofer, pp. 1–9. https://doi.org/10.1109/EGG.2016.7829815

Parajuly, K., Wenzel, H., 2017. Potential for circular economy in household WEEE management. J. Clean. Prod. 151, 272–285. https://doi.org/10.1016/j.jclepro.2017.03.045

Patrick, J., 1993. Cognitive aspects of fault-finding training and transfer. Trav. Hum. 56, 187–209.

Patton, R.., Frank, P.M., Clark, R.N., 2000. Issues of Fault Diagnosis for Dynamic Systems. Springer.

Patton, R., Clark, R., Frank, P., 1989. Fault Diagnosis in Dynamic Systems. Theory and Application.

Prist, M., 2020. Machine learning-as-a-service for consumer electronics fault diagnosis: A comparison between matlab and azure, in: IEEE International Conference on Consumer Electronics.

Raihanian Mashhadi, A., Esmaeilian, B., Cade, W., Wiens, K., Behdad, S., 2016. Mining consumer experiences of repairing electronics: Product design insights and business lessons learned. J. Clean. Prod. 137, 716–727. https://doi.org/10.1016/j.jclepro.2016.07.144

Repair Cafe International Foundation, 2020. Repair Monitor - Analysis Results 2019.

Sabbaghi, M., Cade, W., Behdad, S., Bisantz, A.M., 2017. The current status of the consumer electronics repair industry in the U.S.: A survey-based study. Resour. Conserv. Recycl. 116, 137–151. https://doi.org/10.1016/j.resconrec.2016.09.013

Shahbazi, S., Jönbrink, A.K., 2020. Design guidelines to develop circular products: Action research on nordic industry. Sustain. 12, 1–14. https://doi.org/10.3390/su12093679

Stahel, W.R., 2013. Policy for material efficiency - Sustainable taxation as a departure from the throwaway society. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 371. https://doi.org/10.1098/rsta.2011.0567

Stahel, W.R., 2006. The Performance Economy, 2nd editio. ed. Palgrave Macmillan.

Stamminger, R., Hennies, L., 2016. An empirical survey on the obsolescence of appliances in German households. Resour. Conserv. Recycl. 112, 73–82. https://doi.org/10.1016/j.resconrec.2016.04.013

Svensson-Hoglund, S., Richter, J.L., Maitre-Ekern, E., Russell, J.D., Pihlajarinne, T., Dalhammar, C.,

2021. Barriers, enablers and market governance: A review of the policy landscape for repair of consumer electronics in the EU and the U.S. J. Clean. Prod. 288. https://doi.org/10.1016/j.jclepro.2020.125488

Tansel, B., 2020. Increasing gaps between materials demand and materials recycling rates: A historical perspective for evolution of consumer products and waste quantities. J. Environ. Manage. 276, 111196. https://doi.org/10.1016/j.jenvman.2020.111196

Tecchio, P., Ardente, F., Mathieux, F., 2016. Analysis of durability, reusability and reparability - Application to dishwashers and washing machines, EUR 28042 EN. https://doi.org/10.2788/51992

Terzioğlu, N., 2021. Repair motivation and barriers model: Investigating user perspectives related to product repair towards a circular economy. J. Clean. Prod. 289. https://doi.org/10.1016/j.jclepro.2020.125644

USA Department of Defense, 1988. Maintainability Design Techniques.

Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., 2018. Resources , Conservation & Recycling Ease of disassembly of products to support circular economy strategies 135, 323–334. https://doi.org/10.1016/j.resconrec.2017.06.022

Wani, M.F., Gandhi, O.P., 1999. Development of maintainability index for mechanical systems. Reliab. Eng. Syst. Saf. 65, 259–270. https://doi.org/10.1016/S0951-8320(99)00004-6

World Design Organization, 2021. Definition of Industrial Design [WWW Document]. World Des. Organ. URL http://wdo.org/about/definition/

CHAPTER 2

PRODUCT DESIGN FOR A CIRCULAR ECONOMY: FUNCTIONAL RECOVERY ON FOCUS[1]

---

[1] Pozo Arcos, B., Balkenende, A.R., Bakker, C.A., Sundin, E., 2018. Product design for a circular economy: functional recovery on focus. pp. 2727–2738. https://doi.org/10.21278/idc.2018.0214

Abstract

This paper explores existing design strategies, guidelines and product features that enable functional recovery operations like repair, refurbishing or remanufacturing. A circular economy demands for products to be kept as valuable as possible for as long as possible. Therefore, recovery operations should be easy to perform in an efficient manner, which is influenced by product design. As a result of the literature review conducted, this paper presents a categorization of functional recovery guidelines for product design and identifies the need to plan for recovery at early design stages.

Keywords

Sustainability, design guidelines, end of use, recovery operations, early design phase

2.1. Introduction

Products are nowadays discarded and replaced due to irreparable failures, technological obsolescence, and fashion trends. These product replacement activities promote an increase in resource consumption that translates into negative environmental impact, for the most common action after the replacement desire is to “throw away” the old. By performing recovery operations on them like maintenance, upgrade, repair, refurbishment, remanufacturing or parts harvesting a product’s functionality, as well as, its value would be preserved and the environmental burden reduced (Chiu and Chu, 2012; Bakker et al., 2014; Go et al., 2015; den Hollander et al., 2017; Favi et al., 2017; Harivardhini et al., 2017; Suhariyanto et al., 2017).

Over the past years, product design strategies have taken into consideration environmental damage by focusing efforts on redesigning individual qualities, individual products or a product’s industrial process to reduce its environmental impact. This was carried out by minimising the consumption of natural resources and energy or(and) by putting a focus on recycling operations (Ceschin and Gaziulusoy, 2016). However, most of the in-use product design strategies focus on a single product’s use cycle.

Designing products for one lifespan does not fit well with the demands of a circular economy. The reason for it being that, the circular economy’s main goal is to close the loop of materials and avoid the generation of waste, as a natural ecosystem would do, while promoting economic growth. This implies, as den Hollander et al. (2017) put it, that the resources that enter the economic system must remain accounted for before, during and after their lifetime as useful products. In order to do so, products need to be brought back to its original state or similar after they have been used so they can be reused. The circular economy principles establish a hierarchy of preferred recovery strategies. Reuse is the most preferred one. It preserves the product’s integrity and requires relatively little resources to bring a product back into the economic system. Recycling is the least preferred one as only part of the materials is recovered, while product integrity and value are completely lost. The recycling process is destructive in nature which leads to a loss of material quality (Lacy and Rutqvist, 2015) and the recovery efficiency obtained is low when compared to functional recovery operations (Ng and Song, 2015). The most adequate recovery strategy depends on the type of product. However, the overall design strategy of a circular economy is clear, keep products functional and valuable for as long as possible except for products that consume high amounts of resources, like energy or water, during their use phase (Allwood et al., 2011). For resource consuming products, there might be an optimal lifespan based on the environmental load trade-off between the substituting solution and the product in use, depending on the technological progress on the reduction of consumption over time (Bakker et al., 2014). Thus, if optimal recovery becomes a design driver, as the circular economy prescribes, design strategies to create new products must be focused on contributing to efficient recovery operations, which allow the material quality to be preserved.

In this context, the question that this paper addresses is “How can product design ease the process of recovering functionality from products?” As a result of a literature review, design strategies, guidelines and product features that enhance a product’s potential to have multiple or/and long-life cycles are presented with a focus on the recovery operations to be performed on them and the expected quality output of each recovery strategy. The hypothesis that product design influences value recovery is well presented and found to be stated reiteratively in literature. This paper also reveals the lack of research on product design for circular economy at early design stages given the little amount of found papers; and the necessity to plan for the necessary recovery operations early in the design process so that the process becomes more efficient. The scope of the research has been limited by the assumption that the necessary business model for a successful value recovery process is in place (Bocken et al., 2016).

2.2. Methodology

To answer the research question previously presented**,** a systematic literature review was carried out inspired by the method proposed in Waddington et al. (2012). First, a comprehensive research covering scientific and non-scientific papers on the topic of circular economy was done. Second, a more systematic literature review was conducted. The electronic database Scopus was used to retrieve scientific papers. The search terms used to retrieve the documents from Scopus were divided in three categories: product design, end of life strategies and circular economy. The search terms used for each of the categories were:

1) Search terms related to product design: “concept* design”; “early stage” AND “product design”; “sustainable” AND “product design”; “circular” AND “product design”; “ecodesign"; “design for sustainability”; “design for environment”

2) Search terms related to end of life strategies: “life-cycle”; “end of life”; “end of use” “closed loop”; “resource effic*”; “reuse*”; “repair*”; “remanufacture*”; “recover”
3) Search terms related to circular economy: “circular economy”

The resulting search strings where a combination of three of these terms maximum within one category or as a combination with another category. One example of a generated search string would be: “early stage” AND “product design” AND “circular economy”. The symbol “*” was used to retrieve words with the same root but different endings, i.e. concept and conceptual would be searched as “concept*”. Only articles, reviews and conference papers where considered without any limitation regarding year or journal. Only documents in English where considered. The literature search was carried out in the first week of October of 2017.

The search engine was set to look for the aforementioned keywords in either the title, the abstract or the author’s keywords. Given the large amount of papers retrieved, the collection of papers was narrowed down by looking only into the title and abstract to determine the relevancy of the paper to the research., which was determined by searching specifically for keywords like “product design” “early stage” and the main recovery operations that the authors where interested in “reuse” “repair” “refurbish” “remanufacture” “maintenance”. This reduced the number of articles from thousands (the retrieved papers count for around 13000 in total) to 20. Finally, through snowballing –looking into referenced papers by the sampled papers- 7 more articles were added to count up to 27 papers in total for the second, systematic literature review.

2.3. Results and Discussion

2.3.1. Scientific Papers related to Product Design and Circular Economy

By looking at the chronological development of publications on Scopus over the past years, it is clear to see that there has been a growing number of papers being published since 2014 that relate the aforementioned category of search terms related to product design with (AND) the search term “circular economy”. Only 3 articles refer to early design stages or concept design, them being conference papers dating from the years 2016 and 2017. Figure 1 shows the chronological development of publications in Scopus.

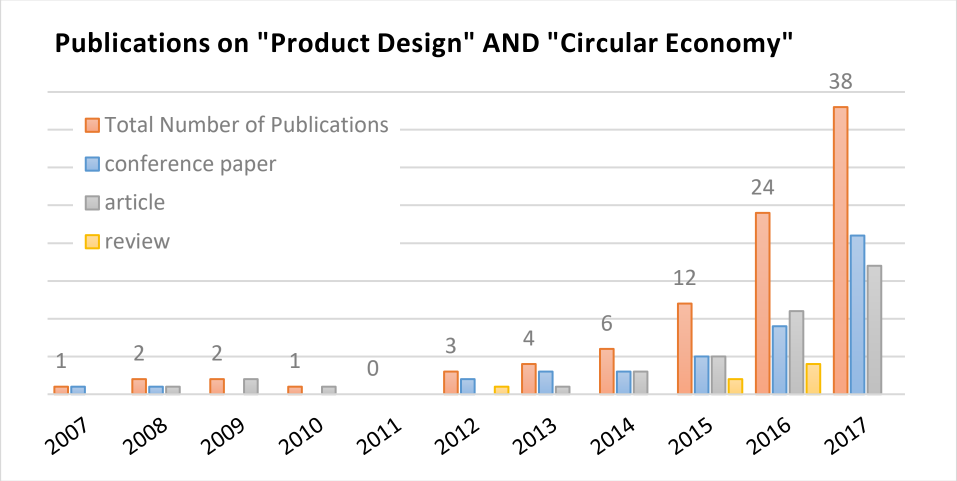


Figure 1- Distribution of number of publications for each year when using the search term circular economy and all the aforementioned terms in the category of product design.

Despite the fact that a circular economy shifts, by its principles, the term of "end of life" to the term "end of use" at least for the recovery processes of repair, refurbishment and remanufacturing; there are not any results to be found with the keyword "end of use". This might be due to the fact that the term "end of life" has been used in literature to refer to the moment when a product is obsolete, in the eyes of the user, or cannot perform its functions any longer without distinction on whether it is the first use cycle or the last. However, it is not considered to be a gap of knowledge.

2.3.2. How can product design improve functional recovery from products?

In dealing with this research question, two perspectives have been taken. A retrospective one, going from finished products to design recommendations for an improved and more efficient end of life recovery process and a forward-looking perspective, going from design to product in which design strategies and guidelines are the starting point. Both approaches meet when considering value recovery operations, which are focused on functionality and appearance, as the main focus of the product design process.

Product design in retrospective: finished products as a reflection of the design process

Product design features are defined as the characteristics of a product that describe its appearance, components and capabilities. They represent an adequate source of knowledge since they are the result of design decisions. Their detailed definition during the design process is of great relevance for after production activities, especially functional recovery activities, for they can ease or hinder the performance of operations and thus, the overall efficiency of the process.

The literature, majorly concerning EOL decision making and management, suggests which products' features have the highest influence on the recovery process and also, which product features affect the choice of the end of life (use) strategy. The criterion to categorize the features found in literature was determined by the authors based on whether the product features are determined by design, e.g. height, weight; or "imposed" by a product's context, e.g. technology around a product, consumer's acceptance, trends, business model, etc. This article will refer to product design features and leave product context features aside. Although product context features influence the potential economic success of a reused product they are considered to be beyond the scope of this research.

Product design features are classified by whether they refer to the product's architecture or to the product's usage features. They both influence the ease of recovery of a product. Product architecture features are primarily related to the nature, geometry, and number of components and the way in which these are assembled. Product usage features refer to characteristics of the product that deteriorate, thus becoming relevant for the performance of the product while in use or for future uses. As a result of looking into papers that fall under the category of end-of-life decision making, product features that determine which end of life strategy will be the most adequate for each product have been mapped. The collected data advises on the influence of product features into recovery strategies. However, it was found difficult to determine specifically which particular features influenced, directly or indirectly, which particular operations from the recovery process, i.e. cleaning, diagnosing, disassembling, reassembling, etc. The majority of the papers refer explicitly and generally to recovery strategies but implicitly to the recovery operations that need to be performed to recover the product. In addition, by looking into papers focused on specific recovery strategies, product characteristics that hinder the expected recovery strategies like maintenance, remanufacturing, or broadly speaking the reusability of a product, have also been mapped. It was found again that most of the stated product features refer to recovery strategies and not particular operations. Both results have been presented in Table 1, which aims to map the influence that product features have on different recovery strategies.

Table 1 Influential product features with respect to different end of life processes

Field of Study	Authors	Product architecture features	Product usage features	Recovery strategies/operations referred
End-of-life decision making	(Rose and Ishii, 1999)	Number of parts*, number of materials*, number of modules, functional complexity (relationship between modules and functions they perform), hazardous materials, size (*) critical characteristics to predict EOL strategy	Wear out life, level of cleanliness of product* –after its use.	Reuse, service, remanufacture, recycle or disposal
	(Ramani et al., 2010)	Product structure, disassembly level and sequence	Material properties, functional performance, reliability	Reuse, refurbishing, remanufacturing and material recovery
	(Ma and Kremer, 2016)	Product structure, joining and geometrical relationship among components, disassembly sequence, direction and force	-	Reuse, recycling and remanufacturing
	(Chiu and Chu, 2012)	Product architecture, disassembly sequence	Number and type of materials,	Reuse, remanufacture and recycling
Maintenance – only for mechanical products	(Coulibaly, et al., 2008)	Complexity of the structure, i.e. geometry of parts and assembly links (fasteners)	Survivability (ability of the product to continue to work after the failure of a considered component)	Failure detection, diagnostic, reparation and test
Re-manufacturing	(Hatcher et al., 2011)	Product structure or geometry and joining or fastening methods	Value of materials, durability of parts	Disassembly, cleaning, differ from one product to another
	(Sundin and Bras, 2005)	Product and part geometries, fasteners and joining methods,	Process resistance of parts	Remanufacturing, refurbishment
Reparability	(Pamminger et al., 2017)	Product structure, joining elements, assembly of components (sequence, number of parts, directions)	Ageing resistance materials, robustness	Repair, reuse and remanufacture. Disassembly, reassembly and diagnosis

Planning for the Recovery Process through Product Design

Efficient product recovery would be achieved if the end of life strategy was planned for early in the design process (Ng and Song, 2015). This idea, also suggested in literature related to EOL management, is thought to facilitate efficient and effective take-back and recovery (Ramani et al., 2010). Planning means expecting the product to go through a certain recovery process, after a certain period of time –use phase of the whole lifecycle- and adapting its features to the process. It can only happen when a recovery strategy has already been decided for the product, which dictates the design strategy to be adopted. It is logical and necessary to make the product suitable to go through the recovery operations before the product has been released to production, when changes cannot be made. Therefore, planning for a product´s recovery would be done during the design process and not after production. Shin et al. (2011) support the idea of planning at the beginning of product conceptual design so that end of life requirements will be considered together with customer requirements.

Planning for recovery operations can avoid the high labour costs of remanufacturing, mentioned by Prendeville and Bocken (2017) as an inhibitor for their case study, by reducing operation times and therefore, labour costs. It can also help in reducing storage costs associated to remanufacturing, if they are planned for it during the product layout. Schöggl et al. (2017) also remark that planning would help in reducing repair costs because the potential to improve performance decreases the further the product is closer to production. Additionally, planning influences the environmental impact of a product. Walker (2012) emphasizes the importance of considering all the operations around the product, including the value recovery ones, and how energy intensive they are. He demonstrates how maintenance operations can be relevant in determining a product's environmental impact. Sanyé-Mengual et al. (2014) have also shown how different maintenance operations can result in highly different environmental impact figures. They study two different products, demonstrating that if maintenance tasks are planned for and well communicated to consumers, the environmental impact due to maintenance tasks, which is not frequently considered, could be reduced. Finally, since recovery operations are reliant on the infrastructure in place, where the operations will be performed, through planning the task can be optimized and eased.

Product Design to make products more circular

As it has been previously shown through the aforementioned retrospective and has been stated by Go et al. (2015), product design decisions will inevitably affect recovery efficiency. Therefore, product design strategies have to focus on recovering and/or preserving a product's integrity if circular economy instructions become a driver for design. This paper presents design strategies that put product value recovery on the focal point following the typology of key concepts for a circular economy by den Hollander et al. (2017) with some exceptions. Design for recycling, emotional durability and recontextualization strategies have not been included in the paper for the reasons that: recycling does not preserve the functionality of the product, design for emotional durability is of a strong subjective nature and it is not recovery focused and finally, design for recontextualization has also been omitted for there is not specific product outcome or operation to be performed.

The preferred design strategies for product value recovery are presented along the corresponding necessary recovery operations and also, the expected quality output that should result from recovery process. This approach has been taken so that it is clear in general terms what the procedures for recovery are for each plan of action. This is presented in Table 2. There are two clear categories within the design strategies, design strategies targeting product use extension and design strategies aiming at product reuse. However, they are not exclusive from each other. This is to say that life extension strategies can be combined with product reuse strategies with the aim to develop a product whose value will be easy to recover and maintain, for instance.

Table 2 Design strategies for functional value recovery and the recovery operations that allow for the desired quality output.

Product Design for:	Strategy's Goal	Recovery Operations	Source for Operations	Operation's Goal	Output Quality
Preventive Maintenance	Enable use extension	Cleaning, diagnosis, product specific overhauling activities to rise quality levels up to OR and test	(Coulibaly et al., 2008) (Kimura, 1999)	To retain a product's functional capabilities and/or cosmetic condition.	Similar or lower than OR
Upgrading (Hardware)		Cleaning, diagnosis, disassembly, modules	(Go et al., 2015)	Enhancing, relative to the original design specifications, a	Higher than original requirements for the

		replacement, reassembly, testing		product´s functional capabilities and or cosmetic condition	upgraded modules
Repairing (Corrective Maintenance and Breakdown Maintenance)	Product reuse	Core collection*, diagnosis, cleaning, disassembly, specific component remediation, reassembly, testing (*) product specific	(Pamminger et al., 2017)	Correction of specific faults to bring a product back to working or cosmetic conditions	Similar or lower than OR
Refurbishing or Re-conditioning		Core collection, diagnosis, cleaning, disassembly, storage, product repair/remediation, reassembly, testing	Deduced from remanufacturing process	Bring back to working or cosmetic condition	Similar or lower than OR
Part harvesting	Part reuse	Part collection, diagnosis, cleaning, disassembly, storage, repair/remediation, reassembly, testing	Deduction from remanufacturing process	Collection of working product's parts for new products.	OR or higher(1)
Remanufac-turing	Product reuse	Core collection, diagnosis, cleaning, disassembly, storage, product repair/remediation, reassembly, testing	(Sundin and Bras, 2005) (RIC, 2016)	Bring product back to original performance specifications	OR or higher(1)

Design strategies focused on preventive maintenance aim to design a product where the removal of agents not specified in the product's original requirements as well as product specific operations will be easy to perform. Maintaining a product requires of product specific operations like refilling of fluid agents or worn out parts replacement. It is evident that maintaining the sharp edge of a knife –a sharp edge is considered to be OR- differs greatly from maintaining a vehicle to OR, although both they both aim at maintenance. It is important to notice that product maintenance requires of periodical monitoring and diagnosis (Iung and Levrat, 2014). Hardware upgrading strategies are mainly focused on the successful replacement of modules to gain more functionalities relative to the original functions. Repairing strategies are similar to those of corrective maintenance and breakdown maintenance. The strategy aims to ease repairing operations on products so that they can be easily recovered to a functional state and then, reused. Refurbishing or reconditioning strategies –synonyms in terms of den Hollander et al. (2017)- are similar, in terms of the necessary operations to perform to recover the product, to those of remanufacturing taken from Go et al. (2015), and Sundin and Bras (2005) and to those of part harvesting. The difference lies in the output quality reached after the process.

The output quality of different strategies is directly related to the recovery process and can be a driver for design choices. For instance, if what is expected from a product is to have lower than OR requirements for certain features, design choices might change. It is also interesting to notice that remanufacturing processes can result higher than OR standards. This is common for mechanical products whose failures commonly occur when at the beginning of their use life. Remanufacturing companies, by offering reused and therefore, tested products, have the capability to offer higher than out-of-the-conveyor standards. It is common practice for engines, they are less prone to fail when they are given a second (or other) life through remanufacturing.

By looking into which recovery operations each design strategy leads to, design guidelines for specific recovery tasks have been mapped. The rationale behind this classification is that, as it is represented in Table 3**,** most operations are common among the different design strategies, however, the difference lies in the level of “deepness” in which they are performed in a product. For instance, cleaning for maintenance might refer to surface cleaning whereas cleaning for remanufacturing involves cleaning every component of an assembly to the core (including the core, if necessary). Some recovery operations are not needed in all the strategies. Another example to illustrate this idea, core collection, in the case of repair, is a product specific operation that depends on the business model. Products aimed to be repaired might undergo similar operations than those that want to be refurbished however, the level at which operations for recovery are performed varies. As an example, cleaning a product that is only aimed to be repaired might involve only superficial cleaning and around the repaired element, while a product that is aimed to be refurbished will require deeper cleaning of the overall product. However, as it is noticeable, the cleaning task on both products should be easy to perform.

Table 3 Recovery operations for each design strategy

Recovery Strategy	Operation level	Cleaning	Diagnosis/ Testing	Dis-assembly	Re-assembly	Storage	Disassembly stopping point
Maintenance	Superficial	x	x	x	x		Superficial
Upgrading	Only to upgradable modules	x	x	x	x		Upgradable module
Repair	Only on failing parts	x	x	x	x		Up to damaged component
Refurbishment	Failing parts + overall product but not in depth, just enough to make it marketable	x	x	x	x	x	Up to core
Part Harvesting	Like remanufacturing but only for specified parts	x	x	x	x	x	Up to desired part, might include the desired part
Remanufacture	All operations performed on the entire product – core + the rest	x	x	x	x	x	Up to core, might include the core

Operation focused guidelines are not exclusive, but rather they are to be used in conjunction. Since they are defined per operation, various design guidelines are to be used for the same product if it has to undergo multiple recovery operations. However, from the results found it is unclear which guidelines should have preference over other guidelines in the situation of a trade-off between product requirements. Additionally, it has not been found at which stage of the design process shall they be used.

Common operations in all design strategies are cleaning, diagnosis or testing and disassembly and reassembly. In fact, the degree of cleanliness in a product after its use is mentioned in Rose and Ishii (1999) as a critical feature to decide for the most adequate end of life strategy. Inspection or diagnosis tasks become especially relevant for maintenance operations (Coulibaly et al., 2008). Diagnosing a product or inspecting it will give information of its condition and functionality therefore; it is also a critical operation. Finally, non-destructive disassembly and reassembly operations are necessary in order to have access to the subassemblies of a product. It is a critical task because it determines the accessibility and reparability, to some extent, of a product. For instance, if a product cannot be disassembled in a non-destructive manner because it has been glued, it will take more time and work labour to recover and thus, can make the process less economically interesting.

Found design guidelines to ease cleaning tasks, depicted in Table 4, address a products geometry and its surface. It must be said, that cleaning refers to a general, standard cleaning process, not to a cleaning method in particular. Design guidelines that refer to product diagnosis, Table 5, address a product's structure and the needed equipment for testing. Guidelines on disassembly and reassembly, Table 6, address four main product features: a product's assembly configuration, its sequence, reversibility and the number of tool changes; a product's fixtures, referring to the different types, their quantity, their wear resistance, the placement and its variety; a product's geometry and the tools required to perform the task like disassembly guides. Finally, storage operations become relevant for operations like refurbishing, part harvesting and remanufacturing. Storage operations are referred, in remanufacturing literature, as an operation that has to be performed when the product as a whole is irreparable but some parts are useful. When this is the case, it becomes beneficial to store the spare functional parts to potentially be used in other products (Sundin and Bras, 2005). Presented in Table 7, they are associated to geometric and aesthetical properties of products.

Table 4 Product guidelines to ease the operation of cleaning

Ease of cleaning refers to the removal of external, undesired agents from a product		
Geometry	Minimize geometric features that trap contaminants Reduce the number of cavities that are capable of collecting residue Avoid sharp edges and thresholds	(Go et al., 2015) (Allwood et al., 2011)
Surface	Protection against corrosion and dirt Protect against contamination caused by wear	

Table 5 Product guidelines to ease product diagnosis operations

Ease of Diagnosis Refers to physical inspection, to quickly check the condition of the components and functionality testing of electronic or mechanical components		
Product Structure	Make wear of parts detectable and visible. Predefined wear facings to prevent attached components to be affected, signals and sign to point out wearing Provide easy access to test points Aim to concentrate wear damage in small detachable parts (inserts and sleeves)	(Go et al., 2015); (Tischner, U.; Hora, 2012); (Allwood et al., 2011)
Tools	Reduce the number of different testing and inspection equipment pieces needed and the level of sophistication required Provide good testing documentation and specifications	

Table 6 Product design guidelines to ease disassembly and reassembly

Disassembly and reassembly guidelines Deconstructing the product in a non-destructive manner to perform repairing and cleaning.			
Assembly configuration	Sequence	Set centre-elements on a base part Aim at self-locating interfaces Mark parts which must be removed first Avoid multiple directions and complex movements for disassembly Avoid the need for specialized disassembly procedures Avoid long disassembly sequences: consider part order, part disassembly directions and number of reorientations. Locate parts with the highest value in easily accessible positions Find an optimized disassembly plan Find an optimized disassembly stopping point Create modular subassemblies which do not require further disassembly operations	(Favi et al., 2017) (Go et al., 2015) (Tischner, U.; Hora, 2012) (Allwood et al., 2011) (Harivardhini et al., 2017); (Hui et al., 2008)
	Reversibility	Plan for a reversible assembly process Avoid permanent fasteners that require destructive removal. Allow for non-destructive disassembly using snap-fit types of connections, active disassembly using smart material and heat-reversible.	
	Tools	Consider number of tool changes	
Fixtures	Type	If destructive removal is necessary, ensure that damage to the core does not happen Reduce the number of fasteners prone to damage and breakage during removal Use fasteners rather than adhesives	(Go et al., 2015); (Tischner, U.; Hora, 2012); (Favi

		Use fasteners that are easy to remove or destroy Use reversible joints or connectors with fracture points Easy detachable connections Avoid welding and jamming of parts Ensure screw threads are sufficiently robust	et al., 2017); (Billatos and Basaly, 1997); (Ramani et al., 2010)
	Quantity	Reduce the total number of fasteners in the unit Reduce the number of press-fits Minimize the number of joints and connections	
	Wear	Increase corrosion resistance of fasteners	
	Placement	Reduce the number of fasteners not in direct line of sight Make joints visible and accessible, avoid hidden joints Provide easy access to disjoining, fracture or cutting points	
	Variety	Standardize fasteners by reducing the number of different types of fasteners and the number of different sized fasteners Use the same fasteners for many parts	
Product Geometry		Create geometry and shape with the purpose of facilitating handling operations Modularize valuable modules. Increase product accessibility by eliminating visual and physical obstructions Merge components, whenever possible, with the aim to minimise the number of components and to reduce the number of assembly and disassembly operations Develop standard interface for the connection of different modules	(Allwood et al., 2011) (Favi et al., 2017)
Tools		Provide good documentation of specifications and clear installation manuals. Avoid need for specific tools	(Go et al., 2015)

Table 7 Product design guidelines to ease storage

Ease of Storage Refers to the operations to keep valuable parts safe for future usage		
Geometry	Use identical or grossly dissimilar parts Avoid protrusions outside regular volume	(Allwood et al., 2011)
Aesthetics	Colour coding	

2.4. Conclusions

Product design plays a key role in achieving profitable end-of-life operations (Ramani et al., 2010). Therefore, product design should prepare products to have multiple life cycles, when circular economy is a driver for design. If products are designed for an efficient and affordable recovery, they can be valuable for a longer time. The most stated product features from EOL decision making and EOL management are: a product's geometry, the linkages between its components and how they are arranged as a whole. They influence a product's potential to be recovered after it has been used. It follows then, that if these features are settled adequately to match the recovery operation that they will undergo, the process of recovery will turn out to be more efficient, which can be quantified in terms of costs and required time per operation, as well as, the product's quality after going through the process. The efficiency of the recovery process relies greatly on whether it has been planned for in the product or not. Planning for the recovery operations, as the design strategies prescribe, is also useful to overcome challenges like high labour costs or storage costs associated to remanufacturing and refurbishing. Through planning the environmental impact of a product can be reduced by considering, for example, how resource intensive are the maintenance operations required for a product. It also helps in avoiding unwanted recovery results, like not being able to access a part or requiring for a specific unavailable tool.

From the design strategies that focus on multiple lifecycles, it has been found that they unclearly state the necessary operations required for each recovery strategy and the expected output quality. Hence, translating into bad guidance for designers given the broad sense of the terms and the inaccuracy in defining the process that products would undergo. This article has been able to put together those three relevant elements for the recovery process and has been able to conclude that different design strategies that aim for a product to have multiple lifecycles, do have recovery operations in common although these operations will differ from each other in the degree of effort required to perform the recovery, which depends on the product condition before recovery and the expected quality output of the company and the market. Following this idea, this research has been able to point out common critical operations for functional recovery. Those being: cleaning, diagnosis, disassembly and reassembly.

Shown that these guidelines have not been tested for implementation at early design stages, since they are the result of post-production objects analysis. The guidelines implementation needs to be tested. There is little information on how to use these guidelines or which guidelines should be prioritized over the others in case of a trade-off between them. Is it more important to prioritize reassembly or diagnosis, for instance? Also, at which point of the design process should these guidelines be implemented? The results of the paper are limited in the sense that they have not been implemented during the process with real cases. Scientific papers following up on the implementation of these design guidelines at early design stages have not been found. Instead, most of the papers refer to these guidelines as prescriptions or suggestions to be taken into account for future products. It is the aim of the researchers to investigate in the future design practice for functional value recovery. Also, a question that remains unanswered is "how to plan for the recovery operations through product design?" It is the intention of the researchers to continue with further investigations on the design practice to find out.

2.5. Limitations

Design strategies influencing the choice of material and manufacturing process and product structure alone cannot guarantee the success of the recovery operation. It is clear that the necessary business model to allow for an economically successful process has to be put into place, and set in parallel with the design strategies to define distribution, logistics, and management of the second life products, for instance. This has been an assumption used during the research process. The presented design strategies do not consider business capabilities, which are highly relevant when trying to market recovered products. The circular economy requires a more complex infrastructure than the one required in a linear one in terms of supply chain, logistics, marketing, recovery facilities, and labour. The scope has been narrowed down to product-level requirements that make a product adequate to go through recovery processes successfully; it has not looked into a system level.

Another assumption made during this research is that there is an existing market that would demand for reused and long-life products without which these strategies would not make sense. The economy markets are driven by customer demands and this research assumes that this demand for reused products exits.

References

Allwood, J. M., Ashby, M. F., Gutowski, T. G., and Worrell, E. (2011). Material efficiency: A white paper. Resources, Conservation and Recycling, 55(3), 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002

Bakker, C., Wang, F., Huisman, J., and Den Hollander, M. (2014). Products that go round: Exploring product life extension through design. Journal of Cleaner Production, 69, 10–16. https://doi.org/10.1016/j.jclepro.2014.01.028

Billatos, S. B., and Basaly, A. N. (1997). Recycling issues. In green technology and design for the environment (p. 296).

Bocken, N. M. P., Bakker, C., and Pauw, I. De. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 1015(0), 20. https://doi.org/10.1080/21681015.2016.1172124

Ceschin, F., and Gaziulusoy, I. (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. Design Studies, 47, 118–163. https://doi.org/10.1016/j.destud.2016.09.002

Chiu, M.-C., and Chu, C.-H. (2012). Review of sustainable product design from life cycle perspectives. International Journal of Precision Engineering and Manufacturing, 13(7), 1259–1272. https://doi.org/10.1007/s12541-012-0169-1

Coulibaly, A., Houssin, R., and Mutel, B. (2008). Maintainability and safety indicators at design stage for mechanical products. Computers in Industry, 59(5), 438–449. https://doi.org/10.1016/j.compind.2007.12.006

den Hollander, M. C., Bakker, C. A., and Hultink, E. J. (2017). Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. Journal of Industrial Ecology, 21(3), 517–525. https://doi.org/10.1111/jiec.12610

Favi, C., Germani, M., Luzi, A., Mandolini, M., and Marconi, M. (2017). A design for EoL approach and metrics to favour closed-loop scenarios for products. International Journal of Sustainable Engineering, 10(3), 136–146. https://doi.org/10.1080/19397038.2016.1270369

Go, T. F., Wahab, D. A., and Hishamuddin, H. (2015). Multiple generation life-cycles for product sustainability: The way forward. Journal of Cleaner Production, 95, 16–29. https://doi.org/10.1016/j.jclepro.2015.02.065

Harivardhini, S., Murali Krishna, K., and Chakrabarti, A. (2017). An Integrated Framework for supporting decision making during early design stages on end-of-life disassembly. Journal of Cleaner Production, 168, 558–574. https://doi.org/10.1016/j.jclepro.2017.08.102

Hatcher, G. D., Ijomah, W. L., and Windmill, J. F. C. (2011). Design for remanufacture: a literature review and future research needs. Journal of Cleaner Production, 19(17–18), 2004–2014. https://doi.org/10.1016/j.jclepro.2011.06.019

Hui, W., Dong, X., and Guanghong, D. (2008). A genetic algorithm for product disassembly sequence planning. Neurocomputing, 71(13–15), 2720–2726. https://doi.org/10.1016/j.neucom.2007.11.042

Iung, B., and Levrat, E. (2014). Advanced maintenance services for promoting sustainability. Procedia CIRP, 22(1), 15–22. https://doi.org/10.1016/j.procir.2014.07.018

Kimura, F. (1999). Life Cycle Design for Inverse Manufacturing. In Environmentally Conscious Design and Inverse Manufacturing Conference Proceedings (p. 995).

Lacy, P., and Rutqvist, J. (2015). Waste to Wealth. Accenture, 293. https://doi.org/10.1057/9781137530707

Ma, J., and Kremer, G. E. O. (2016). A systematic literature review of modular product design (MPD) from the perspective of sustainability. International Journal of Advanced Manufacturing Technology (Vol. 86). The International Journal of Advanced Manufacturing Technology. https://doi.org/10.1007/s00170-015-8290-9

Ng, Y. T., and Song, B. (2015). Product Characteristic Based Method for End-of-Life Product Recovery. In A. Y. C. Nee (Ed.), Handbook of Manufacturing Engineering and Technology (pp. 3377–3403). springer-verlag london.

Pamminger, R., Kuso, S., Wimmer, W., and Podhardsky, G. (2017) . Re-design of a digital voice recorder to meet the needs of circular economy-Status analysis. 2016 Electronics Goes Green 2016+, EGG 2016, (7829815), 7829815. https://doi.org/10.1109/EGG.2016.7829815

Prendeville, S., and Bocken, N. (2017). Design for Remanufacturing and Circular Business Models. Sustainability Through Innovation in Product Life Cycle Design, 269–283. https://doi.org/10.1007/978-981-10-0471-1

Ramani, K., Ramanujan, D., Bernstein, W. Z., Zhao, F., Sutherland, J., Handwerker, C., ... Thurston, D. (2010). Integrated Sustainable Life Cycle Design: A Review. Journal of Mechanical Design, 132(9), 91004. https://doi.org/10.1115/1.4002308

RIC. RIC001.1-2016 - American National Standard - ANSI approved (2016).

Rose, C. M., and Ishii, K. (1999). Product End-of-Life Strategy Categorization Design Tool. Journal of Electronics Manufacturing, 9(650), 41–51. https://doi.org/10.1142/S0960313199000271

Sanyé-Mengual, E., Pérez-López, P., González-García, S., Lozano, R. G., Feijoo, G., Moreira, M. T., ... Rieradevall, J. (2014). Eco-designing the use phase of products in sustainable manufacturing:

The importance of maintenance and communication-to-user strategies. Journal of Industrial Ecology, 18(4), 545–557. https://doi.org/10.1111/jiec.12161

Schöggl, J. P., Baumgartner, R. J., and Hofer, D. (2017). Improving sustainability performance in early phases of product design: A checklist for sustainable product development tested in the automotive industry. Journal of Cleaner Production, 140, 1602–1617. https://doi.org/10.1016/j.jclepro.2016.09.195

Suhariyanto, T. T., Wahab, D. A., and Rahman, M. N. A. (2017). Multi-Life Cycle Assessment for sustainable products: A systematic review. Journal of Cleaner Production, 165, 677–696. https://doi.org/10.1016/j.jclepro.2017.07.123

Sundin, E., and Bras, B. (2005). Making functional sales environmentally and economically beneficial through product remanufacturing. Journal of Cleaner Production, 13(9), 913–925. https://doi.org/10.1016/j.jclepro.2004.04.006

Tischner, U.; Hora, M. (2012). Sustainable electronic product design. In Waste electrical and electronic equipment (WEEE) handbook (p. 405). Elsevier Ltd. https://doi.org/10.1533/9780857096333.4.405

Waddington, H., White, H., Snilstveit, B., Hombrados, J. G., Vojtkova, M., Davies, P., ... Tugwell, P. (2012). How to do a good systematic review of effects in international development: a tool kit. Journal of Development Effectiveness, 4(3), 359–387. https://doi.org/10.1080/19439342.2012.711765

Walker, A. (2012). Life-cycle thinking, analysis and design. In Designing for zero waste: consumption, technologies and the built environment (pp. 145–167). Taylor and Francis.

*Note to the chapter: on page 26, section 2.3.1, line 4, the sentence was published with the following text: " In total 93 articles, of which”. However, this text led to confusion and has been removed.

CHAPTER 3

PRACTICES OF FAULT DIAGNOSIS IN HOUSEHOLD APPLIANCES: INSIGHTS FOR DESIGN[2]

---

[2] Pozo Arcos, B., Bakker, C., Flipsen, B., Balkenende, R., 2020. Practices of fault diagnosis in household appliances: Insights for design. J. Clean. Prod. 265, 121812. https://doi.org/10.1016/j.jclepro.2020.121812

Abstract

Fault diagnosis is the process of identifying and characterising a fault when a failure occurs. It is, therefore, an essential step to take before product-repair. In this study, we ask how conventional users diagnose faults in household appliances and how the design of these appliances facilitates or hampers the process of fault diagnosis. To investigate this we qualitatively analyse the content of iFixit's online repair forum for three products: kitchen blenders, vacuum cleaners, and refrigerators. First, we develop a conceptual analysis framework based on the literature. Second, using conventional content analysis, we correlate facilitating and hampering features with the appliances' design. The process of fault diagnosis can be described by the subsequent actions of fault detection, fault location, and fault isolation. Our results show that consumers detect faults by noticing five types of symptoms. Subsequently, two distinct diagnosis approaches can be distinguished. One follows a trial and error approach where the user performs diagnosis actions, which usually result in replacing a potentially defective component until the symptoms disappear. The other occurs when the symptoms are error codes; the defective part can be more accurately identified, and the diagnosis is straightforward. The results also show that appliances are not designed to make fault diagnosis easy. Access to and visibility of components are often blocked, making fault isolation challenging. User manuals commonly lack relevant explanations, for instance when symptoms are different from error codes. Based on these findings, we propose a number of design recommendations to facilitate fault diagnosis for household appliance users.

Keywords

Product Design, Circular Economy, Fault diagnosis, Repair, Troubleshooting, Design guidelines

3.1. Introduction

The inertia principle described by Walter Stahel in his book “The performance economy” (Stahel, 2006) states that the preferred operations for a circular economy are those which preserve a product’s integrity (i.e. aiming to reuse products instead of recycling them), even though ultimately and unavoidably products will have to be recycled at some point. Repair practices in products have the benefit of slowing down resource loops (Bocken et al., 2016), and require less investment in transportation and processing than other recovery operations (Scott and Weaver, 2014). Hence, product repairs can make a considerable positive impact in a circular economy.

The current design of consumer electronics and household appliances tends to lean towards hindering product reparability by conventional product users. The testimony developed by iFixit for the workshop “Nixing the fix”, hosted by the United States Federal Trade Commission, gives examples of how manufacturers purposely hinder repairs by design (iFixit, 2019). A product’s design influences how time-consuming, and complicated the repair will be, as well as how economically viable (Behdad and Sabbaghi, 2017; Gandhi and Wani, 1999; Imrhan, 1992a). The impact of design in repair practices is also evident for users, who take repair decisions based on the convenience and ease of accessibility of repair as designed into the products (European Comission, 2018). Hence, many authors agree that repairs could be facilitated if they were considered during the design process (Behdad et al., 2016; Bereiter and Miller, 1990; Gandhi and Wani, 1999; Imrhan, 1992b; Kelley and Rosen, 1985; Thompson and Tjiparuro, 2004; USA Department of Defense, 1988).

Currently, research is being conducted on developing indicators to measure the reparability of electronic products (Cordella et al., 2019), and on exploring how to improve repair through design (Pamminger et al., 2017). Nonetheless, how the initial process of fault diagnosis takes place on actual product-repairs and how it is influenced by design has not yet been studied; but it is essential. Fault diagnosis reveals the operational state of a product and its components (Tecchio et al., 2016; USA Department of Defense, 1988). It is directly associated with the difficulty (Behdad et al., 2016) and time spent on repairs (USA Department of Defense, 1988). Moreover, it reveals the appliance’s condition after use (Dindarian et al., 2012; Parajuly and Wenzel, 2017).

The process of fault diagnosis is briefly mentioned in the scientific literature on the repair process of consumer electronics (Behdad and Sabbaghi, 2017) and dishwasher and washing machines (Tecchio et al., 2016). Other scientific papers focus on specific diagnosis techniques that assure quality and reliability before product release (Benko et al., 2004; Marijan et al., 2010; Shin et al., 2016) or refer to electronically controlled and monitored devices (Friedrich and Gohner, 2015; Kanma et al., 2003; Rogers et al., 2019; Utton and Scharf, 2004). However, there is no generic description that explains how non-professional users should proceed when diagnosing faults in household appliances, nor how design features influence it.

Given this gap, the aim of this research project is to gain an understanding of how conventional users diagnose faults in household appliances and how the design of these appliances facilitates or hampers the process of fault diagnosis. Understanding both aspects will increase the efficiency of product-repairs and provide designers with valuable information on how to facilitate fault diagnosis and repair. To study this, we qualitatively analysed the content of iFixit's online community repair forum. Three electromechanical appliances were selected as product demonstrators: kitchen blenders, refrigerators and vacuum cleaners. Household appliances are of particular interest for the circular economy due to their extensive presence in homes and their often low repair rates (Bovea et al., 2016; Stamminger and Hennies, 2016).

We first present a conceptual framework of the process of fault diagnosis used for the repair forum content analysis (Section 2). In Section 3 we summarise the scientific literature on design guidelines to facilitate fault diagnosis. Section 4 presents the method we used to analyse the content. In Section 5 we present the results of the analysis; these are then discussed in Section 6, which also introduces a set of design recommendations for facilitating diagnosis in household appliances based on the results. Last, in Section 7, we summarise the main conclusions.

3.2. Theoretical framework

In this section, we develop a theoretical framework to capture the process of fault diagnosis for consumer goods. The section presents an overview of insights obtained from both the academic and non-academic literature regarding the process of fault diagnosis in household appliances.

Relevant literature was obtained through searching in Scopus, Web of Science and Google Scholar, and subsequent snowballing. Search strings related to “household appliance or domestic product” were combined with search strings on “troubleshooting or detection or diagnosis" of "faults or failures" related to "repair". The body of relevant academic literature turned out to be very limited, only to some extent addressing ways to detect specific faults in specific appliances, and not addressing at all the process of fault diagnosis. We therefore expanded our search to the far more abundant literature on fault diagnosis in professional systems on the one hand and to "grey literature" on troubleshooting of household appliances and consumer electronics on the other hand. In the latter case we selected publications in which the process of fault diagnosis was thoroughly described.

Scientific literature referring to the process of fault diagnosis is abundant in the fields of control and automation engineering and expert systems development. Both fields show a difference in the number of stages of the process but have a similar final goal: to detect and characterise faults in the system's components. In control theory, fault diagnosis consists of two stages, fault detection and isolation (FDI) (Isermann, 2006; Patton et al., 2000). In literature on expert systems, fault diagnosis consists of three steps: fault detection, fault location and fault isolation (Khaksari, 1988). In both descriptions, the first step is fault detection: noticing faults present in a system through symptoms or variations in the measurements of the parameters of the system (Khaksari, 1988; Patton et al., 2000). Fault detection results in a list of symptoms (Isermann, 2006). Subsequently, literature from expert systems defines fault location with the aim of localising the subsystem in which the malfunction lies (Khaksari, 1988). Fault location is normally performed by monitoring systems which make use of causal relationship models or abnormal behaviour models (Patton et al., 2000). It also makes use of the heuristic knowledge of the process (Isermann, 2006) The fault location procedure can be written as an algorithm and embedded in computer systems. Lastly, both definitions include fault isolation, in which the source of the fault is determined (Patton et al., 2000).

Non-academic literature from professional repairers Davidson (2004), Kleinert (2013) and Mostia William L. (2006) gives a detailed description of fault diagnosis without software support. These processes are described below.

Davidson, (2004) describes a process that consists of four steps, starting with fault detection by (1) checking for product symptoms with a method dubbed "the three Ss": sight, sound, smell. When the product is switched OFF, the technician checks for physical signs of faults like burned printed circuit boards or pulled wiring. When the product is ON, a smell of smoke, observable abnormal behaviour of the components, and unexpected sounds are possible indicators of faults. Second, (2) in the fault location stage, symptoms are associated with plausible causes. The operator's experience and heuristic knowledge of product failure, common product faults, the product's assembly structure and subsystems as well as any interdependencies indicates the possible fault location. In the third step (3), the technician isolates the fault by checking the condition of the potentially defective components. Several tests can be performed until the defective part is identified, which then leads to (4) component removal and replacement.

The fault diagnosis process described by Mostia William L. (2006) takes a technician's perspective and consists of seven steps. The "logical or analytical troubleshooting framework" is iterative and starts by defining the problem. Someone reports the problem to the technician. The technician then collects information about the problem: the product symptoms, what does work in the system, the product's construction, drawings, the built-in product indicators, product documentation, and historical information. Third, this information is analysed to propose a solution. Fourth, the sufficiency of the information is checked. Based on the information, in the fifth step a solution is proposed and, sixth, tested. The seventh step is the actual product repair.

The process described by Kleinert (2013) explains fault diagnosis as a product-specific process that leads to repairs. It is performed by following a set of product-specific tests dependent on the symptom noticed. The tests are presented in the form of questions that guide the repairer through the fault isolation stage.

Our literature research on complex systems shows, despite the differences in the number of steps, that fault location is the step prior to fault isolation. Therefore, the three steps approach seems to be more complete and explicit. We therefore will use these process stages for describing the fault diagnosis of household appliances. The findings have been amalgamated into a conceptual framework of the fault diagnosis process (figure 1).

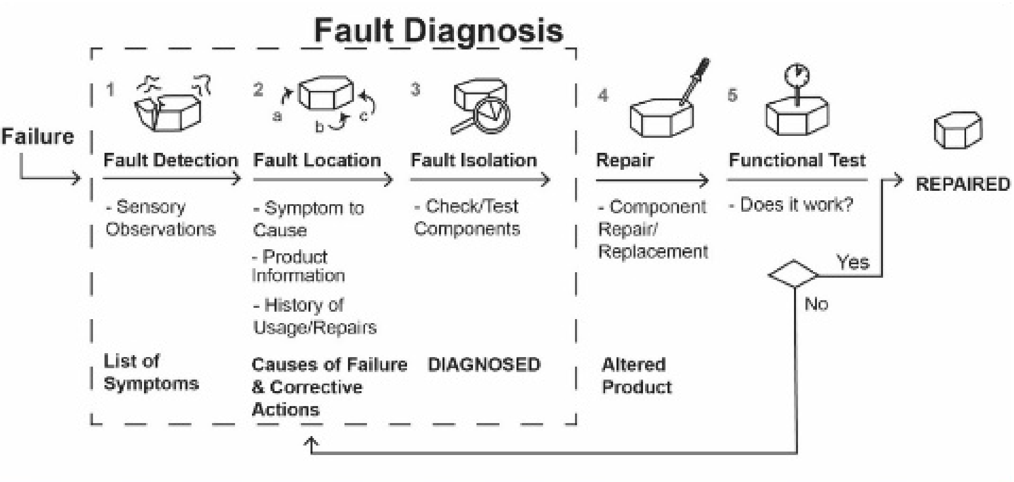


Figure 1. Conceptual framework of the process of fault diagnosis

3.3. Designing for fault diagnosis

In this section, we present a brief literature review exploring how the process of fault diagnosis can be facilitated during the design process. Due to the lack of information on the diagnosis of household appliances, other products, such as machinery and military systems, were considered; only the scientific literature was reviewed.

Literature related to the design and maintenance of machinery and military equipment recognises that facilitating fault diagnosis at early design stages is economically beneficial. It reduces the product's lifecycle costs associated with machine downtime and required time and skills for maintenance (Behdad et al., 2016; Gandhi and Wani, 1999; Imrhan, 1992b; Thompson and Tjiparuro, 2004; USA Department of Defense, 1988). It also increases the product's quality, availability, and value (Clark and Paasch, 1996; Paasch and Ruff, 1997). However, this is not yet common practice. Most of the design efforts in mechanical systems focus on reliability, and considerations of the fault diagnosis process are mostly based on observations made after design and production (Alexanders et al., 1993; Imrhan, 1992a).

Designing for fault diagnosis requires designers to make the process of determining the parameters that cause a failure (fault diagnosis) easier to perform (Paasch and Ruff, 1997). The complexity of the fault diagnosis process could be reduced if designers consider how technicians interact with malfunctioning equipment (Bereiter and Miller, 1990). Case et al. (2010) and Clark and Paasch (1996) suggest that designers should consider maintenance data to improve the product's diagnosability. Okogbaa and Otieno (2007) propose that designers have an intensive understanding of the system to increase a product's maintainability, which includes the diagnostic process. They consider a system's configuration, topology, component interdependency and failure distribution as important knowledge for design.

In general, fault diagnosis would be easy to perform if machines were designed to be simple and modular, and with accessible components (Paasch and Ruff, 1997). Simplicity can be achieved by: reducing the number of the components, consolidating functions, improving access to parts and reducing system support requirements (USA Department of Defense, 1988). Moreover, some systems facilitate diagnosis by including a sensor-based diagnosis system, often referred to as Built-In Test (BIT) (Paasch and Ruff, 1997). However, this comes with the drawback of potentially adding complexity (Bozin, 1985; Cook, 1980; as referred in (Paasch and Ruff, 1997)) making repairs even more challenging for users (McCollough, 2009).

In machinery, diagnosis can be improved during concept design by choosing a system structure where the potential candidates (components) for any possible set of abnormalities would be low; meaning fewer measurements for fault isolation. The structure should be modular, keeping the components independent (from other subfunctions), and the performance of each set of components should be known without disassembly, utilising indicators such as built-in gauges, indicator lights, and meter readings (Clark and Paasch, 1996; Paasch and Ruff, 1997). A highly diagnosable system would be one in which any possible set of abnormal performance measurements would have few associated failure possibilities, which should be noticeable without disassembly. Furthermore, fault detection and isolation time in equipment could be reduced by improving the location and orientation of components (Guo et al., 2018; Imrhan, 1992b). Components should be visually and anthropometrically accessible, and critical components (components without which the product will not work) should be labelled and coded to help the operator with tasks such as part identification and appropriate use (Imrhan, 1992b). Gandhi and Wani (1999) propose facilitating diagnosis by including built-in "malfunction annunciation features" in machinery such as audible signals or a visual display, and allowing for visual and manipulative actions to inspect the components.

Taken together, these studies support the notion that fault diagnosis can be facilitated by designing an adequate physical structure and built-in test system in the product. The features that make a complex system diagnosable are: a function distribution throughout the components that requires few measurements to isolate a fault; a spatial distribution of components that allows for visual as well as manual access; critical components that are coded and labelled; and, including "malfunction annunciation features" in the product. Given the complexity of the products referred to in the literature, we expect that facilitating diagnosis in household appliances (products of generally much lower complexity) could be done following similar recommendations.

3.4. Method

We analysed three product cases to understand the process of fault diagnosis and the product features that influence this process. The method followed to analyse iFixit's content is presented in table 1 and described in the following subsections.

Table 1. Overview of the methodology used to qualitatively analyse the data for the study

Method		**Topic**	**Sub-steps (per product case)**	**Outcome**
1	Directed Content Analysis of iFixit's forum	Fault diagnosis process	1. Content categorization into the 3 fault diagnosis stages using the conceptual framework (figure 1) 2. Coding of product symptoms and possible faults, and knowledge used and actions taken for fault diagnosis. 3. Categorization of codes	Process followed and actions taken by conventional users to diagnose appliances
2	Conventional Content Analysis of iFixit's forum	Product features	1. Highlight text to capture easy and difficult situations for diagnosis 2. Code associated component(s) and feature(s) 3. Categorize the (positive or negative) influence of product features on the diagnosis process	Preliminary recommendations on design for fault diagnosis

3.4.1. Source selection

iFixit's online forum was selected as the source of information because it contains a vast amount of written descriptions about repairing consumer durable goods. The forum threads are structured in the form of questions and answers. The forum is used by both professional repairers and lay product users. Forum users share their experiences with solving issues, they ask for further help, or add information. As a result, the fault diagnosis process is fully described and readily available online, and the interventions during the repair process are chronologically ordered. The retrospective nature of the data takes away the need for the researcher to be present when the failure occurs and makes text analysis preferable as opposed to other qualitative research methods.

3.4.2. Product case selection

The focus of this study is on household appliances. This is due to the lack of scientific knowledge on the matter and their overall presence in households. From the available household appliances on the market today, we selected electromechanical appliances as relevant cases. We postulated that the combination of both mechanical and electronic technologies would reveal more content for the analysis, and would potentially allow comparisons to be made between them.

The criteria for selecting relevant cases within the electromechanical technology was based on (1) number of parts, (2) level of complexity, (3) size, and (4) functions and operating principles. Three cases were selected from the available content at iFixit: kitchen blenders, refrigerators, and vacuum cleaners. We expected these three appliances to be varied enough in their characteristics, while being technologically sufficiently similar to gather knowledge about significant product features for the diagnosis process.

3.4.3. Content selection

The content from the forum was obtained in the form of an SQL database. The database was queried with MySQL software to select content that fulfilled the following criteria: (1) the entries were written in English; (2) they had not been removed from the webpage, i.e. spam messages; (3) the question title referred to a failure that users aimed to solve; (4) the label assigned to the content contained the keywords referring to the appliances, and (5) there was at least one reply to the questions. We used the search terms “blender” and ”food processor” for small food processing appliances. From the total, 11 questions were related to the appliances’ fault diagnosis. For vacuum cleaners, we separately searched on “vacuum” ”cleaner”, ”hoover”, and “sweeper”. From the total, 24 questions were relevant; for cooling units, we searched on “refrigerator” and ”fridge” resulting in 156 relevant questions. All the input related to these questions was analysed.

3.4.4. Content analysis

The content was analysed for each product case separately; we used two steps because the process of diagnosis had to be understood before identifying which product features were influential. How iFixit users perform the process of fault diagnosis was studied using a directed content analysis approach (Hsieh and Shannon, 2005); the theoretical framework outlined in

Section 2 guided the analysis. The content of each forum thread was coded and categorised using the stages of fault diagnosis: detection, location or isolation. We also open-coded the described product symptoms (table 2). These were later categorised into five types: (a) product underperformance; (b) absence of response to user commands; (c) emits unintended signals; (d) emits designed signals (e) intermittent performance. In addition, we open-coded the recommended actions for fault isolation and the potential causes of failure (table 2). Using a MS Excel file, we counted the frequency of occurrence for each category, and registered the sequence of the diagnosis process and the number of possible faults for each symptom. We used the same methodology for all three cases.

Table 2. Fault diagnosis of kitchen blenders: codes and associated categories

Open code	Diagnosis Stage and Result	Category
Does not chop food well	Fault detection	(a) product underperformance
Liquid leaks		(a) product underperformance
Release smoke		(a) product underperformance
Slower rotating speed		(a) product underperformance
Does not work at all		(b) absence of response to user commands
Irresponsive to commands		(b) absence of response to user commands
Louder noise than expected		(c) emits unintended signals
Abnormal noises		(c) emits unintended signals
Blinking light		(d) emits designed signals
Works intermittently		(e) intermittent performance
Knowledge of product construction	Fault location	-
Experience with product usage		-
Knowledge on components physics of failure		-
Check the blade motor connection	Fault Isolation	Check component condition
Ask for warranty support		Check external support
Check for correct product alignment		Check component condition
Check sharpness of blades		Check component condition
Check for stuck food in blades		Maintenance operation
Check connections of power system		Check component condition
Check for cracked soldering		Check component condition
Visually inspect the container		Check component condition
Check safety subsystem		Check component condition
Bearing (worn out)	Cause of failure	-
Rubber gasket (rotten)		-
Loose collar		-
Circuit board		-
Blades (unsharp)		-
Cracked container		-
Contact of the safety system		-

A conventional content analysis (Hsieh and Shannon, 2005) was then performed to understand how product features influence the process of fault diagnosis. By reading the content of the forum and using external sources such as product diagrams and online repair tutorials to check the product's construction and to understand to which specific components users referred to in their questions, we could understand the descriptions and references mentioned in the forum. We then highlighted the text in which users appeared to have problems during the process, as well as for situations that were remarkably easy. An action was considered easy when accomplishing it required single or few actions and low skills. An action was considered problematic when the user claimed to have difficulties, disappointment, unsuccessful results or expressed not being able to perform the task; or when repair tutorials showed that performing the actions required multiple steps and tools. The observations were coded and a category was assigned to each coded product feature, referring to the quality that feature provides to the product, e.g. accessibility. The observations were then evaluated as positive (facilitating diagnosis) or negative (hampering diagnosis) for the steps of the diagnosis process (1) fault detection, (2) fault location, and (3) fault isolation, depending on whether or not they reduced time and uncertainty during the process. The codes and categories of each case are presented in the results section.

3.5. Results - Product case studies at iFixit

This section presents the results of the qualitative analysis of the content of iFixit's Q&A forum. Sections 5.1. to 5.3. show the results for each case; they address the process of fault diagnosis and correlated design features. Section 5.4. presents a summary of the results.

3.5.1. Fault diagnosis of blenders

The blenders described in the selected content had similar designs.They consist of a transparent, detachable jar with coupled blades at the bottom; and a base to which the jar attaches, containing the electric motor and other power and control components.

Fault detection occurs by noticing four types of symptoms: (a) product underperformance, i.e. "doesn't chop food well", or "the blades are stall"; (b) absence of response to users commands, i.e. "not working at all"; (c) emitting unintended signals like louder than expected noises, liquid leaks, or smells of smoke; or (d) emission of designed signals, like a blinking light.

Different symptoms require different fault isolation actions. For symptoms of type (a) and (c), the most recommended actions are to visually and manually inspect the condition of the components with the highest likeliness to fail (the blade-motor connection). The inspection is aimed at ensuring that the components are in good condition and functioning, e.g. is a rubber gasket not burned; do bearings rotate. The number of possible causes of failure mentioned for these symptoms is three.

Symptoms of the type (b) and (d) are associated with the circuit board and triggering of the safety system or the power subsystem (electronic and electric components). Visual inspection for loose wiring or cracked soldering is suggested. The recommended action for the safety system is to check the correct alignment between the jar and the base, a condition without which the product will not start. The number of possible causes of failure mentioned for these symptoms is one.

The various ways in which the design of the blender influences the diagnosis process is summarized in table 3.

Table 3. Relevant design features to the process of fault diagnosis in kitchen blenders.

Fault Diagnosis Observation (Condensed Description)	**Feature coding**	**Category**	**Impact On Diagnosis***
Some blenders have a safety system by which the appliance can only work when, both jar and base, are correctly aligned. A user utilised the jar from a previously owned product to determine whether the defective part was in the jar or the base. Thus, when the user connected the older jar in the new base, the defective component could be located.	Connectors – Backward compatibility	Interchangeability	Positive for (3)
Some blenders allow the base to spin without the jar, so the user can quickly see whether the defective component is in the base or the jar.	Component – functionally independent	Modularity	Positive for (3)
The base was easily opened to inspect the components visually and compare the product's interior with pictures of the same model. The comparison resulted in successful diagnosis.	Case – easy-to-open Interior – easy-to-inspect	Accessibility Visibility	Positive for (3)
The jar lets the user see whether the food is well blended or whether the blades were spinning. Moreover, the transparency of the product material allowed the user to quickly inspect the jar for cracks.	Component – transparent material	Visibility	Positive for (1), (2), (3)

A blinking light appeared while the user was using the product. It narrowed down the possibilities of fault to either the user making incorrect use of the product or a problem with the safety system itself. Thus, useful for diagnosis.	Embodied signal – blinking light	Feedback	Positive for (1), (2), (3)
The access to the bearings in the jar was blocked because they were encapsulated in the plastic of the jar's body. Hence, the bearing could only be accessed by destructive means (with a rotary tool). Manual inspection, as well as replacement, were hindered.	Component – irreversible encapsulation	Accessibility	Negative for (3)
The interior of a product was difficult to access because of deeply recessed fasteners which require non-standard tools. Access to the product's interior is difficult.	Fasteners – deeply recessed	Accessibility	Negative for (3)

** (1) fault detection, (2) fault location, and (3) fault isolation.*

3.5.2. Fault diagnosis of vacuum cleaners

The vacuum cleaners referred to in the selected content vary in design: some are powered by batteries, others by electrical outputs; some are robot-controlled, others are user-controlled, and some use rotating brushes at the hose's end. However, they are all built with a motor with a coupled fan, a hose, a deposit, and with power, command and control components.

The fault detection in vacuum cleaners occurs while using the appliance; users notice three types of symptoms: (a) product underperformance, e.g. “not having suction” or “brush not rotating”; (b) absence of response to user commands, e.g. “not turning on”; or (e) intermittent performance, e.g. “works only for a few minutes and then stops”.

Fault isolation requires symptom-dependent actions. Symptoms of type (a) are often caused by excessive dirt in the filter or blockages in the suction hose. In these cases, standard maintenance operations are suggested: replacing the bag and cleaning or replacing the filter protecting the motor. The number of possible causes of failure mentioned for this symptom is three.

Symptoms of type (b) refer to problems in the power system. Here, visual inspection and electrical current continuity measurements are recommended to verify the condition of electronic components. For example, components in a bad state could be burnt or loose wiring. The state of electronic components is measured with a multimeter; the suggested process starts with the plug and continues to the motor (or vice-versa), testing the components for continuity one by one. The number of possible causes of failure mentioned for this symptom is three.

Symptoms of type (e) are associated with excessive dirt in the filter, obstructions in the hose, a battery in a bad state, a motor failure, or a circuitry failure. The suggested actions are maintenance operations on the filters and hose, replacement of the battery, and continuity measurement and visual inspection for burnouts and loose wiring in the motor and electric (cables and connections) and electronic components (circuit boards). The maximum number of possible causes of failure mentioned for this symptom is six.

The product features listed in table 4 are influential at different process stages when performing fault diagnosis.

Table 4. Relevant design features during fault diagnosis of vacuum cleaners

Fault Diagnosis Observation (Condensed Description)	**Feature coding**	**Category**	**Impact On Diagnosis ***
Some models have hoses that can be detached at different points, which allows quick inspection for blockages at different points.	Hose – sectionability	Visibility	Positive for (3)
In the case of a hose blockage, those which the user can access with fingers are easier to clean than narrow ones.	Hose – ergonomic geometry	Accessibility	Positive for (3)
Checking for blockages in the hoses is easier to perform in rigid (straight) hoses where the user can directly look through the pipe, as opposed to flexible (curved) hoses.	Hose – straight shape	Visibility	Positive for (3)
The built-in test system of a vacuum cleaner revealed the bad condition of a battery. The user hadn't charged the battery in two years and after charging, the diagnostic system said that the battery had not been charged. The diagnosis revealed that the battery was in poor condition, although the user was not able to understand the message because it contradicted the actions taken by the user. The diagnosis was correct even though the user needed help interpreting the message.	Component - Built-in test	User Feedback & Information	Positive for (3)
Automatic safety switches confused the user during diagnosis because they were unaware of their existence. Typically, the symptoms from these components are intermittent functioning, which makes isolation difficult. The status of the components might be good when the product is switched OFF, and only show intermittent functioning when ON. Thus, it is difficult to isolate the fault unless the users know that these features and specific failure modes exist.	Safety switches – not signalled	Information	Negative for (2), (3)
The manual's information is not regarded as helpful by users. Quoting a user at the forum: "The troubleshooting "tips" in the factory instructions — like other videos I have seen — belabour the obvious and offer "duh" "solutions" to non-problems. (My machine will not run. Solution: Make sure it is plugged in. Duh!)"	User manual – unhelpful	Information	Negative for (2)

**(1) fault detection, (2) fault location, and (3) fault isolation*

3.5.3. Fault diagnosis of refrigerators

Most of the questions studied were related to refrigerators where the cooling action is based on a vapour-compression system to exchange heat. The major components are a well-insulated cabinet, a compressor, heat exchanger coils (for evaporation and condensation) with coupled fans powered by an electric motor, an expansion valve, a thermostat, a thermistor, a power subassembly, and the control and command components.

Fault detection occurs by noticing symptoms. The reported symptoms have been grouped into five types: (a) product underperformance, i.e. “higher temperature than expected”, “doesn’t make ice/defrost”, “abnormal frost”; (b) absence of response to users commands, i.e. “not working at all” or “not responding when buttons are pressed”; (c) emits unintended signals, like “weird noises”; or (d) emits designed signals, like error codes; (e) working intermittently, e.g. “refrigerator cools intermittently” which is noticed by listening to the fan and compressor.

The process of fault location differs by symptom type. For symptoms of types, (a), (b), (c), and (e), the answers either suggest possible causes of failure, or they first recommend tests on components (before suggesting causes of failure). In the first case, the causes are presented together with descriptions of the product’s architecture, operating principles, and means to isolate faulty components for each cause. In the second approach, the correct functioning of the main components is tested guided by the operating principles of the appliance, but the rationale behind the suggestions is not explained. The answers call directly for fault isolation actions.

Fault isolation for symptoms (a), (b), (c), and (e) requires performing different techniques until the symptoms disappear. Type (a) symptoms are attributed to a failure in the fan or in the motor placed next to the heat exchangers (coils), undesired particles in the coils, malfunctioning compressor, defective start relays, malfunctioning defrost system (sensors or heater), or defective control board, or sensors.

The recommended actions to confirm if the fan-motor unit is defective are: manually rotating the fan, comparing the sound of its rotation to a taxonomy of sounds presented in the user manual, and testing the motor using a multimeter. When accumulation of undesired materials could be the reason of failure, it is recommended to perform maintenance operations such as dust removal from the heat exchangers; defrost the unit, and visually inspect the components supported by a taxonomy of frost patterns; however, manufacturers do not provide this. The compressor can be inspected by sound and manual inspections to check that it is not "too hot to touch" (even a taxonomy of sounds for the compressor is available). Relays can be inspected by measuring the continuity of electric current. In the case of control boards, fridge reset and part replacement are recommended. The maximum number of possible causes of failure mentioned for symptom type (a) is twelve.

Type (b) symptoms are associated with the door switch and loose display wiring. Therefore, manual inspection, continuity measuring, visual inspection of electronic components are recommended techniques for fault isolation. The maximum number of possible causes of failure mentioned for these symptoms is three.

Type (c) symptoms are normally noticed in fridges with water dispenser units. Filter replacement, maintenance operations such as pipe defrosting and system pressure checks are recommended. The maximum number of possible causes of failure mentioned for these symptoms is four.

Type (e) symptoms are mostly associated with the main control board or dirty condenser coils. Users are advised to replace the control board or perform maintenance operations such as cleaning The maximum number of possible causes of failure mentioned for these symptoms is ten.

For type (d) symptoms and, in particular, error codes, the answers either explain the meaning of error codes or refer to external sources that explain them. Fault isolation for type (d) symptoms only requires checking the meaning of the error codes. The symptoms could be associated with any component that is electronically controlled. The error codes in refrigerators require the user to either visually inspect wiring connections, reset the fridge, or directly replace the part. The maximum number of possible causes of failure mentioned for these symptoms is two.

Many of the reported diagnosis actions are affected by the appliance's features. Table 5 presents a shortened description of the observation from which these conclusions were drawn.

Table 5. Relevant design features for the process of fault diagnosis in refrigerators

Fault Diagnosis Observation (Condensed Description)	**Feature coding**	**Category**	**Impact On Diagnosis***
Error codes in refrigerators are designed to pinpoint the fault that causes the code to appear, making fault diagnosis concise and specific.	Embodied Signals – Error Codes	User Feedback & Information	Positive for (1) and (3)
When the door switch of a refrigerator is pressed, the user can instantly hear whether the evaporator fan works. Thus, mechanical switches are valuable when ensuring the correct functioning of the components they control and when narrowing down the potential causes of malfunction to the components associated with that switch.	Component - switch associated with an action	User Feedback	Positive for (1),(2),(3)
Embodied signals can help in ensuring whether the components they are associated with are working. For example, a sound signal when the refrigerator door is open was useful in determining whether the door switches were working correctly.	Embodied Signals – Sound to action	User Feedback	Positive for (1), (2),(3)
A user at iFixit favoured manual opposed to the automatic defrosting system because symptoms were more difficult to notice "On an automatic-defrost unit, you cannot see if the evaporator coils are frosted over" and the current state of the system could be followed up.	component – automatic	Visibility	Negative for (1)
Inspections in sensors and control board are challenging: testing whether a sensor works requires measuring ambient temperature as well as temperature in the fridge for each test. Moreover, the results have shown that users do not feel at ease with measuring electric currents, and most of them do not have the ability to use a multimeter.	Sensors & control boards – difficult to test	Autonomy	Negative for (3)
The components with a high likelihood of failure such as fans and coils are normally confined by plates and placed in areas difficult to access.	Frequently failing components – difficult areas of access	Accessibility	Negative for (3)
Visually inspecting the patterns of frost in the evaporator coils is challenging due to its confinement behind a cover plate. The coils become visible by unscrewing the plate. However, frost could be covering the fasteners and blocking access, so visually inspecting the frost pattern becomes a time-consuming and challenging process.	components – confined behind plates	Visibility	Negative for (3)
A refrigerator with both freezer and fridge unit displayed an error symbol without specifying which of the units was defective.	Embodied signals – uninformative symbols	User Feedback	Negative for (2)

Some user manuals do not give the meaning of error codes.	User's manual – missing Diagnosis information	Information	Negative for (2)

** (1) fault detection, (2) fault location, and (3) fault isolation.*

3.5.4. Summary of results

Fault detection in the appliances occurs by noticing symptoms using sensory observations while the appliances are switched on. We identified a total of five types of symptoms which differ in their nature and the number of possible causes. Symptoms of underperformance or intermittent performance show the highest number of possible causes of failure, as opposed to those from embodied signals, which are associated with only 1 or 2 possible causes. A summary of the total number of possible causes of failure associated to each symptom is presented in table 6.

Table 6. Different types of symptoms and the maximum number of associated possible causes of failure in a single question regarding a particular symptom.

Symptom	Blender	Vacuum Cleaner	Refrigerator
(a) Under-performance	3	3	12
(b) Absence of response to commands	1	3	3
(c) Abnormal inbuilt signals	3	-	4
(d) Designed Signals	1	-	2
(e) Intermittent performance	-	6	10

The most frequently suggested actions for fault isolation are:

- Visual inspection of components to check for good condition and correct functioning,
- Auditory inspection, in some cases abnormal sounds can be compared to a taxonomy of sounds,
- Manually manipulating components to check whether they function correctly,
- Maintenance operations such as bag replacement or filter replacements,
- Component replacement,
- Unit reset,
- Measuring the continuity of electrical current,
- Follow-up on error codes.

The type of symptom influences the location and isolation process. If the symptoms are not error codes, fault location requires product knowledge and experience. The answers often explain the rationale behind the product failure, including a description of the product's construction, its operating principles and, in some cases, the physics of failure of components. The user has to perform the recommended fault isolation action until the symptom disappears. Hence, products are mostly diagnosed through trial and error. If the symptoms are error codes, fault location is performed by the product's electronic control system. Hence, in these cases the answers in the forum do not describe the rationale behind the failure; they directly refer to the meaning of the error code.

The efficiency of the process of diagnosis is affected by the design of the appliances. The qualitative analysis has shown how different features affect different stages of the diagnosis process (table 7). The most recurrent features are accessibility and visibility of components, and the direct feedback and information the appliance provides to the user.

Table 7. Overview of the qualities (bold) and specific product features that influence a product's diagnosability. [+] evaluated as a positive feature, [-] evaluated as a negative feature

Qualities and Design Features relevant for Fault Diagnosis	**(1) Fault Detection**	**(2) Fault Location**	**(3) Fault Isolation**
	[Symptom Observation]	[Symptom to cause deduction]	[Component Inspections]
Interchangeability			
Connectors – backward compatibility			+
Modularity			
Component - functionally independent			+
Accessibility			
Housing – easy-to-open			+
Component – irreversible encapsulation			-
Fasteners – Deeply Recessed			-
Hose – Ergonomic geometry			+
Frequently failing components – difficult areas of access			-
Visibility			
Component – transparent material	+	+	+
Component – automatic	-		
Component – confined behind plates			-

Hose – sectionability			+
Hose – straight shape			+
Feedback and Information to User			
Embodied signal – blinking light	+	+	+
Embodied signal – error codes	+		+
Embodied signal – sound to action	+	+	+
Component – switch associated with an action	+	+	+
Component – built-in test			+
Safety switches – unsignalled		-	-
Embodied signal – uninformative symbol		-	
User's manual – missing diagnosis information		-	
User's manual – unhelpful		-	
Autonomy			
Sensors & Control boards – difficult to test			-

3.6. Discussion

We set out to explore how the process of fault diagnosis is influenced by design in household appliances. We looked into the process of diagnosis first, to then understand how design features affect the process.

Diagnosis process

Two distinctly different approaches to fault diagnosis are recognised in the forum. When the symptoms are easily interpretable error codes, diagnosis is accurate, quick, straightforward, and requires a low level of expertise. The number of possible causes of failure is limited to two or less. The control system performs the diagnosis and it is the user who is charge of carrying out corrective actions. This way of diagnosing appliances resembles the process described in literature for monitored industrial systems.

For symptoms other than error codes, we found that the number of possible causes of the appliance's failure can be significantly higher. One symptom can be related to many causes of failure so that many interactions are required to isolate the fault. Diagnosis becomes more time consuming, less accurate and requires the use of logic and knowledge of the product to locate the fault, i.e. operating principles of the system, product construction, or physics of failure. The time and effort required for diagnosis in these cases are uncertain. Many users are unable to carry out the fault diagnosis process and need the use of expert knowledge (through the forum) to bypass fault location. Even then, the efficiency of the diagnosis process remains cumbersome, as we observed a strong tendency for tedious trial-and-error approaches towards fault isolation. The number of trial and error operations required can be as large as the number of possible causes of failure associated with the symptoms.

The theoretical framework presented in Section 2 formed a useful guide to analysing the diagnosis process as described in the iFixit forum. Taking a user's perspective, the framework adequately represents the process of fault diagnosis on household appliances for symptoms other than error codes. We identified three stages before product repair: fault detection, fault location and fault isolation. Nonetheless, if the symptoms were error codes, the stages of fault location and isolation should not appear as this would be performed by the control system.

Design aspects

Comparing the results from the repair forum analysis with the literature on design features in section 3, we conclude that the current design of most appliances does not allow for easy diagnosis. We will briefly expand on this here.

The use of designed signals and error codes is recommended to easily locate faults in products. We found two types of feedback signals (see table 5): one type that confirmed that a subsystem in the appliance worked as it should, using sounds or lights associated to actions.The second type alerted the user when something was wrong such as error codes and symbols. Both types of feedback signals were used for fault location and isolation. Hence, our results extend those presented in (Clark and Paasch, 1996; Gandhi and Wani, 1999; Paasch and Ruff, 1997) on malfunction annunciation features by including "functioning" annunciation signals. The current design of feedback signals does however not seem particularly user-friendly. In some instances users were confused about their meaning or felt that they revealed obvious information (see table 4). Furthermore, (ibid) suggest that the presence of designed signals should take away the need of partial disassembly. However, our results do not show that.

With respect to recommendations on providing visual and manual access to components, our results agree with the recommendations made in the literature by (Guo et al., 2018; Imrhan, 1992b; Paasch and Ruff, 1997; USA Department of Defense, 1988). Fault isolation often requires inspecting the appliance's interior which implies that the appliance has to be partially disassembled. Hence, when access to the interior is hindered, the diagnosis process becomes difficult. Fault isolation was furthermore tedious and time consuming with deeply recessed fasteners (table 3) and encapsulated or confined components (table 3,5). In line with (Paasch and Ruff, 1997) and (McCollough, 2009), we found that the presence of automatic systems tended to increase the product's complexity and hampered the fault diagnosis process (table 5).

Interestingly, visual inspections were facilitated if the appliance's body was transparent, or if the removal of the outer casing gave a complete overview of the appliance's internal components. These product features have not been previously mentioned in literature.

Functionally independent components are beneficial for fault isolation because components are easier to inspect and test (Clark and Paasch, 1996; Paasch and Ruff, 1997). Our results confirm this. Taking the case of the blender as an example (table 3), we saw a big difference in the number of actions required when the base of the blender would work independently as compared to went it didn't.

Last, we observed that many of the appliances were malfunctioning due to the lack of adequate maintenance during the appliance's useful life. Automatic maintenance scheduling is recommended in (USA Department of Defense, 1988) to facilitate diagnosis but the results show that this was not (sufficiently) provided in the appliances. Some of the symptoms that users reported were resolved by simply performing standard maintenance tasks such as replacing a filter. Hence, it could be recommended that appliances explicitly 'demand' certain maintenance tasks to be performed.

In conclusion, the results clearly show potential for improvement of ease of fault diagnosis in appliances.

Design recommendations for fault diagnosis

Based on the findings, we present design recommendations for fault diagnosis (Table 8) and relate them to the affected diagnosis stage. Our recommendations show an overlap with guidelines to facilitate product maintenance (Imrhan, 1992b; USA Department of Defense, 1988), repair and product upgradability (Cordella et al., 2019; Mulder et al., 2012). We complement these with new features that are relevant for diagnosis only: adequate feedback and information to the user, and visual access to components.

Table 8. Design recommendations to facilitate the process of diagnosis in appliances

Design Features	**Design Recommendation**	**Facilitated Diagnosis Stage**
Interchangeability	Provide backward compatibility to the interface between components of new product models to facilitate component testing	3
Modularity	Provide the product's functional subsystems with working independency to reduce the number of potential causes of failure associated with them	2,3
Accessibility	Use product housings that are easy-to-open to facilitate access to the product's interior for inspection	3
	Avoid irreversibly encapsulating components in the product's housing to allow inspecting them without the need for destroying the housing	3
	Use superficially recessed screws to facilitate disassembly	3
	Provide tubular components with an ergonomic internal geometry to facilitate the elimination of obstructions	3
	Arrange components with short lifespans and exposed to frequent wear and tear in an accessible and ergonomic disposition to facilitate manual and tool manipulations	3
Visibility	Use transparent materials for product and component housing to avoid disassembly for inspection	1,2,3
	Provide tubular components with a straight shape and sectionable parts to facilitate interior inspection at different points of its longitude	3
	Provide a full view of the product's interior when removing the outer casing to facilitate component inspection	3
Feedback & Information to the user	Provide components with performance indicators and/or mechanical switches to instantly provide feedback to the user or operator on the component's condition	1,2,3
	Design symbols and error codes so they clearly pinpoint the defective unit to avoid the need for subsequent fault isolation actions.	2
	Reveal the meaning of error codes and available diagnosis modes to users to facilitate fault isolation	1,2,3
	Reveal the existence of safety features, the product's operating principles, and potential causes of failures, to facilitate the process of fault location.	2
	Indicate the user when maintenance tasks should be performed to avoid product failure	1,2,3

** (1) fault detection, (2) fault location, and (3) fault isolation.*

3.7. Conclusions

In this paper, we set out to improve our understanding of how conventional users diagnose faults in household appliances and how the design of these appliances facilitates or hampers the process of fault diagnosis. To study this, we qualitatively analysed the content of iFixit's online repair forum using three types of household appliances. The forum entries were analysed using a conceptual framework that distinguishes fault detection, fault location, and fault isolation.

The content analysis revealed five types of common symptoms in household appliances: (a) Under-performance, (b) Absence of response to commands, (c) Abnormal inbuilt signals, (d) Designed Signals, and (e) Intermittent performance. In general, symptoms derived from error codes require less time and expertise, and result in a more accurate diagnosis process. Error codes exempt the user from doing fault location and isolation. However, they come at the expense of increasing the system's complexity and ease of inspection.

The analysis also showed that the studied appliances had not been designed for an easy diagnosis process. In most cases, access (visual and manual) to components was difficult and the feedback provided to the user was hard to understand. Successful diagnosis almost always required (partial) disassembly of the product.

Our paper contributes to the theory of design for fault diagnosis. Despite its exploratory nature, this is the first study that offers a description of the process of fault diagnosis of household appliances as performed by non-professional repairers. We also are the first to formulate design recommendations on how to facilitate fault diagnosis by conventional users. This new understanding should help designers in taking the process of fault diagnosis into account during their practice and as a result, improve the efficiency of future product repairs.

Further research is recommended to explore relevant design features in a larger range of household appliances. Moreover, the applicability to and implementation of the proposed design recommendations to actual product design should be examined to discover potential trade-offs that arise upon implementation, and to establish the impact on design practice.

Acknowledgements

We would like to thank Kyle Wiens and iFixit for making their forum database available.

This work was funded by the European Commission under the Horizon 2020 Marie Skłodowska Curie Action 2016 (Grant Agreement number 721909).

References

Alexanders, S.M., Lee, W.Y., Graham, J.H., 1993. Design-based diagnosis. Int. J. Prod. Res. 31, 2087–2096. https://doi.org/10.1080/00207549308956846

Behdad, S., Sabbaghi, M., 2017. Environmental Evaluation of Product Design Alternatives : The Role of Consumer ' s Repair Behavior and Deterioration of Critical Components. J. Mech. Des. 139, 1–10. https://doi.org/10.1115/1.4036777

Behdad, S., Sabbaghi, M., Esmaeilian, B., Cade, W., Wiens, K., 2016. Business outcomes of product repairability: A survey-based study of consumer repair experiences. Resour. Conserv. Recycl. 109, 114–122. https://doi.org/10.1016/j.resconrec.2016.02.014

Benko, U., Petrovčič, J., Juričić, Đ., Tavčar, J., Rejec, J., Stefanovska, A., 2004. Fault diagnosis of a vacuum cleaner motor by means of sound analysis. J. Sound Vib. 276, 781–806. https://doi.org/10.1016/j.jsv.2003.08.041

Bereiter, S.R., Miller, S.M., 1990. Difficulties in troubleshooting automated manufacturing systems. Int. J. Ind. Ergon. 5, 91–104. https://doi.org/10.1016/0169-8141(90)90031-V

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bovea, M.D., Ibáñez-Forés, V., Pérez-Belis, V., Quemades-Beltrán, P., 2016. Potential reuse of small household waste electrical and electronic equipment: Methodology and case study. Waste Manag. 53, 204–217. https://doi.org/10.1016/j.wasman.2016.03.038

Case, K., Nor, A., Teoh, P.C., 2010. A diagnostic service tool using FMEA. Int. J. Comput. Integr. Manuf. 23, 640–654. https://doi.org/10.1080/0951192X.2010.486007

Clark, G.E., Paasch, R.K., 1996. Diagnostic Modeling and Diagnosability Evaluation of Mechanical Systems. J. Mech. Des. 118, 425. https://doi.org/10.1115/1.2826903

Cordella, M., Alfieri, F., Sanfelix, J., 2019. Analysis and development of a scoring system for repair and upgrade of products - Final report. https://doi.org/10.2760/725068

Davidson, H.L., 2004. Troubleshooting and Repairing Consumer Electronics- 3rd edition. TAB electronics.

Dindarian, A., Gibson, A.A.P., Quariguasi-Frota-Neto, J., 2012. Electronic product returns and potential reuse opportunities: A microwave case study in the United Kingdom. J. Clean. Prod. 32, 22–31. https://doi.org/10.1016/j.jclepro.2012.03.015

European Comission, 2018. Behavioural Study on Consumers ' Engagement in the Circular Economy.

Friedrich, A., Gohner, P., 2015. Fault diagnosis of automated systems using mobile devices, in: 2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA). IEEE, pp. 1–8. https://doi.org/10.1109/ETFA.2015.7301524

Gandhi, O.P., Wani, M.F., 1999. Development of maintainability index for mechanical systems. Reliab. Eng. Syst. Saf. 65, 259–270. https://doi.org/10.1016/S0951-8320(99)00004-6

Guo, C., Lyu, C., Chen, J., Zhou, D., 2018. A design approach based on a correlative relationship between maintainability and functional construction [Podejście projektowe oparte na korelacyjnym związku między konserwowalnością a funkcjonalną budową produktu]. Eksploat. i Niezawodn. 20, 115–124. https://doi.org/10.17531/ein.2018.1.15

Hsieh, H.-F., Shannon, S.E., 2005. Three Approaches to Qualitative Content Analysis. Qual. Health Res. 15, 1277–1288. https://doi.org/10.1177/1049732305276687

iFixit, 2019. Repair Market Observations: iFixit's testimony to the FTC.

Imrhan, S.N., 1992a. Equipment design for maintenance: Part II – The scientific basis for the guide. Int. J. Ind. Ergon. 10, 45–52. https://doi.org/10.1016/S1572-347X(00)80019-1

Imrhan, S.N., 1992b. Equipment design for maintenance: Part I — Guidelines for the practitioner. Int. J. Ind. Ergon. 10, 35–43. https://doi.org/10.1016/0169-8141(92)90046-3

Isermann, R., 2006. Fault-Diagnosis Systems, Fault-Diagnosis Systems: An Introduction from Fault Detection to Fault Tolerance. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/3-540-30368-5

Kanma, H., Wakabayashi, N., Kanazawa, R., Ito, H., 2003. Home appliance control system over Bluetooth with a cellular phone. IEEE Trans. Consum. Electron. 49, 1049–1053. https://doi.org/10.1109/TCE.2003.1261194

Kelley, B.A., Rosen, R.D., 1985. Considerations for the Systematic Design of Machine Self-Diagnosis. IEEE Trans. Ind. Appl. IA-21, 116–123. https://doi.org/10.1109/tia.1985.349671

Khaksari, G., 1988. Expert Diagnosis System, in: First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems. pp. 43–53.

Kleinert, E.T.A.-T.T.-, 2013. Troubleshooting and repairing major appliances, Third edit. ed. McGraw-Hill, New York.

Marijan, D., Zlokolica, V., Teslic, N., Pekovic, V., Tekcan, T., 2010. Automatic functional TV set failure detection system. IEEE Trans. Consum. Electron. 56, 125–133. https://doi.org/10.1109/TCE.2010.5439135

McCollough, J., 2009. Factors impacting the demand for repair services of household products: The disappearing repair trades and the throwaway society. Int. J. Consum. Stud. 33, 619–626. https://doi.org/10.1111/j.1470-6431.2009.00793.x

Mostia William L., J., 2006. Troubleshooting - A Technician's Guide (2nd Edition). ISA.

Mulder, W., Blok, J., Hoekstra, S., Kokkeler, F.G.., 2012. Design for Maintenance, guidelines to enhance maintainability, reliability and supportability of industrial products. University of Twente.

Okogbaa, O.G., Otieno, W., 2007. Design for Maintainability, in: Environmentally Conscious Mechanical Design. John Wiley & Sons, Inc., Hoboken, NJ, USA, pp. 185–247. https://doi.org/10.1002/9780470168202.ch6

Paasch, R.K., Ruff, D.N., 1997. Evaluation of Failure Diagnosis in Conceptual Design of Mechanical Systems. J. Mech. Des. 119, 57. https://doi.org/10.1115/1.2828789

Pamminger, R., Kuso, S., Wimmer, W., Podhardsky, G., 2017. Re-design of a digital voice recorder to meet the needs of circular economy-Status analysis, in: 2016 Electronics Goes Green 2016+, EGG 2016. Fraunhofer, pp. 1–9. https://doi.org/10.1109/EGG.2016.7829815

Parajuly, K., Wenzel, H., 2017. Potential for circular economy in household WEEE management. J. Clean. Prod. 151, 272–285. https://doi.org/10.1016/j.jclepro.2017.03.045

Patton, R.., Frank, P.M., Clark, R.N., 2000. Issues of Fault Diagnosis for Dynamic Systems. Springer.

Rogers, A.P., Guo, F., Rasmussen, B.P., 2019. A review of fault detection and diagnosis methods for residential air conditioning systems. Build. Environ. 161, 106236. https://doi.org/10.1016/j.buildenv.2019.106236

Scott, K.A., Weaver, S.T., 2014. To Repair or Not to Repair: What is the Motivation? 1–31.

Shin, Y., Seo, J.A., Lim, T.H., Lee, S.H., Kim, S., 2016. Case study of fault detection and diagnosis of a household air conditioner with a dynamic refrigeration cycle simulator. Appl. Therm. Eng. 94, 198–208. https://doi.org/10.1016/j.applthermaleng.2015.10.037

Stahel, W.R., 2006. The Performance Economy, 2nd editio. ed. Palgrave Macmillan.

Stamminger, R., Hennies, L., 2016. An empirical survey on the obsolescence of appliances in German households. Resour. Conserv. Recycl. 112, 73–82. https://doi.org/10.1016/j.resconrec.2016.04.013

Tecchio, P., Ardente, F., Mathieux, F., 2016. Analysis of durability, reusability and reparability - Application to washing machines and dishwashers. https://doi.org/10.2788/630157

Thompson, G., Tjiparuro, Z., 2004. Review of maintainability design principles and their application to conceptual design. J. Process Mech. Eng. 218, 103–113. https://doi.org/10.1243/095440804774134280

USA Department of Defense, 1988. Maintainability Design Techniques.

Utton, P., Scharf, E., 2004. A fault diagnosis system for the connected home. IEEE Commun. Mag. 42, 128–134. https://doi.org/10.1109/MCOM.2004.1362556

CHAPTER 4

FAULTS IN CONSUMER PRODUCTS ARE DIFFICULT TO DIAGNOSE, AND DESIGN IS TO BLAME: A USER OBSERVATION STUDY[3]

---

[3] Pozo Arcos, B., 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. J. Clean. Prod. 128741. https://doi.org/10.1016/j.jclepro.2021.128741

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.

Keywords

Circular economy, product design, repair, fault diagnosis, troubleshooting, consumer products

4.1. Introduction

Repair practices can positively contribute to the decoupling of consumption from resource use in a circular economy (Stahel, 2006). Repairing instead of replacing products has the potential to increase resource efficiency and decrease the environmental impact resulting from premature product replacements (Bakker et al., 2014; Stahel, 2006; Truttmann and Rechberger, 2006). Consequently, improving the reparability 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 (European Commission, 2015). Moreover, there is a growing societal interest in repairs stirred by consumers and grassroots associations which aim to repair their products (Terzioğlu, 2021).

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 (Cuthbert et al., 2016; Pozo Arcos et al., 2018). 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 (Brusselaers et al., 2019; Sabbaghi et al., 2016).

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 (Go et al., 2015; Pozo Arcos et al., 2018; USA Department of Defense, 1988). Den Hollander (2018) 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 (Baek et al., 2020; Jiang et al., 2018; Marcu et al., 2017). 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 (Bhavana, 2020; Rashid, 2019; Suresh, 2019). Moreover, most academic studies on the repair process focus on product disassembly (De Fazio et al., 2021; Mathieux et al., 2018) and the development of repair indicators (measuring the reparability of a product) (Bracquene et al., 2018; Cordella et al., 2019; Flipsen et al., 2019). 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 (Jaeger-Erben et al., 2021; Rogers et al., 2021; Terzioğlu, 2021). 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 (Pozo Arcos et al., 2020), 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 were 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 reparability 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.

4.2. 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.

4.2.1. The Diagnosis Process

The process of fault diagnosis determines the defective component of a malfunctioning product in three steps (Pozo Arcos et al., 2020) (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.

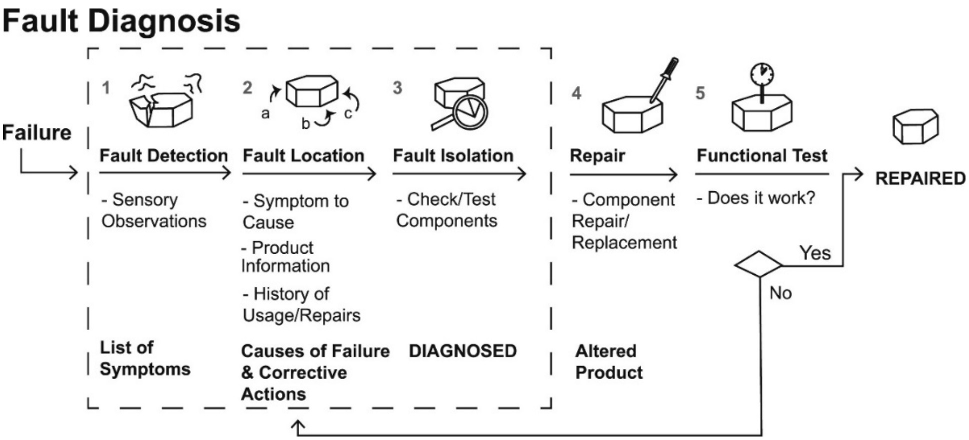


Figure 1 Model of the process of fault diagnosis by product users (Pozo Arcos et al., 2020)

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.

4.2.2. 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 (2006) and Angeli (2010) 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 (2019) 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 (Robertson, 2017; Simon et al., 1987). Similarly, fault diagnosis requires an ability to combine repair experience and technical knowledge to relate symptoms to possible problems (Kluge and Termer, 2017; Morris and Rouse, 1985; Wasserkrug et al., 2019).

Robertson (2017) describes two main strategies people use to search for a solution (Robertson, 2017): 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 recognises 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 (2018) defines “blind search” as a type of weak strategy whereby all potential solution candidates are checked randomly. Jonassen and Hung (2006) 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 (Patrick, 1993; Robertson, 2017).

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.

4.3. Method

4.3.1. 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 (Hoppmann, 2009; Whalley and Kasto, 2014). 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 (Crandall et al., 2006).

4.3.2. 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.

4.3.3. 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:

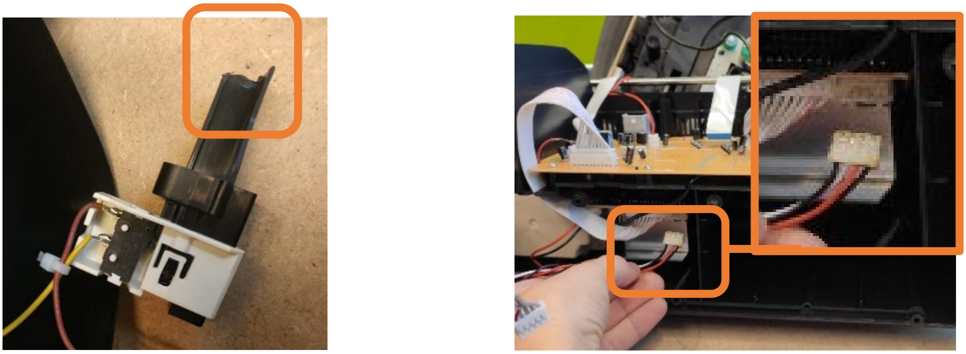
- The products include a variety of design features that could influence the diagnosis. Using Pozo Arcos et al. (2020), we selected products with different features to access the components, to provide feedback to users, to interchange components, and with different types of functional modules.
- The 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 (iFixit, 2019) and the Repair Café’s report on frequently repaired faults in 2019 (Repair Cafe International Foundation, 2020)
- The fault was provoked in an internal component to observe the participants interacting with a large diversity of design features and components.

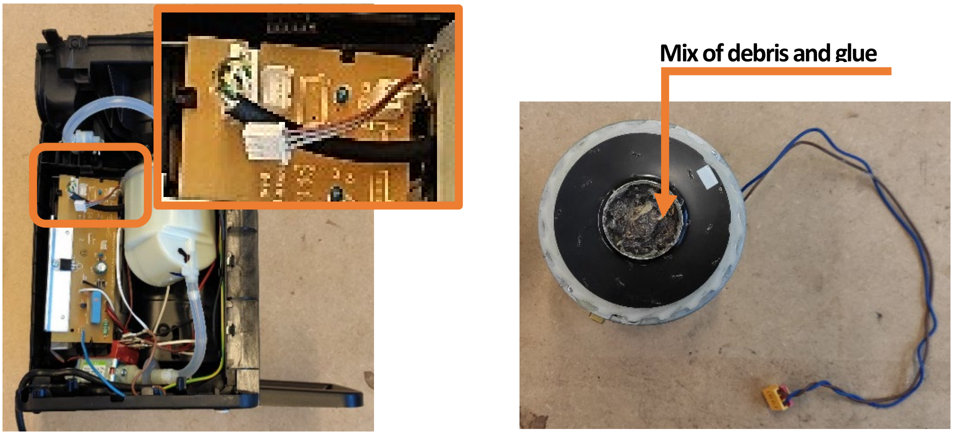
- Each fault would provoke one of the different type of symptoms described in Pozo Arcos et al. (2020): under-performance, absence of response to commands, abnormal inbuilt signals, and designed signals. The symptom of intermittent failure was excluded because it would be hard to replicate and control.

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 2 - 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.

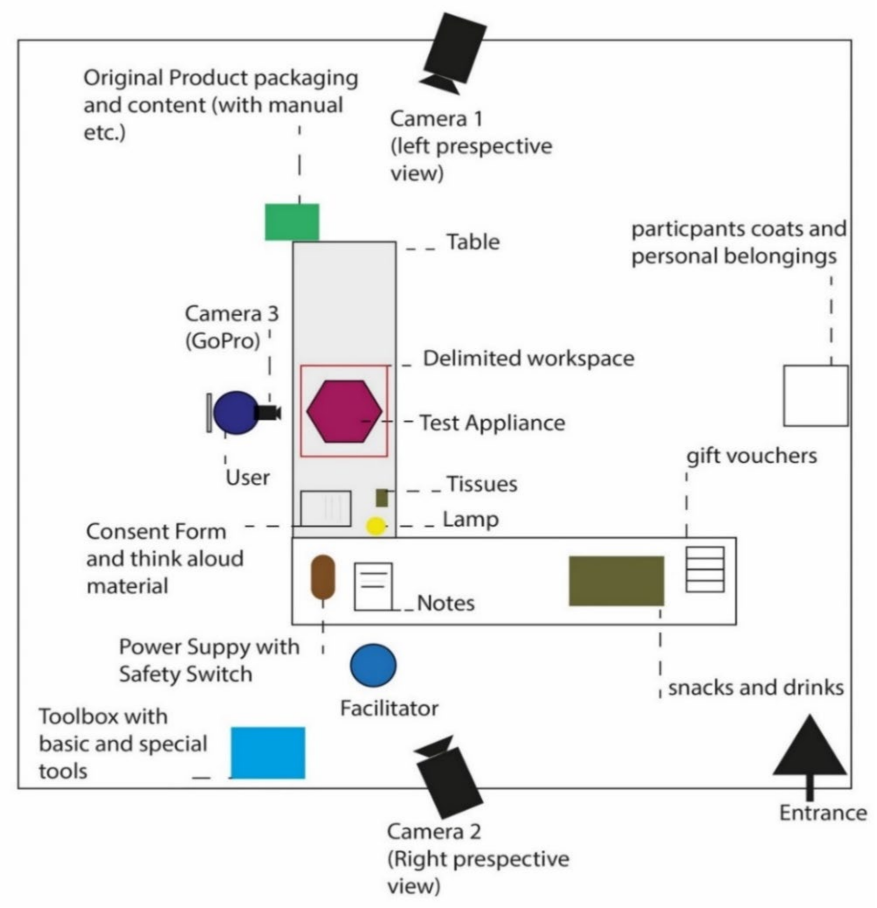


Figure 3 - Room set-up for participant observation

4.3.4. 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 (Van Someren et al., 1994), 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 familiarise 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
Behaviour 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.

4.3.5. 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 analysed 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. (2021) disassembly map method for noting the disassembly steps. Then, we analysed the transcribed content (Figure 4 – columns 2 and 3).

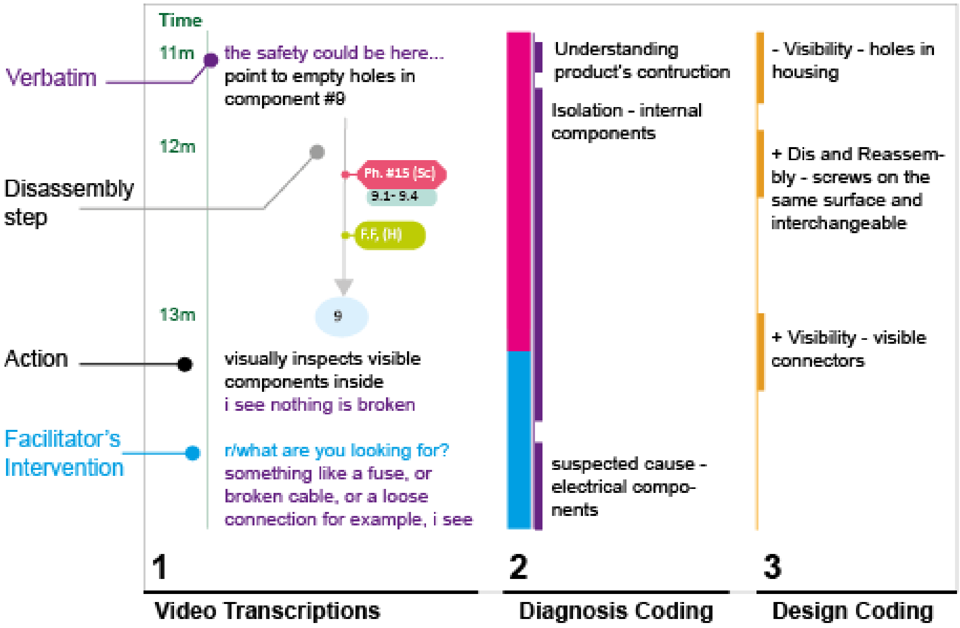


Figure 4 - Example of Case Record with labelled entries. The left column shows the transcription of the participants’ thinking aloud, the observed actions, disassembly steps, and facilitator

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 analysed first; design features were analysed 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” (Bloor and Wood, 2006),. 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 analysed 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 about solving the problem. User has a correct suspicion of possible component at fault and directly searches those	Based on codes: "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 (2018). We also considered design features affecting the diagnosis process from our previous study (Pozo Arcos et al., 2020). 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” (Moss, 1985, p.37)

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” (Moss, 1985, p. 36)
Accessibility	Features and spatial arrangements in the product or parts that provide access to components without the complete removal of a part (Moss, 1985)
Visibility	Features related to the visible surfaces of a component or its visual inspection (Pozo Arcos et al., 2020)
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 (Pozo Arcos et al., 2020)
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 (Brennan et al. 1994, p. 59)
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 (Keoleian & Menery, 1993) or to prevent interruptions in the functioning of a product (Kuo et al., 2001)
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 analysed by two researchers to minimise the risk of bias. Following recommendations for teamwork qualitative research by Milford et al., (2017), both researchers coded the case reports and checked for intercoder agreement. The reports with discrepancies in the coding were discussed and co-analysed until both researchers agreed.

Once all data had been coded and qualitatively analysed, 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 (Field, 2005). We conducted one-tailed Man-Whitney U tests $(n_i = 12)$ 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 $(n_i = 6)$. This test is an extension of the Man-Whitney U test when more than two independent samples (products) are compared (Field, 2005).

4.4. 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.

4.4.1. 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, visualising 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.

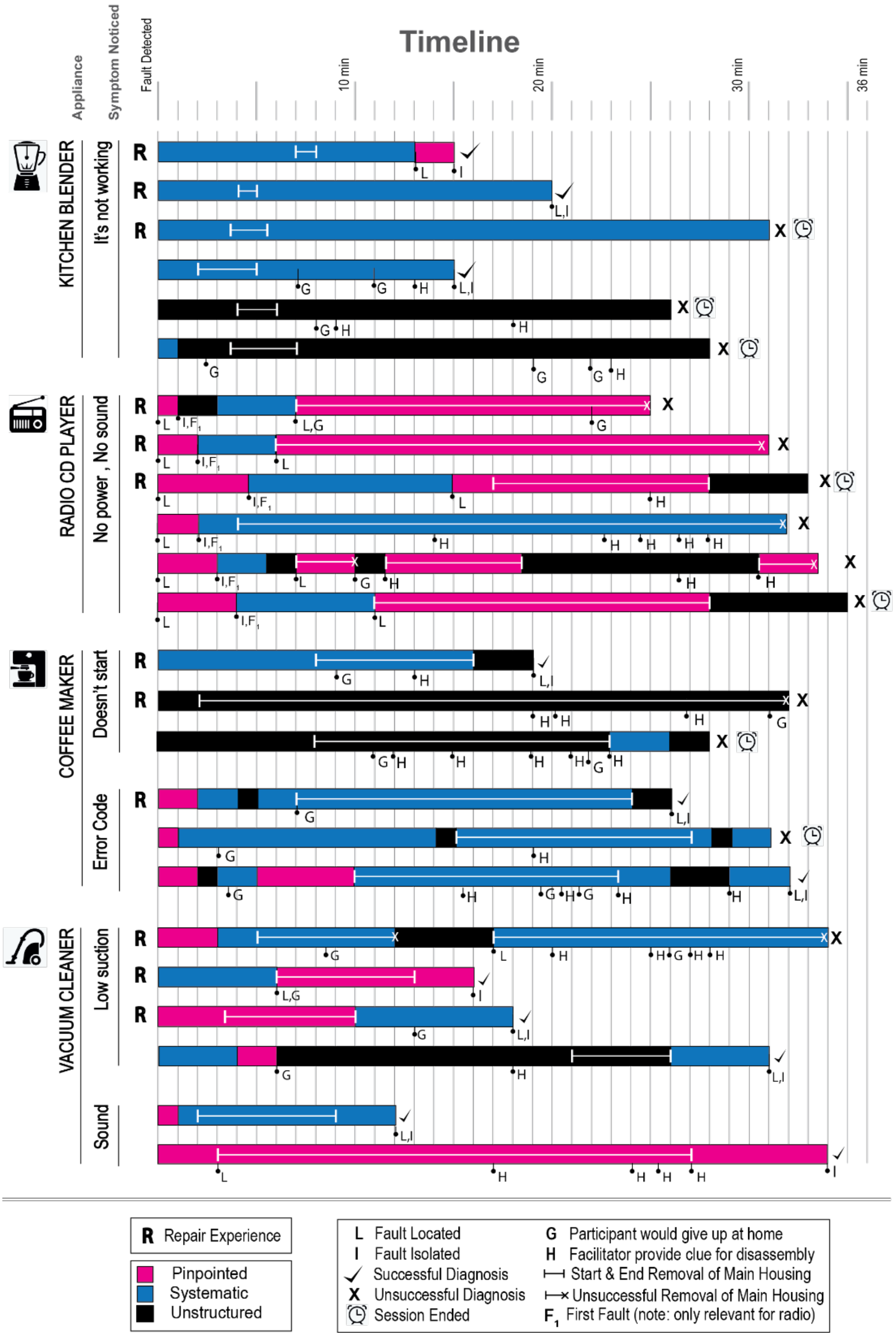


Figure 5: Summary of 24 User Observations grouped by product type and symptom detected by the participants.

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 cleaner's 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 recognisable 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

			Initial Strategy		
Product	**Observed Symptoms**	**# of Participants**	**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 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.

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

**(significance at P<0.05)*

We also analysed 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 required time 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.

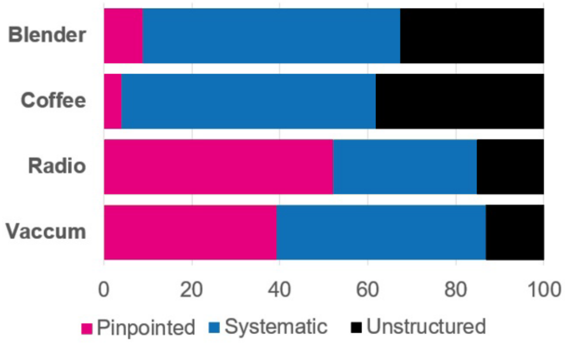


Figure 6 - Ratio of followed search strategies per product type

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 colour 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	+L	+I	Quick inspection of components without removal of fasteners or components.
	Sectionable component			
	Long cables			
	Lid			
	Opening in the casing			
	Non-ergonomic geometry		-I	Difficult inspection of components, could imply further disassembly
	Non removable encapsulation		-I	Components cannot be checked
DISASSEMBLY	Seams (of housing)		+I	Understand product's construction
	Visible fastener head			
	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)		-I	Understand product's construction + Component Release *(*) and provokes fear of breaking the product when attempting to detach*
	Hidden high force snap fits*			
	Screws located away from component they fasten			
	Deeply recessed fasteners			
	Non removable encapsulation		-I	Components cannot be disassembled
INTER CHANGEABILITY	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	+D	+L	+I	Confirms the user that components are working
	Click sound during attachment/ detachment				
	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	+D	+L	+I	Quick Inspection without disassembly (*) *and understand working mechanism of the product*
	Full view of components*				
	Coloured wires		+L		Understand working mechanism of the product
	Visible relationship between components				
	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

4.4.3. 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), although some required help. 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.

4.5. 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.

4.5.1. 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.

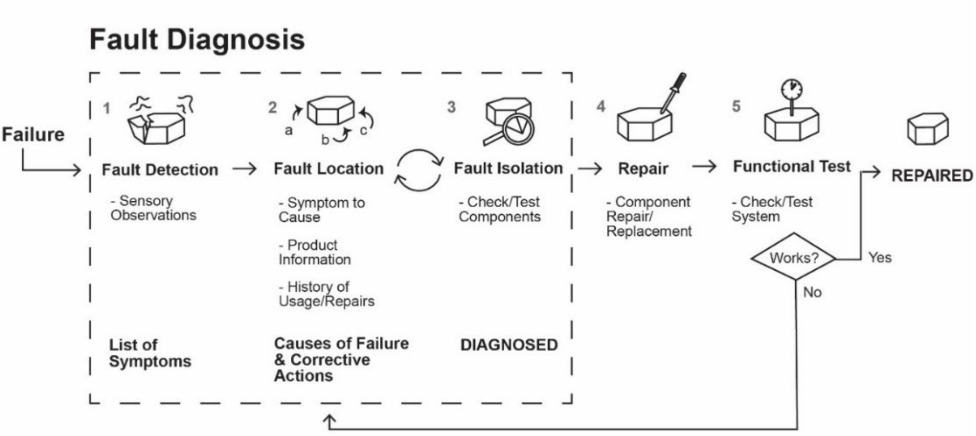


Figure 7 – Updated Framework of the Process of Fault Diagnosis by End-users

4.5.2. 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 (Bovea et al., 2016; Flipsen et al., 2017; Pérez-Belis et al., 2017). 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 Mourris and Rouse (1985) 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 recognise 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.

4.5.3. 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. Minimise 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 colours.	●						●	●	●

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 (Blomsma et al., 2019; Bovea and Pérez-Belis, 2018; Shahbazi and Jönbrink, 2020). Also, visibility of components, needed to guide users through the disassembly (guideline 2) has been identified as a relevant criterion for product reparability (Flipsen et al., 2019).

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 (den Hollander, 2018; Pozo Arcos et al., 2020). Second, guideline 3 expands guidelines for inspection from Go et al. (2015). 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.

4.6. 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 analysed 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 analyse 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?

4.7. 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 in 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 Reparability methods and contribute to the body of knowledge of product reparability.

Furthermore, these results are relevant for future product reparability policy and legislation. The Circular Economy Action Plan by the European Commission aims to support the "Right to Repair"(European Commission, 2020). Accordingly, Ecodesign Regulations include reparability 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.

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).

References

Angeli, C., 2010. Chapter 4: Diagnostic Expert Systems: From Expert's Knowledge to Real-Time Systems, Advanced Knowledge Based Systems: Model, Applications & Research. Jones & Bartlett Learning.

Baek, J.M., Ji, S.H., Koo, J.C., 2020. A cost effective on-site fault diagnosis method for home appliance rotor failures. Microsyst. Technol. 9. https://doi.org/10.1007/s00542-020-04892-9

Bakker, C., Wang, F., Huisman, J., Den Hollander, M., 2014. Products that go round: Exploring product life extension through design. J. Clean. Prod. 69, 10–16. https://doi.org/10.1016/j.jclepro.2014.01.028

Bhavana, K., 2020. Internet of Things Enabled Device Fault Prediction System Using Machine

Learning.

Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D.C.A., Hildenbrand, J., Kristinsdottir, A.R., Kristoffersen, E., Shabazi, S., Nielsen, K.D., Jönbrink, A.K., Li, J., Wiik, C., McAloone, T.C., 2019. Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. J. Clean. Prod. 241. https://doi.org/10.1016/j.jclepro.2019.118271

Bloor, M., Wood, F., 2006. Keywords in Qualitative Methods. https://doi.org/10.4135/9781849209403

Bovea, M.D., Ibáñez-Forés, V., Pérez-Belis, V., Quemades-Beltrán, P., 2016. Potential reuse of small household waste electrical and electronic equipment: Methodology and case study. Waste Manag. 53, 204–217. https://doi.org/10.1016/j.wasman.2016.03.038

Bovea, M.D., Pérez-Belis, V., 2018. Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment. J. Environ. Manage. 228, 483–494. https://doi.org/10.1016/j.jenvman.2018.08.014

Bracquene, E., Brusselaers, J., Dams, Y., Peeters, J., De Schepper, K., Dublou, J., Dewulf, W., 2018. Repairability criteria for energy related products.

Brusselaers, J., Bracquene, E., Peeters, J., Dams, Y., 2019. Economic consequences of consumer repair strategies for electrical household devices. J. Enterp. Inf. Manag. https://doi.org/10.1108/JEIM-12-2018-0283

Cordella, M., Alfieri, F., Sanfelix, J., 2019. Analysis and development of a scoring system for repair and upgrade of products - Final report. https://doi.org/10.2760/725068

Crandall, B., Klein, G., Hoffman, R., 2006. Working minds: a practitioner's guide to cognitive task analysis. .

Cuthbert, R., Giannikas, V., McFarlane, D., Srinivasan, R., 2016. Repair Services for Domestic Appliances .., in: Service Orientation in Holonic and Multi-Agent Manufacturing. pp. 31–39.

De Fazio, F., Bakker, C., Flipsen, B., Balkenende, R., 2021. The Disassembly Map: a new method to enhance design for product repairability. Manuscr. Submitt. Publ.

den Hollander, M.C., 2018. Design for Managing Obsolescence: A Design Methodology for Preserving Product Integrity in a Circular Economy. https://doi.org/10.4233/uuid:3f2b2c52-7774-4384-a2fd-. TU Delft Univ. https://doi.org/10.4233/uuid:3f2b2c52-7774-4384-a2fd-7201688237af

Duris, F., 2018. Arguments for the effectiveness of human problem solving. Biol. Inspired Cogn. Archit. 24, 31–34. https://doi.org/10.1016/j.bica.2018.04.007

European Commission, 2020. A new Circular Economy Action Plan For a cleaner and more competitive Europe. Commun. FROM Comm. TO Eur. Parliam. Counc. Eur. Econ. Soc. Comm. Comm. Reg.

European Commission, 2015. Closing the loop - An EU action plan for the Circular Economy. Commun. FROM Comm. TO Eur. Parliam. Counc. Eur. Econ. Soc. Comm. Comm. Reg. https://doi.org/10.1016/0022-4073(67)90036-2

Field, A., 2005. Discovering Statistics Using SPSS, Second Edi. ed. SAGE.

Flipsen, B., Bakker, C., Van Bohemen, G., 2017. Developing a reparability indicator for electronic products, in: 2016 Electronics Goes Green 2016+, EGG 2016. Fraunhofer IZM, pp. 1–9. https://doi.org/10.1109/EGG.2016.7829855

Flipsen, B., Huisken, M., Opsomer, T., Depypere, M., 2019. IFIXIT Smartphone Reparability Scoring: Assessing the Self-Repair Potential of Mobile ICT Devices. PLATE Conf. 2019 18–20.

Go, T.F.F., Wahab, D.A.A., Hishamuddin, H., 2015. Multiple generation life-cycles for product sustainability: The way forward. J. Clean. Prod. 95, 16–29. https://doi.org/10.1016/j.jclepro.2015.02.065

Hoppmann, T.K., 2009. Examining the "point of frustration". the think-aloud method applied to online search tasks. Qual. Quant. 43, 211–224. https://doi.org/10.1007/s11135-007-9116-0

iFixit, 2019. Anwers [WWW Document]. URL https://www.ifixit.com/Answers (accessed 12.1.19).

Jaeger-Erben, M., Frick, V., Hipp, T., 2021. Why do users (not) repair their devices? A study of the predictors of repair practices. J. Clean. Prod. 286, 125382. https://doi.org/10.1016/j.jclepro.2020.125382

Jiang, Y., Li, C., Li, N., Feng, T., Liu, M., 2018. HAASD: A dataset of household appliances abnormal sound detection. ACM Int. Conf. Proceeding Ser. 6–10. https://doi.org/10.1145/3297156.3297186

Jonassen, D.H., Hung, W., 2006. Learning to troubleshoot: A new theory-based design architecture. Educ. Psychol. Rev. 18, 77–114. https://doi.org/10.1007/s10648-006-9001-8

Kluge, A., Termer, A., 2017. Human-centered design (HCD) of a fault-finding application for mobile devices and its impact on the reduction of time in fault diagnosis in the manufacturing industry. Appl. Ergon. 59, 170–181. https://doi.org/10.1016/j.apergo.2016.08.030

Marcu, M., Darie, M., Cernazanu-Glavan, C., 2017. Component level energy accounting and fault detection on electrical devices using power signatures. I2MTC 2017 - 2017 IEEE Int. Instrum. Meas. Technol. Conf. Proc. 4–9. https://doi.org/10.1109/I2MTC.2017.7969888

Mathieux, F., Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., Dewulf, W., Duflou, J.R., 2018. Ease of disassembly of products to support circular economy strategies. Resour. Conserv. Recycl. 135, 323–334. https://doi.org/10.1016/j.resconrec.2017.06.022

Milford, C., Kriel, Y., Njau, I., Nkole, T., Gichangi, P., Cordero, J.P., Smit, J.A., Steyn, P.S., Mugo, J., Beksinska, M., Mtshali, M., Mkhize, N., Luthuli, F.S., Mthimkhulu, S., Mosery, F.N., Munakampe, M.N., Silumbwe, A., 2017. Teamwork in Qualitative Research: Descriptions of a Multicountry Team Approach. Int. J. Qual. Methods 16, 1–10. https://doi.org/10.1177/1609406917727189

Morris, N.M., Rouse, W.B., 1985. Review and Evaluation of empirical research in troubleshooting. J. Hum. Factors Soc. 27.

Moss, M.A., 1985. Designing for Minimal Maintenance Expense: The Practical Application of Reliability and Maintainability, Quality and Reliability. Taylor & Francis.

Patrick, J., 1993. Cognitive aspects of fault-finding training and transfer. Trav. Hum. 56, 187–209.

Pérez-Belis, V., Braulio-Gonzalo, M., Juan, P., Bovea, M.D., 2017. Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment. A Spanish case study. J. Clean. Prod. 158, 261–275. https://doi.org/10.1016/j.jclepro.2017.04.143

Pozo Arcos, B., Bakker, C., Flipsen, B., Balkenende, R., 2020. Practices of fault diagnosis in household appliances: Insights for design. J. Clean. Prod. 265, 121812. https://doi.org/10.1016/j.jclepro.2020.121812

Pozo Arcos, B., Balkenende, A.R., Bakker, C.A., Sundin, E., 2018. Product Design for a Circular Economy : Functional Recovery on Focus 2727–2738.

Rashid, R.A.R.A., 2019. Machine Learning for Smart Energy Monitoring of Home Appliances Using IoT, in: International Conference on Ubiquitous and Future Networks, ICUFN. pp. 66–71.

Repair Cafe International Foundation, 2020. Repair Monitor - Analysis Results 2019.

Robertson, I.S., 2017. Problem Solving - Perspectives from Cognition and Neuroscience, Second. ed. Routledge.

Rogers, H.A., Deutz, P., Ramos, T.B., 2021. Repairing the circular economy: Public perception and participant profile of the repair economy in Hull, UK. Resour. Conserv. Recycl. 168. https://doi.org/10.1016/j.resconrec.2021.105447

Sabbaghi, M., Esmaeilian, B., Cade, W., Wiens, K., Behdad, S., 2016. Business outcomes of product repairability: A survey-based study of consumer repair experiences. Resour. Conserv. Recycl. 109, 114–122. https://doi.org/10.1016/j.resconrec.2016.02.014

Shahbazi, S., Jönbrink, A.K., 2020. Design guidelines to develop circular products: Action research on nordic industry. Sustain. 12, 1–14. https://doi.org/10.3390/su12093679

Simon, H.A., Dantzig, G.B., Hogarth, R., Plott, C.R., Schelling, T.C., Shepsle, K.A., Thaler, R., Tversky, A., 1987. INFORMS Journal on Applied Analytics Decision Making and Problem Solving.

Stahel, W.R., 2006. The Performance Economy, 2nd editio. ed. Palgrave Macmillan.

Suresh, K., 2019. Smart home services using cloud and internet of things. Int. J. Adv. Trends Comput. Sci. Eng. 8(4) 8, 1560–1567.

Terzioğlu, N., 2021. Repair motivation and barriers model: Investigating user perspectives related to product repair towards a circular economy. J. Clean. Prod. 289. https://doi.org/10.1016/j.jclepro.2020.125644

Truttmann, N., Rechberger, H., 2006. Contribution to resource conservation by reuse of electrical and electronic household appliances. Resour. Conserv. Recycl. 48, 249–262. https://doi.org/10.1016/j.resconrec.2006.02.003

USA Department of Defense, 1988. Maintainability Design Techniques.

Van Someren, M.W., Barnard, Y.F., Sandberg, J.A.C., 1994. The think aloud method: a practical approach to modelling cognitive.

Wasserkrug, S., Krüger, M., Feldman, Y.A., Shindin, E., Zeltyn, S., 2019. What's wrong with my dishwasher: Advanced analytics improve the diagnostic process for Miele technicians. Interfaces (Providence). 49, 384–396. https://doi.org/10.1287/inte.2019.1006

Whalen, J., 2019. Design For How People Think Using Brain Science to Build Better Products, Interactions.

Whalley, J., Kasto, N., 2014. A qualitative think-aloud study of novice programmers' code writing strategies. ITICSE 2014 - Proc. 2014 Innov. Technol. Comput. Sci. Educ. Conf. 279–284.

*Note to the chapter. The text "although some required help" has been added on section 4.4.3, page 131, line 5. In addition, the notation reference to the sample size of the statistical analysis on the last paragraph of section 4.3.5 has been changed from N into n_i. Both changes were made to avoid confusion.

CHAPTER 5

HOW USER MANUALS SUPPORT THE DIAGNOSIS OF COMMON FAULTS IN HOUSEHOLD APPLIANCES: AN ANALYSIS OF 150 MANUALS [4]

---

[4] Pozo Arcos, B., Bakker, C., Balkenende, R., 2021 How User Manuals Support The Diagnosis Of Common Faults In Household Appliances: An Analysis of 150 Manuals.(submitted)

Abstract

Keeping products in use by repairing them when they fail is at the core of sustainable consumption. Repairing instead of replacing products requires limited energy and resources, and reduces the amount of waste from product discards. User manuals can play a relevant role in facilitating product repairs. They are the accredited source of product information for end-users: The European standard on product safety recommends that products be accompanied by manuals communicating product information concerning the product's lifecycle (e.g. installation, usage, maintenance, and disposal) including how to solve common product faults. Similarly, recent Ecodesign regulations and reparability studies recommend providing diagnosis information to facilitate repairs. User manuals are thus an important means for the diagnosis and subsequent repair of household appliances.

Despite increasing societal demand for repairable products, few studies have been conducted on the extent to which manuals contribute to the fault diagnosis and subsequent repair process. Such a study could provide a better understanding of the end user's perspective when a product fails. Hence, in this study, we analysed current guidance provided by manuals for the diagnosis process, answering the research question: 'To what extent do user manuals provide sufficient information to diagnose the most frequent faults in household appliances?' We examined the diagnosis instructions provided in the user manuals of four different household appliances. We analysed the manuals using data on the appliances' most frequently failing components and a framework that considers three steps towards a successful diagnosis: fault detection, fault location, and fault isolation. In total, we analysed 150 user manuals of 48 brands available on the European market.

We show that manuals do not instruct the diagnosis of frequently failing components. They mainly refer to causes of failure and directly recommend corrective actions after fault detection. Thus, they rarely include a three-step fault diagnosis process to identify and isolate a faulty component. Based on these results, we have extended the framework for the process of fault diagnosis to include the step from cause identification to corrective action. Both routes, the component-oriented and the cause-oriented route in fault diagnosis should be considered during the design of products for easy fault diagnosis, and should be included in future regulations that address product reparability.

Ch. 5 - How User Manuals Support the Diagnosis of Common Faults in Household Appliances: an Analysis of 150 Manuals

Keywords

Troubleshooting, Fault Diagnosis, Design for Repair, Circular Economy, Product Design, Sustainable Consumption

5.1. Introduction

Repairing products instead of replacing them when they fail is at the core of sustainable consumption and is considered a core recovery pathway in a circular economy (Ellen MacArthur Foundation, 2020). Product repairs extend a product's lifespan and consequently, delay its disposal. They slow the flow of products that enter the economic system, which is one the strategies towards a circular economy (Bocken et al., 2016). Repairs have a low environmental impact, and in the case of small household appliances, tend to be a better option than replacement (Bovea et al,, 2020). Extending the life of products requires little energy and few resources (Cooper and Gutowski, 2017) and contributes to a reduction of energy associated to new productions (Stahel, 2006). Moreover, product repairs run on "manpower" and can be done locally. So they can have an added positive socioeconomic impact by creating jobs at home and boosting economic development (stahel, 2006). Hence, the societal, economic, and environmental impact of repairs makes them not only a circular economy strategy but also a sustainable choice (Nikolaou et al, 2021).

The process of fault diagnosis is important to facilitate repairs in a circular economy. It is "the action to identify and characterize the fault" (IEC, 192-06-20, 2015). In other words, it reveals what needs to be repaired in a product and is therefore a fundamental step before effectively starting the repair action. Facilitating the fault diagnosis process can ease the repair process by reducing the amount of time, number of errors, and complexity associated with the repair process (Kluge and Termer, 2017; Morris and Rouse, 1985; Patrick, 1993). When successfully completed, the process of fault diagnosis identifies the defective component, thereby helping to determine whether a repair is feasible and worthwhile. Knowing which component failed helps to estimate the required skills, labour time, costs of replacement parts, shipping time, and other associated repair costs. Moreover, a smooth fault diagnosis can promote sustainable behaviour: Consumers feel more inclined to repair if any uncertainties associated with a product malfunction are reduced (Brusselaers et al., 2019; McCollough, 2009; Sabbaghi et al., 2016; Scott and Weaver, 2014). Hence, facilitating the diagnosis process could help in reducing commonly described consumer barriers to repair such as inconvenience, lack of time, lack of skills, and associated financial costs to the repair (Jaeger-Erben et al., 2021; Laitala et al., 2021; Terzioğlu, 2021)

Guidance during the diagnosis procures a more effective outcome (Kluge, 2017). A recent study showed that for end users guidance is decisive in successfully diagnosing the faults in malfunctioning appliances (Pozo Arcos 2020). These findings agree with recent requirements in Ecodesign regulations and reparability studies, which concur that the provision of diagnosis information is necessary to facilitate product repairs. Ecodesign regulations for washing machines in Commission Regulation, 2019/2023/EC (2019), and dishwashers in Commission Regulation 2019/2022/EC (2019) now require that user manuals provide fault diagnosis information. For instance, they stipulate facilitating the identification of error signals in the appliances, their meaning, and subsequent actions to take. New upcoming ecodesign regulations aimed to enforce the Circular Economy Action Plan (The European Commission, 2020) are expected to include similar requirements.

Likewise, reparability analysts and researchers have indicated that manufacturers should provide diagnosis information to facilitate repairs (Repair Cafe International Foundation, 2020; Tecchio et al., 2019).User manuals can better support the diagnosis process if they, at least, provide sufficient information to diagnose common faults (Bracquene et al., 2018; Cordella et al., 2019). Moreover, product safety standards recommend that manufacturers provide diagnosis information in user manuals. The European Safety Directive 2001/95/EC (2001) requires that products intended for consumers are accompanied by a user manual which includes information and advice relevant to the product's lifetime. The standard for compliance with the Safety Regulation, (EC/IEEE 82079-1:2019), recommends that manuals include information to correct potential product failures. Hence, manuals should facilitate the diagnosis and correction of potential product failures. Yet, no studies have analysed which common faults are included in the manuals, and how their diagnosis and correction is facilitated. Instead, studies on the content of user manuals found in the literature examine topics like the usability and accessibility of manuals (Cifter and Dong, 2010), their effect on customer satisfaction (Gök et al., 2019), how the content should be developed for optimal product use (Renaud et al., 2019), or how alternative media such as virtual and artificial reality can be used to present the manual's information (Flotynski et al., 2019; Müller et al., 2013). Similarly, the literature on repair practices does not discuss the diagnosis step, even though it notes that the current content of user manuals is insufficient to facilitate repairs ((Bracquené et al., 2021; Pozo Arcos et al., 2020; Sabbaghi et al., 2016). Thus to date, no studies have examined this claim in detail. Hence, it is unclear how much support manuals provide to end-users regarding the diagnosis of malfunctioning appliances.

In this study, we address the research question: ‘To what extent do user manuals provide sufficient information to diagnose the most frequent faults in household appliances?’. To this end, we analysed the troubleshooting sections of a broad and varied sample of user manuals of products commonly present in European households. We limited our analysis to widely available domestic appliances, due to the variety of design features and components they embody, and the availability of data on failure rate. ICT equipment is not within the scope of this study as these products are designed and used in a different way and subject to different regulations. For the analysis, we used a framework of the fault diagnosis process, applying the data on the appliances’ most frequently reported faults.

In the following section (section 2), we introduce the theoretical framework used for the analysis. The methodology is outlined in section 3. In section 4, we report the results of our analysis. In section 5, we discuss the results; and in section 6, we present our conclusions.

5.2. Fault Diagnosis Process by End Users

In this section, we briefly present the theoretical concepts guiding our analysis. The circular economy has brought attention to the process of fault diagnosis for its relevance not only for repairs but also for the processes of remanufacturing, refurbishment, and part harvesting (Pozo Arcos et al., 2018). Moreover, the process of fault diagnosis is also used for revealing the potential of reuse of discarded products (Dindarian et al., 2012; Parajuly and Wenzel, 2017). However, few studies have examined how end users perform the fault diagnosis process in view of subsequently repairing a product. In the case of household appliances, the most recent study on the topic of fault diagnosis by end users is presented by Pozo Arcos et al. (2021). The study describes a framework of the diagnosis process based on a literature review and refined and validated with 24 participants during an observatory study. The framework is shown in figure 1.

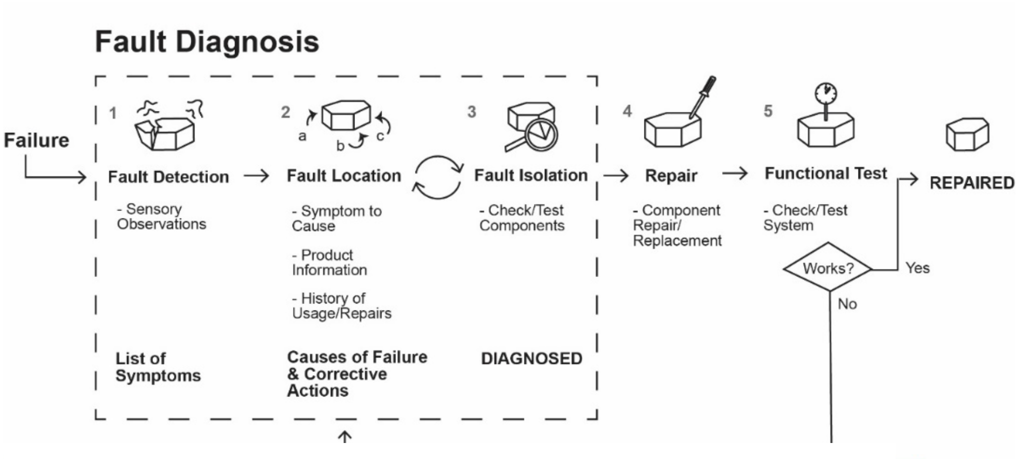


Figure 1 - Framework of the Diagnosis Process Performed by Users

The framework illustrates three steps end-users follow from product failure to the identification of the fault i.e. the diagnosis of the appliance. The first step towards the diagnosis is to detect the fault in the malfunctioning appliance. The user observes symptoms of malfunction and uses those together with other product information to deduce possible causes of failure, i.e. fault location. Subsequently, the user, will test or check the condition of the suspected components. This last step is called fault isolation. The study showed that users iterate between fault location and fault isolation until the fault is found.

The framework shown in figure 1 is the most accurate representation available of the diagnosis process by end users of a household appliance. Therefore, it will be the conceptual framework that will be used for the analysis of the diagnosis instructions provided in the manuals.

5.3. Method

We present the criteria for the selection of the appliances and user manuals, and the procedure followed to analyse the manuals' troubleshooting sections.

5.3.1. Selection of the manuals

We aimed to have a broad and varied sample of manuals from frequently used products in European households. Hence, we applied criteria that considered different European manufacturers and consumers (see table 1).

Table 1 - Criteria for Selection of User Manuals

	Criteria	Indicators & Rationale
	Appliance type	
a	The appliances are frequently sold in Europe and representative of commonly purchased EEE (Electronic and Electric Equipment) in Europe	The indicator of "kg per capita put on the market" from Eurostat (accessed February 2021) revealed the average kg of different appliances purchased per citizen. Using the average weight of an appliance, we could make a rough estimate of the number of appliances purchased per year, per citizen. Eurostat uses the 10 categories from EU WEEE Directive 2012 (Directive 2021/19/EU) to report results
b	Data on frequently failing components was available	Failure rate statistics from reliable, open sources such as scientific papers and repair associations
c	The appliances include a variety of different components and functions	Heater, water circulation systems, electric motors, cooling system, electronics, suction
d	The appliances are marketed by many different European brands.	We selected appliances marketed by multiple brands to allow comparing the results between brands,
	Appliance brand	
e	The brands selected should represent a variety of sectors	Brands of different sizes and different market segments
	Appliance model	
f	The appliances are sold in the EU market at the time of the study	The appliance models were on sale on the official brand webpage in January 2021.
g	The appliance models should represent different consumer segments.	We selected models in both the low and high price range
h	User manuals of the appliance models are available on the official company webpage	Essential to be able to conduct the analysis

To select the manuals, we first defined the appliance types, then, the brand, and finally the appliance models. The appliance type selection started with criterion ‘a’ (see table 1), which narrowed down our selection of product categories to large and small household appliances. These were the most sold product categories in 2017 (Eurostat statistics, accessed February 2021). Using criterion ‘b’, we limited our selection to those appliances with failures that had been studied in scientific papers or reports. Using criterion ‘c’ we selected a variety of electromechanical appliances with representative functions e.g. heating, cooling, suction, blowing, rotating, circulating water. We further refined our selection using criterion ‘d’, which helped us choose cylinder vacuum cleaners over stick or upright, or single dose coffee machine in lieu of percolators.

To select the brands, we sourced brand names from different consumers and manufacturers associations and applied criterion e. Last, we selected different models within a brand using criteria ‘f’, ‘g’, and ‘h’. Our final selection of appliance type and brands can be found in table 2. Details of the models can be found in the supplementary material.

Table 2 – Appliances and brands investigated in this study

Appliance Type	Appliance Brand
Single Dose Coffee Machines	BOJ, caffitali, Delizio, De'Longhi, Dualit, Ikohs, Illy, Krups, Lavazza, Philips, Tassimo (Bosch)
Free Standing Front Load Washing Machine	AEG, ASKO, Bauknecht, Beko, Bosch, Electrolux, Gorenje, Haier, LG, Miele, Samsung, Siemens, V-ZUG, Whirlpool, Zanussi
Cylinder/Canister Vacuum Cleaner	AEG, Bosch, Dirt Devil, Dyson, Fakir, Hoover, Inventum, Miele, Numatic, Philips, Rowenta, Severin, Vorwerk
Free Standing Fridge And Freezer	Beko, Electrolux, Fisher and Paykel, Gorenje, Hotpoint, Indesit, LG, Liebherr, Miele, Neff, Panasonic, Russell Hobbs, Samsung, Severin, Siemens, Smeg,

5.3.2. Analysis of the user manuals

To analyse the content of the manuals, we first developed criteria based on the framework of fault diagnosis by end users presented in Pozo Arcos et al., (2021) (figure 1). This framework describes three steps to diagnose an appliance: fault detection, fault location, and fault isolation. A manual that facilitates the diagnosis process would be expected to guide the user through these consecutive steps.

Based on the framework, the manuals are expected to provide a clear description of the symptoms to facilitate the fault detection step. In the case of error signals, it would be helpful if the manuals described both: the malfunction as well as the error signal (Pozo Arcos et al., 2021). Following fault detection, the manuals are then expected to facilitate fault location by relating symptoms to related possibly defective components. In the case of symptoms in the form of error signals, their meaning and possible causes for their occurrence should also be described. After the potentially faulty components are located, the faults need to be isolated. Fault isolation is facilitated if the manuals explain how to check the condition of components, which implies knowledge of the healthy and the defective state of the component. In some instances, components may require (partial) disassembly of the appliance to inspect the components. In those cases, the manual should also explain the required disassembly steps.

We developed a criterion from each of the diagnosis steps. We restricted the analysis to the five most frequent faults in the appliances and added a criterion to consider possibly unexpected findings. A summary of the criteria for analysing the user manuals is presented in table 3

Table 3 - Criteria for the Analysis of User Manuals

Criteria for Analysing the Guidance of User Manuals to Fault Diagnose Household Appliances	
1	The manual facilitates the diagnosis of the most frequent faults in an appliance
2	The manual facilitates fault detection by clearly describing the symptoms related to the most common faults
3	The manual facilitates fault location by relating the symptoms to the components that are likely to be faulty
4	The manual facilitates fault isolation by providing instructions on how to inspect the condition of the located component. It provides information on both the healthy and the defective status of a component, and information on how to reach the component if this is necessary for inspection
5	Remarks concerning diagnosis not covered by the above criteria

As a second step, we collected data on the five most frequently failing components for each of the four appliances, the related symptoms, and possible defects in the components. Data on frequently failing components were available in the literature (Pozo Arcos et al., 2020; Tecchio et al., 2019), and reports from consumer and grass root repair associations like Test ankoop, Which? and the Repair Cafe (Bracquene et al., 2018; Repair Cafe International Foundation, 2020). Table 4 presents a description of the datasets and the top 5 frequently failing components for each of the appliances. Data on common defects and symptoms were gathered from online repair tutorials found on the video platform YouTube. We chose this source due to its wiki-based nature, which provides large amounts of information from different product experts and users. Moreover, we preferred to rely on an audio-visual medium to be able to quickly compare whether the appliances corresponded to those selected in our criteria. We searched for terms such as "troubleshooting [appliance type]" or "most common symptoms of [appliance type]".

Table 4 - Dataset on Frequently Failing Components used in the Study

Appliance	Top 5 Frequently Failing Components	Source of Data
Coffee Maker	Flow Sensor,	Repair Monitor 2020 (N=1053)
	Pump,	
	Heater	
	Water Pipes	
Vacuum cleaner	Filter	Test ankoop 2015 (N= 19000) Which? 2015 (N= 637) Repair Monitor 2020 (N=699)
	Hose	
	Engine	
	Power Cable And Plug	
	Rewinding Mechanism	
Washing Machines	Electronics	Tecchio 2019 (N=9492)
	Shock Absorbers and Bearings	
	Door	
	Carbon Brushes*	
	Pumps	
	Engine*	
	Drain System	
Refrigerator	Electronics, Condenser Coils,	Pozo Arcos 2020 (N=117)
	Evaporator Coils	
	Defrosting System	
	Compressor	

**Note to the table: There is a difference in technology between current washing machine models and those examined by Tecchio et al. (2019); some components reported as frequently failing are no longer embodied in modern washing machines. For instance, current models of washing machines do not include carbon brushes; instead, they are embodied with brushless or Variable-Frequency Drive (VFD) motors. These components were not considered in the analysis, we only included the most frequently failing component from the database.*

In a next step, we analysed the manuals quantitatively and qualitatively. We limited the analysis to one manual per brand and appliance type because we observed that within a brand, product models of similar technology and function had the same troubleshooting sections. For each of the frequently failing components, we analysed the manual's troubleshooting sections by first checking whether the component was mentioned at all, and next, by mapping the extent to which the manual guided the user through the fault diagnosis process (from symptom to faulty component) in order to identify the defective component. We used the five criteria in Table 3 to structure our analysis. The framework's steps were used as indexes for the content, as suggested by Ritchie and Lewis, (2003).

5.4. Results

In this section, we describe the guidance provided by user manuals on diagnosing the appliances' top five common faults. At the end of the section, we provide a summary of our findings. The complete dataset of the analysis is provided as supplementary material.

5.4.1. Single Dose Coffee Makers

We analysed 11 user manuals for single dose coffee makers. The manuals rarely referred to faults in the most frequently failing components, and focused on limescale, a more generic potential cause of failure. Fault detection was facilitated but instructions for fault location and fault isolation were rarely provided. Instead, the manuals commonly advise users to perform maintenance tasks or restart the appliance to remove the cause of the failure (see tables 5 and 6).

Table 5 - Fulfilment of criteria by user manuals of Single Dose Coffee Makers

Criteria		Results Single Dose Coffee Makers
1	The manual facilitates the diagnosis of the most frequent faults in an appliance	The most frequently failing components are the pump, flow sensor, heater, and water pipes. These components were mentioned in all manuals, but only linked to one specific failure mechanism: the build-up of limescale. One manual mentioned a defective sensor, and one manual mentioned "heating problems", where we had to deduce that it referred to problems with the heater. Faults in the pump motor were not referred to in any of the manuals.
2	The manual facilitates fault detection by clearly describing the symptoms related to the most common faults	All manuals facilitated the fault detection step for 3 of the most frequently failing components by providing at least one symptom description, commonly how the product would malfunction e.g. when the coffee machine takes longer than expected to start. Dedicated error signals were less frequently used (in 4 manuals). The manuals described different symptoms for the same fault; we counted up to four different descriptions (see supplementary material).
3	The manual facilitates fault location by relating the symptoms to the components that are likely to be faulty	The fault location step was only facilitated by 3 of the 11 manuals, which related the symptoms of limescale to specific components, namely the pump and the water circuit. The symptom related to a defective sensor was located in a single manual.

4	The manual facilitates fault isolation by providing instructions on how to inspect the condition of the located component	The fault isolation step was rarely facilitated. Only one manual advised diagnosing the pump via a sound inspection, and later, to descale.
5	Remarks concerning diagnosis not covered by the above criteria	Instead of identifying faulty components, the manuals often provided instructions for a corrective action based on the observed symptoms, like descaling the machine (for faults due to limescale) or restarting the appliance (for faults due to "heating problems").

Table 6 –Frequency count of fault and diagnosis steps described in 11 manuals of single dose coffee makers

Faults (Components and Possible Defects)		**TOTAL manuals**	**Step 1 Fault Detection**	**Step 2 Fault Location**	**Step 3 Fault Isolation**
Flow sensor	demagnetized neodymium magnet,	0			
	defective sensor	1	1	1	0
Pump	clogged with limescale	11	11	3	1
	motor failure	0			
Heater	deteriorated filament or thermoblock due to limescale	11	11	3	0
	defective thermofuse	0			
	Heating problem	1	1	0	0
Water pipes	clogged with limescale	11	11	3	0

5.4.2. Cylinder Vacuum Cleaners

We analysed 13 cylinder vacuum cleaner user manuals. For frequently failing components, the manuals mostly focused on the filter and the hose, or referred to a cause like blockage in the airflow. Fault detection and fault location were often facilitated. Fault isolation was occasionally recommended. In most instances, the manuals advised performing a corrective action, often related to overdue maintenance (see tables 7 and 8).

Table 7 - Fulfilment of criteria by user manuals of Cylinder Vacuum Cleaners

	Criteria	Results Cylinder Vacuum Cleaners
1	The manual facilitates the diagnosis of the most frequent faults in an appliance	The most frequently mentioned failing components in vacuum cleaners were the filters, the hose, the engine, the power cable and plug, and the rewinding mechanism. All the manuals recognized faults in the filter and hose due to overdue maintenance. They described 'blockages' in the components as defects. Faults in the power cable and plug were recognized in two manuals, and faults in the engine in one manual, and simply associated with 'damage'. Faults in the rewinding mechanism were never mentioned.
2	The manual facilitates fault detection by clearly describing the symptoms related to the most common faults	All manuals facilitated fault detection of the two most frequent faults by providing different descriptions of symptoms, usually descriptions of malfunctions, e.g. an abnormal noise, or a low or intermittent performance. Symptoms in the form of error signals were referred to in 4 manuals, all related to detecting faults in the filter. (see supplementary material for symptom descriptions)
3	The manual facilitates fault location by relating the symptoms to the components that are likely to be faulty.	The manuals commonly located the faults in defective components. Faults in the filter or the hose were usually described together, and both related to a single symptom (8 manuals).
4	The manual facilitates fault isolation by providing instructions on how to inspect the condition of the located component	Instructions regarding fault isolation were occasionally provided for the filter and hose (5 manuals), but never given for the other faults.
5	Remarks concerning diagnosis not covered by the above criteria	Occasionally, the manuals described a general cause of failure. Instead of locating the faults, 4 manuals described blockage in the airflow together with possibly defective components. In one instance, only blockage in the airflow was mentioned. In general, the manuals instructed performing maintenance tasks such as "clean or replace the filters, and remove the blockage'. Detailed descriptions for performing the maintenance tasks were provided in dedicated sections. For other faults, e.g. in the engine, or the power cable and plug, the user was directly referred to customer support.

Table 8 - Frequency count of fault and diagnosis steps described in 13 manuals of vacuum cleaners

Faults (Components and Possible Defects)		TOTAL manuals	Step 1 Fault Detection	Step 2 Fault Location	Step 3 Fault Isolation
Filters	blocked	13	13	13	5
Hose	blocked	13	13	13	5
Engine	windings burn out, short circuit	0			
	worn out carbon brushes	0			
	damaged	1	1	1	0

Power Cable and Plug	damaged chord or plug	2	2	1	0
	broken switch button	0			
Rewinding Mechanism	short circuit cable reel moulding	0			
	broken button	0			

5.4.3. Washing machines

We analysed 15 user manuals for front load washing machines. For the most frequently mentioned failing components, the manuals described internal errors in different electronics components. In most cases these were sensor errors, and some referred to a blocked pump impeller. Fault detection and location were always facilitated. However, the manuals skipped fault isolation and instructed maintenance tasks or resetting the appliance depending on the component. In a few instances, the manuals directly referred the user to customer support after fault detection (see tables 9 and 10).

Table 9 - Fulfilment of criteria by user manuals of front load washing machines

Criteria		**Results Front Load Washing Machines**
1	The manual facilitates the diagnosis of the most frequent faults in an appliance	The most frequently mentioned failing components were electronic components: shock absorbers, bearings, door components and the pumps, including water circulation and the drain pump. The defects described were mainly related to overdue maintenance e.g. clogged impeller or limescale. Only 5 manuals refer to a fault in the pump. Faults related to the door were included in 8 manuals, and 7 manuals included faults related to electronic components. The described defects in for the door and the electronics were either electronic errors or defective sensors. None of the manuals included faults related to the shock absorbers and bearings.
2	The manual facilitates fault detection by clearly describing the symptoms related to the most common faults	The fault detection step was facilitated in 8 manuals for 3 of the most failing components, but only for specific failure causes. (see table 10). For faults due to overdue maintenance, the manuals described both symptoms of malfunctions and error signals given by the appliance. These were not described in combination, but in separate troubleshooting entries. For faults in electronic components, the manuals only described error signals as symptoms.
3	The manual facilitates fault location by relating the symptoms to the components that are likely to be faulty.	The fault location step depended on the type of fault. Faults due to overdue maintenance were located in specific components, e.g. the drain pump. For faults in electronics components, the meaning of the sensor error codes was provided, e.g. motor error, motor control error, water level error.

4	The manual facilitates fault isolation by providing instructions on how to inspect the condition of the located component	Fault isolation was not mentioned
5	Remarks concerning diagnosis not covered by the above criteria	Instead, the manuals directly recommended corrective maintenance of components e.g. unclogging or cleaning the pump impeller or restarting the appliance. The instructions appeared in a dedicated section of the manual. For faults in electronics, the manuals usually recommended restarting the appliance. Occasionally, the manuals directly recommended contacting customer support.

Table 10 - Frequency count of fault and diagnosis steps described in 15 manuals of washing machines

Faults (Components and Possible Defects)		**TOTAL manuals**	**Step 1 Fault Detection**	**Step 2 Fault Location**	**Step 3 Fault Isolation**
Electronics	defective/ shorted relays,	7	1	1	0
	error control engine		5	5	0
	error water level sensor		5	5	0
	error temperature sensor		4	4	0
	other sensor/unspecified defective		4	4	0
	unplugged wiring between control board and display, bad communication		4	4	0
Shock absorbers and bearings	worn out	0			
Door	door lock error/ jammed	8	8	8	0
	damaged hinges, or ripped or teared seal,	0			
Pumps: (re)circulation/ drain pump	defective motor (short circuit,)	0			
	blocked or clogged impeller	5	5	5	0
Engine	burn out	0			

5.4.4. Fridge – Freezers

We analysed 15 user manuals for free standing fridge-freezer units. The manuals rarely described the complete diagnosis of common faults. Fault detection was always facilitated while fault location was only mentioned for electronic components. Fault isolation instructions were never provided. Instead, the manuals usually advised performing maintenance tasks or resetting the appliance (see tables 11 and 12).

Table 11 - Fulfilment of criteria by user manuals of fridge freezer units

	Criteria	**Results of Fridge-Freezer Units**
1	The manual facilitates the diagnosis of the most frequent faults in an appliance	The most frequently mentioned failing components were electronic components, condenser and evaporator coils, components of the defrosting system, and the compressor. The defects in the condenser coils were described as being due to overdue maintenance in the condenser protective grills e.g. blockage due to dirt. For faults in the evaporator coils, the defects were frosted coils. Faults in electronic components (temperature sensors) were recognized in 2 manuals. One manual mentioned a defective compressor as a fault; another manual included dirty coils as a fault.
2	The manual facilitates fault detection by clearly describing the symptoms related to the most common faults	Fault detection was facilitated by a limited number of manuals for only a few of the faults (see table 12). If the fault was in an electronic component, the manuals described the error signal given by the appliance. Otherwise, the manuals provided descriptions of malfunction in the appliance e.g. incorrect temperature or abnormal frost.
3	The manual facilitates fault location by relating the symptoms to the components that are likely to be faulty.	Fault location was facilitated in all cases where the manuals facilitated fault detection. The manuals then related the symptoms to a single component.
4	The manual facilitates fault isolation by providing instructions on how to inspect the condition of the located component	Instructions regarding fault isolation were never provided.
5	Remarks concerning diagnosis not covered by the above criteria	Instead, the manuals recommended performing maintenance tasks such as defrosting, unclogging, or cleaning. For electronic components, the manuals directly referred the user to customer support after fault

	detection. In the case of the compressor, the manuals advised restarting the appliance

Interestingly some refrigerators included a feature called *smart-diagnostics* by which the fridge could perform a self-diagnosis test and communicate the results to a smartphone app. The results of the test (audible sound signals) could only be interpreted by the app. Similar to the content of the manuals, the app either located the faults and directly recommended maintenance tasks, or referred the user to customer support. The manuals did not include the meaning of the smart-diagnostics audible signals. Hence, we could not conclude for which faults this feature could be used.

Table 12 - Frequency count of fault and diagnosis steps described in 15 manuals of fridge-freezer units

Faults (Components and Possible Defects)		**TOTAL manuals**	**Step 1 Fault Detection**	**Step 2 Fault Location**	**Step 3 Fault Isolation**
Electronics	Short Circuit Control Board, Faulty Start Relay Or Capacitor	0			
	Damaged Temp Sensors (Thermostat, Thermistor), Defrost Sensor	2	2	1	0
Condenser	Dirty Coils	1	1	1	0
	Damaged Fan (Mechanical)	0			
	Short-Circuit, Burn Out Motor-Fan (Electric)	0			
	Ventilation Grills	5	5	5	0
Evaporator	Frosted Coils	2	2	2	0
	Damaged Fan (Mechanical)	0			
	Short-Circuit, Burn Out Motor-Fan (Electric)	0			
Defrosting system	Defective Heater,	0			
	Clogged Drain Pipe	4	4	4	0
Compressor	Defective Compressor	1	1	1	0

5.4.5. Summary of Results

Overall, these results indicate that the manuals mainly focused on solving faults due to overdue maintenance. Other types of faults, for instance due to wear and tear, were hardly ever mentioned, although statistics show they are among the top five most frequent faults.

For those faults included in the manuals, fault detection was always facilitated: the manuals described symptoms related to the faults. The fault location step was facilitated in some cases. Generally, different descriptions of symptoms were related to a single, defective component. However, we also observed specific instances in which the manuals did not locate the fault, but referred to the most likely failure cause in the appliance e.g. limescale. Fault isolation was rarely facilitated. The manuals occasionally advised isolation actions, e.g. inspecting the sound of a pump or checking for blockages in components; but it was more common to find instructions for carrying out maintenance tasks, e.g. cleaning, descaling, unblocking, defrosting; or restarting the appliance.

5.5. Discussion

In this study, we aimed to analyse to what extent user manuals facilitate the diagnosis of frequent faults in four types of household appliances. The results show that manuals usually lack information to accurately diagnose frequent faults as reported by repair centres and consumer organisations. User manuals only facilitate the diagnosis and correction of faults caused by a lack of maintenance, or that are due to an internal state failure of electronic components. We conclude that manuals do not provide support for users to diagnose frequent faults such as a broken pump or a defective magnet in a coffee maker, a motor failure in a vacuum cleaner, or a short circuit in electronic components. In such cases, the user receives no guidance, but is simply referred to customer support or a service centre.

An important finding is that the manuals provide a ‘shortcut’ for the diagnosis of faults caused by lack of maintenance or internal state failure of electronics. After the initial step of fault detection, the detected symptom(s) are immediately related to a potential cause of failure, thus bypassing the process of fault location and fault isolation. Based on the anticipated cause, a corrective action is advised, like decalcification of the appliance or resetting the electronics. This fault diagnosis route (referred to as “cause-oriented”) seems especially effective if (1) the observed symptoms are known to be strongly related to a specific cause, or (2) the observed symptoms are difficult to relate to a specific component (e.g. in the case of scale deposition throughout the appliance), and (3) the subsequent corrective action is straightforward, easy and inexpensive. We have expanded the framework of the diagnosis process to reflect this new finding. (see figure 2).

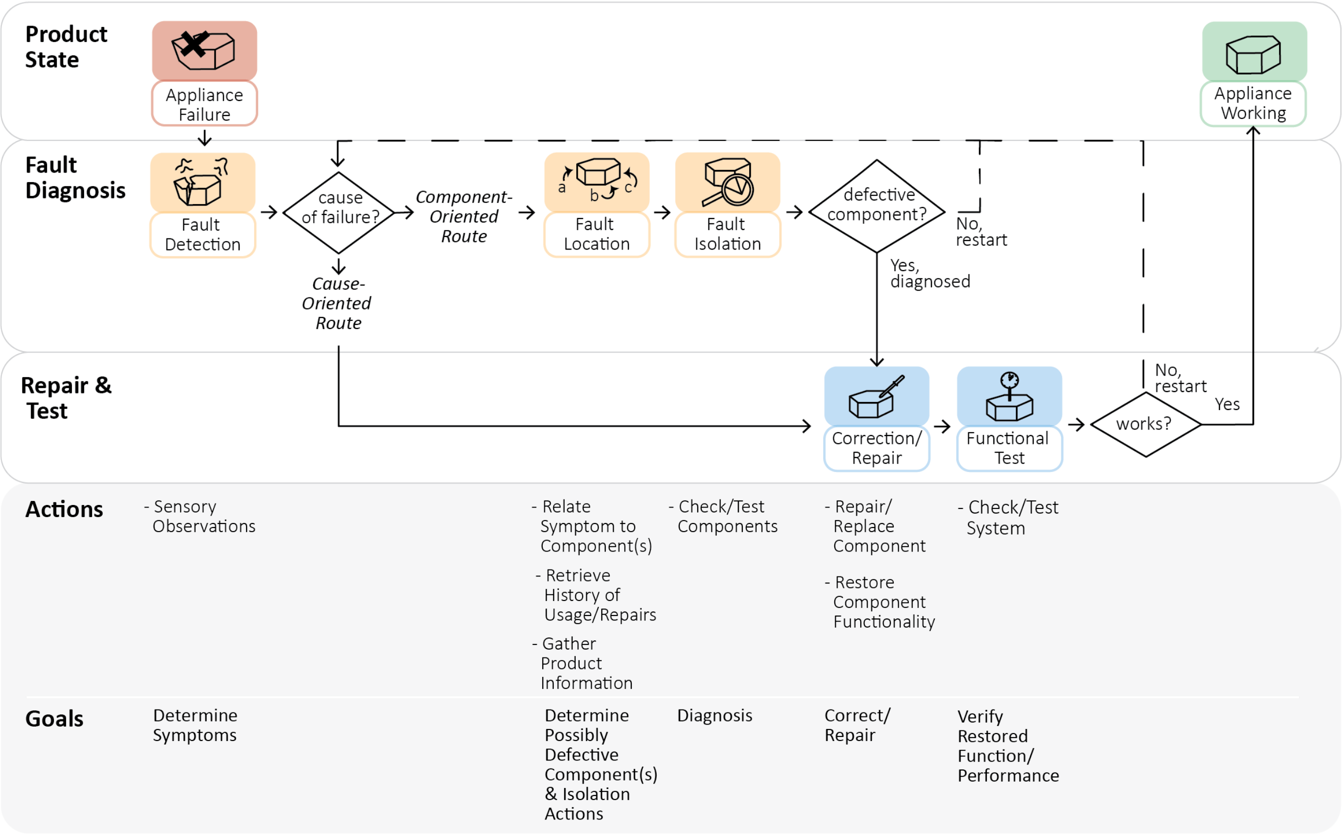


Figure 2 - Expanded Framework of the Process of Fault Diagnosis in Consumer Appliances

The choice made by manufacturers to not give full disclosure on how to diagnose and repair frequently failing components, and instead to limit themselves to faults that occur due to a lack of maintenance, has both advantages and disadvantages. These are discussed from the perspectives of manufacturers and of end-users (consumers).

From the perspective of manufacturers, the potential advantages of this approach include:

- It makes the diagnosis and troubleshooting process relatively risk-free and safe. By only allowing the most basic and straightforward corrective actions (like resetting an appliance, running an automatic descale program or replacing filters), manufacturers avoid potential safety risks that could occur when a user dismantles an appliance in order to diagnose a fault and repair the product.
- In principle, it allows manufacturers to acquire valuable data on frequent failures, as the customer support and service centres can log the complaints, returns, and repairs. This data can serve as a source of informational value to manufacturers and designers (Koppius et al., 2011; Petkova, 2003)
- It may drive sales and profits, as consumers who cannot diagnose and fix their appliances may be inclined to replace them instead of having them repaired, in particular when the appliances are inexpensive. The convenience and complexity associated with a repair are well identified barriers for repair practices (Jaeger-Erben et al., 2021).

Potential disadvantages of this approach for manufacturers include:

- Dissatisfaction among a subset of consumers who want to be able to fully diagnose and repair their products. This may damage the brand, as exemplified by iFixit’s campaign about low reparability scores of certain brands of smartphones. Moreover, Raihanian Mashhadi et al. (2016) found that repair convenience can influence future repurchase decisions or recommendations to other product users of a certain product or brand.
- It could drive up costs, for instance in the case of frequently failing components that are not mentioned in the manuals. Manufacturers may have to deal with relatively high return rates and in-warranty repairs.

From the perspective of end-users, the potential advantages of this approach include:

- An easy, quick, and cheap correction and fault diagnosis process. In many instances, the advice given in the manuals will help consumers fix their appliance without having to open it up. Various manuals of coffee makers now support fault diagnosis due to limescale by simply pressing a button (see results coffee maker table 5 and 6). Other examples include error codes that have clear explanations in the manuals. This shows that a successful fault diagnosis does not always have to result in dismantling an appliance, preventing users from incurring safety risks.
- Educating consumers about the need for maintenance. Having to decalcify a coffee maker in order to make it operational again, teaches a consumer that regular decalcification will prevent this kind of troubleshooting in the future. It might lead to more attention for maintenance (although further research would need to establish whether this learning effect actually happens in practice).

Potential disadvantages of this approach for end-users include:

- It may hamper a consumer's ability to assess the costs of a repair. Not being able to diagnose a fault reliably means that consumers cannot make a cost estimate as to whether to repair or replace a product. This could lead to premature product replacement.
- It may discourage the user from trying to repair the product. If users perceive that the process of fault diagnosis is difficult to perform, e.g. it requires skills, time and effort, they may perceive it as being highly inconvenient and decide not to continue. In a recent study, Terzioglu (2021) found that the required knowledge, skills, and efforts to take on a product repair are some of the perceived technical barriers experienced by users.
- It may lead to a further erosion of consumers' "product literacy" (Kopp, 2012). Lack of information about the product and increased automation of the tasks can limit users' ability to understand how a product works and how it should be maintained and repaired.

Both routes, the component-oriented and the cause-oriented route in the fault diagnosis process should be considered during the design of products for easy fault diagnosis.

Based on the results of this study, we recommend that fault diagnosis should be facilitated as much as possible without the need to open up or dismantle the appliance, for instance through feedback signals and other visual or auditory cues. One example of a coffee maker showed how a pump could be diagnosed following the component-oriented route without disassembly (see coffee maker results table 5 and 6). Moreover, the use of augmented reality and other digital support systems like smartphones is currently being explored in practice (Baek et al., 2020; Flotynski et al., 2019; Müller et al., 2013) and may open up interesting avenues for future diagnosis of household appliances.

Overall, this study contributes to a better understanding of the fault diagnosis process by end users, which in turn contributes to the facilitation of repairs for end users. The expanded framework of the diagnosis process provided in figure 2 describes two ways end users follow to diagnose their appliances. As a result, this study broadens the knowledge on the repair process by end users. The framework of the diagnosis process here presented can be relevant for design practitioners and manufacturers aiming to design easy-to-diagnose products in a circular economy. In addition, our study contributes with criteria to assess the guidance for the diagnosis of appliances provided in user manuals (table 3). While current Ecodesign regulations and product safety standards recommend that user manuals should support the user in solving common faults (see Introduction, paragraph 3), the analysis of the manuals has revealed that the content is currently insufficient to inform the user on frequently occurring faults. Based on this evidence and in view of facilitating product repairs for end users, it is recommended that future sustainable product policy provides clearer directions as to which faults should be diagnosed. The criteria presented in this study (table 3) could be a starting point.

Finally, it is important to bear in mind that this study was scoped to analyse the diagnosis process of household appliances. However, fault diagnosis in the case of other widely adopted consumer products might be different, especially in the case of fully electronic consumer products. Hence, we recommend that future studies look into other types of consumer products to further validate the framework of our diagnosis process. Moreover, future studies should examine the implications of the cause-oriented approach to existing design guidelines for diagnosis, and whether successfully diagnosing the appliances by either route would translate into better product care in the future. Furthermore, examining the impact of facilitating different levels of diagnosis information on a real-life repair-or-replace decision process would help designers, policy makers, and manufacturers better understand to what extent diagnosis information impacts a sustainable behaviour in comparison with other factors.

5.6. Conclusions

In this study, we addressed to what extent user manuals facilitate the diagnosis of frequently failing components. We examined 150 manuals of 4 different household appliances with regard to the top 5 occurring faults in appliances, and three steps towards the diagnosis of an appliance: fault detection, fault location, and fault isolation. The manuals insufficiently facilitate the diagnosis of common faults; most only address overdue maintenance and faults related to the internal state of electronics. Hardware failure due to other causes is rarely addressed.

Our research has led to an expansion of the framework for fault diagnosis. In addition to the component-oriented sequence of fault detection, fault location, and fault isolation, all aimed at pinpointing a specific faulty component, we observed a cause-oriented route to the sequence when a symptom (i.e. fault detection) could be directly related to a probable cause. This cause-oriented alternative is especially clear for those faults due to overdue maintenance and internal error states of electronics. This alternative provides users with a rapid, safe, and cheap way to solve a potential cause failure and successfully conclude the diagnosis process, especially if the cause is removed.

Our complete depiction of the diagnosis process, contributes to design practice, helping designers to consider both alternatives when facilitating the diagnosis process in products and in user manuals. Moreover, we present an example on how the inspection of components can be guided and facilitated without requiring disassembly, thus, with minimal risk for users. Similar approaches could be used for the diagnosis of components if the cause-oriented approach does not resolve the issue. Furthermore, the criteria used in this study can be used in future analyses and included in product reparability policy and requirements. This would assure that the most commonly occurring faults in appliances could be diagnosed by end users.

Declarations

Funding: This work was funded by the European Commission under the Horizon 2020 Marie Skłodowska Curie Action 2016 (Grant Agreement number 721909).

Conflict of Interests: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Availability of data and material: Supplementary material has been provided.

References

Baek, J.M., Ji, S.H., Koo, J.C., 2020. A cost effective on-site fault diagnosis method for home appliance rotor failures. Microsyst. Technol. 9. https://doi.org/10.1007/s00542-020-04892-9

Bracquene, E., Brusselaers, J., Dams, Y., Peeters, J., De Schepper, K., Dublou, J., Dewulf, W., 2018. Repairability criteria for energy related products.

Bracquené, E., Peeters, J., Alfieri, F., Sanfélix, J., Duflou, J., Dewulf, W., Cordella, M., 2021. Analysis of evaluation systems for product repairability: A case study for washing machines. J. Clean. Prod. 281, 125122. https://doi.org/10.1016/j.jclepro.2020.125122

Brusselaers, J., Bracquene, E., Peeters, J., Dams, Y., 2019. Economic consequences of consumer repair strategies for electrical household devices. J. Enterp. Inf. Manag. https://doi.org/10.1108/JEIM-12-2018-0283

Cifter, A.S., Dong, H., 2010. Instruction Manual Usage: A Comparison of Younger People, Older People and People with Cognitive Disabilities, in: Winter, R., Zhao, J.L., Aier, S. (Eds.), Global Perspectives on Design Science Research. pp. 410–425.

Cordella, M., Alfieri, F., Sanfelix, J., 2019. Analysis and development of a scoring system for repair and upgrade of products - Final report. https://doi.org/10.2760/725068

Flotynski, J., Strugala, D., Walczak, K., Englert, A., Maik, M., Nowak, A., Jenek, T., 2019. An immersive service guide for home appliances. IEEE Int. Conf. Consum. Electron. - Berlin, ICCE-Berlin 2019-Septe, 370–375. https://doi.org/10.1109/ICCE-Berlin47944.2019.8966215

Gök, O., Ersoy, P., Börühan, G., 2019. The effect of user manual quality on customer satisfaction: the mediating effect of perceived product quality. J. Prod. Brand Manag. 28, 475–488. https://doi.org/10.1108/JPBM-10-2018-2054

International Electrotechnical Commission, 2015. 192-06-20. Maint. Maint. Support Relat. concepts - Fault Diagnosis Defin. https://doi.org/10.1163/ej.9789004163300.i-1081.494

Jaeger-Erben, M., Frick, V., Hipp, T., 2021. Why do users (not) repair their devices? A study of the predictors of repair practices. J. Clean. Prod. 286, 125382. https://doi.org/10.1016/j.jclepro.2020.125382

Kluge, A., Termer, A., 2017. Human-centered design (HCD) of a fault-finding application for mobile devices and its impact on the reduction of time in fault diagnosis in the manufacturing industry. Appl. Ergon. 59, 170–181. https://doi.org/10.1016/j.apergo.2016.08.030

Koppius, O., Ozdemir, O., van der Laan, E., 2011. Beyond Waste Reduction: Creating Value with Information Systems in Closed-Loop Supply Chains. ERIM Rep. Ser. Res. Manag.

McCollough, J., 2009. Factors impacting the demand for repair services of household products: The disappearing repair trades and the throwaway society. Int. J. Consum. Stud. 33, 619–626. https://doi.org/10.1111/j.1470-6431.2009.00793.x

Morris, N.M., Rouse, W.B., 1985. Review and Evaluation of empirical research in troubleshooting. J. Hum. Factors Soc. 27.

Müller, L., Aslan, I., Krüßen, L., 2013. GuideMe: A Mobile Augmented Reality System to Display User Manuals for Home Appliances. pp. 152–167. https://doi.org/10.1007/978-3-319-03161-3_11

Patrick, J., 1993. Cognitive aspects of fault-finding training and transfer. Trav. Hum. 56, 187–209.

Petkova, V., 2003. An analysis of field feedback in consumer electronics industry. https://doi.org/10.6100/IR571923

Pozo Arcos, B., Bakker, C., Flipsen, B., Balkenende, R., 2020. Practices of fault diagnosis in household appliances: Insights for design. J. Clean. Prod. 265, 121812. https://doi.org/10.1016/j.jclepro.2020.121812

Pozo Arcos, B., 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. J. Clean. Prod. 128741. https://doi.org/10.1016/j.jclepro.2021.128741

Renaud, J., Houssin, R., Gardoni, M., Armaghan, N., 2019. Product manual elaboration in product design phases: Behavioral and functional analysis based on user experience. Int. J. Ind. Ergon. 71, 75–83. https://doi.org/10.1016/j.ergon.2019.02.003

Repair Cafe International Foundation, 2020. Repair Monitor - Analysis Results 2019.

Ritchie, J., Lewis, J., 2003. Qualitative Research Practice: A Guide for Social Science Students and Researchers.

Sabbaghi, M., Esmaeilian, B., Cade, W., Wiens, K., Behdad, S., 2016. Business outcomes of product repairability: A survey-based study of consumer repair experiences. Resour. Conserv. Recycl. 109, 114–122. https://doi.org/10.1016/j.resconrec.2016.02.014

Scott, K.A., Weaver, S.T., 2014. To Repair or Not to Repair: What is the Motivation? 1–31.

Tecchio, P., Ardente, F., Mathieux, F., 2019. Understanding lifetimes and failure modes of defective washing machines and dishwashers. J. Clean. Prod. 215, 1112–1122. https://doi.org/10.1016/j.jclepro.2019.01.044

The European Comission, 2019. Commission Regulation (EU) 2019/2023 laying down ecodesign requirements for household washing machines and household washer-dryers. Off. J. Eur. Union L 315/285.

The European Commission, 2020. A new Circular Economy Action Plan For a cleaner and more competitive Europe, COM(2020) 98 final.

The European Commission, 2019. Commission Regulation (EU) 2019/2022 laying down ecodesign requirements for household dishwashers pursuant. Off. J. Eur. Union L315/267.

The European Commission, 2001. Directive 2001/95/EC of the European Parliament and of the Council of 3 December 2001 on general product safety. Publ. Off. Eur. Union L11, 4–17.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

In this final chapter, I present and discuss the findings, contributions, and implications of my research as described in this thesis. I close by proposing new avenues of research.

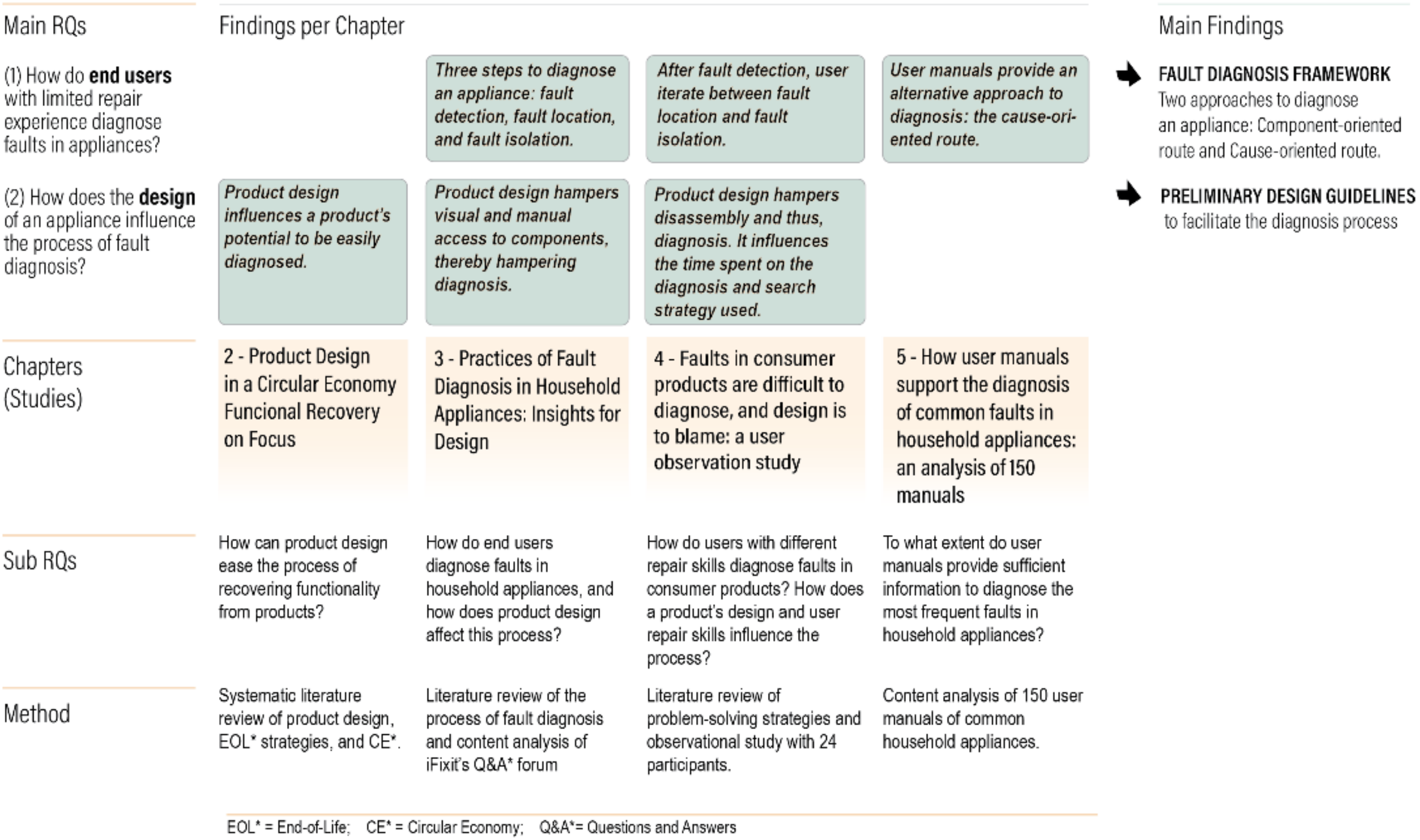
6.1. Summary of Findings

The research aims were to understand the steps end users follow to diagnose a malfunctioning appliance and how the design of an appliance affects this diagnosis process. Consequently, I addressed two main research questions:

1. How do end users with limited repair experience diagnose faults in household appliances?
2. How does the design of a household appliance influence the process of fault diagnosis for end users?

We analysed different sources of data to address both questions, including scientific and grey literature and diagnosis instructions from a repair forum and advice from user manuals. Moreover, we conducted a user observational study where participants were asked to think aloud. Table 6.1 gives an overview of the main findings from each chapter.

Table 6.1 presents the results of each of the studies structured as two main topics, which reflect the main research questions. The different analyses ultimately resulted in two main outcomes: a framework describing the fault diagnosis process followed by end users, and a set of preliminary design guidelines for fault diagnosis. Both results are discussed in the next section



Main RQs	Findings per Chapter				Main Findings
(1) How do **end users** with limited repair experience diagnose faults in appliances?		*Three steps to diagnose an appliance: fault detection, fault location, and fault isolation.*	*After fault detection, user iterate between fault location and fault isolation.*	*User manuals provide an alternative approach to diagnosis: the cause-oriented route.*	**FAULT DIAGNOSIS FRAMEWORK** Two approaches to diagnose an appliance: Component-oriented route and Cause-oriented route.
(2) How does the **design** of an appliance influence the process of fault diagnosis?	*Product design influences a product's potential to be easily diagnosed.*	*Product design hampers visual and manual access to components, thereby hampering diagnosis.*	*Product design hampers disassembly and thus, diagnosis. It influences the time spent on the diagnosis and search strategy used.*		**PRELIMINARY DESIGN GUIDELINES** to facilitate the diagnosis process
Chapters (Studies)	2 - Product Design in a Circular Economy Funcional Recovery on Focus	3 - Practices of Fault Diagnosis in Household Appliances: Insights for Design	4 - Faults in consumer products are difficult to diagnose, and design is to blame: a user observation study	5 - How user manuals support the diagnosis of common faults in household appliances: an analysis of 150 manuals	
Sub RQs	How can product design ease the process of recovering functionality from products?	How do end users diagnose faults in household appliances, and how does product design affect this process?	How do users with different repair skills diagnose faults in consumer products? How does a product's design and user repair skills influence the process?	To what extent do user manuals provide sufficient information to diagnose the most frequent faults in household appliances?	
Method	Systematic literature review of product design, EOL* strategies, and CE*.	Literature review of the process of fault diagnosis and content analysis of iFixit's Q&A* forum	Literature review of problem-solving strategies and observational study with 24 participants.	Content analysis of 150 user manuals of common household appliances.	

EOL* = End-of-Life; CE* = Circular Economy; Q&A*= Questions and Answers

Table 6-1 - Overview of research questions, main findings, and research methods

6.2. Fault diagnosis of household appliances by end users

The first research question addressed in this thesis is: How do end users with limited repair experience diagnose faults in appliances? We conducted three studies to answer this question; see chapters 3, 4, and 5. The findings led to the development of a framework describing the processes users follow to diagnose a fault in household appliances. Two distinct routes were identified: the cause-oriented route and the component-oriented route (see figure 6.1).

The end user fault diagnosis process starts with fault detection (see figure 1). Users notice a failure in the appliance, i.e., it does not perform as required, and identify one or more symptoms. We identified five main types of symptoms appliances can present : (a) under-performance, (b) absence of response to commands, (c) abnormal inbuilt signals e.g., noise, smells, (d) designed signals e.g., designed blinking lights or symbols, and (e) intermittent performance. These are described in more detail in chapter 3.

After fault detection, two different approaches to diagnosis can be distinguished: the component-oriented route and the cause-oriented route. The component-oriented route consists of fault location and fault isolation. This route aims to identify the defective component in the appliance. During fault location, users relate the symptoms to potentially defective components. They use a range of approaches to determine the possibly defective components, for instance, design cues in the product's architecture, knowledge about how the appliance works, or their experience from previous repairs. Once the fault is located, fault isolation takes place. Users then check the condition of the suspected components and, when the defective component is identified, the fault has been diagnosed. The next step is to repair or replace the defective component, followed by testing the appliance's functionality to confirm the component has been repaired.

The second route to diagnosis we identified is the cause-oriented route. After fault detection, symptoms are related to possible causes of failure. Instead of searching for specific components, this route aims to help users directly restore the functionality of the appliance. Next, they check whether the appliance works. A successful functional test means that the appliance has been repaired. However, if the appliance still malfunctions, users need to restart the diagnosis process.

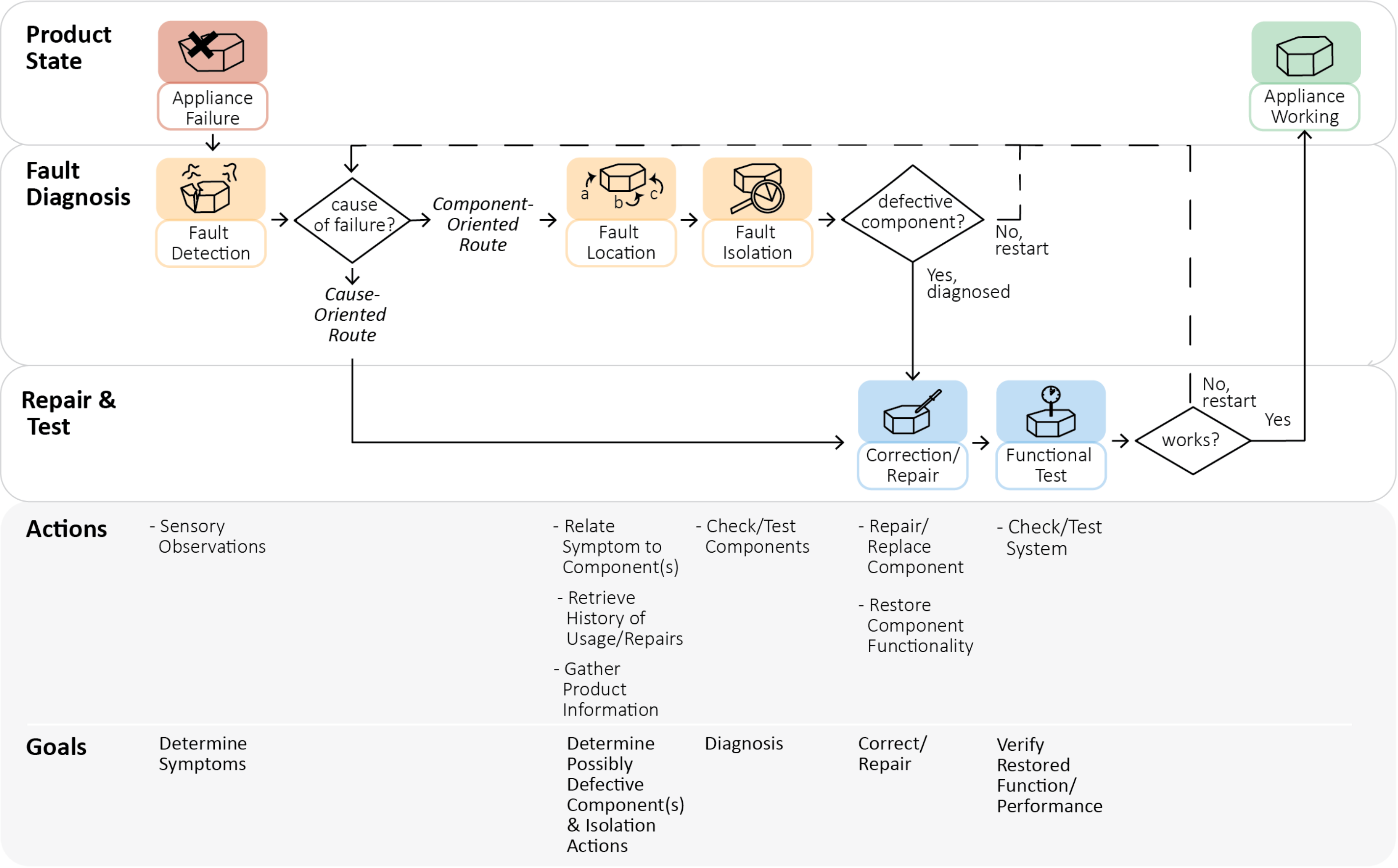


Figure 6-1 Framework of the process of fault diagnosis in household appliances as performed by end users

This description of the diagnosis framework is a good reflection of the definition of fault diagnosis by the International Electrotechnical Commission. The commission defines fault diagnosis as "*the action to identify and characterize the fault. Fault diagnosis may also localize the fault and/or indicate its cause"* (International Electrotechnical Commission, 2015). In the framework, the component-oriented route localizes the fault in a particular component, and the cause-oriented route indicates a cause of failure.

The framework is also in line with descriptions of the process in the literature. The component-oriented route contains the three stages of diagnosis described by, amongst others, Davidson, (2004), Khaksari, (1988), and Mostia William L., (2006). However, it differs from descriptions presented in the literature, as it is not product-specific and from those presented by technicians like Bereiter and Miller, (1989) and Patrick, (1993). However, our description provides a broader and more generalizable understanding of the diagnosis process.

Apart from describing the processes end users follow to diagnose a household appliance, we also explored how end users go through the component-oriented route in more detail. We found that end users generally needed guidance. Member of iFixit's forum asked for help to locate the faults after fault detection (chapter 3), and participants in the user observation study needed hints to continue the disassembly process (chapter 4). Difficult access to components hampered fault location and fault isolation. Furthermore, despite the hints, many could not find the defective component in the appliance in a reasonable time-period (i.e., less than 40min).

The process taken by users to diagnose a fault resembles a generic problem-solving process (Angeli, 2010; Jonassen and Hung, 2006). In chapter 4, end users followed and iterated between different search strategies described in literature (Jonassen and Hung, 2006; Kluge and Termer, 2017). Moreover, participants used design cues to understand how the appliance was constructed. This was similar to gathering information about the system to 'troubleshoot a problem' (Jonassen and Hung, 2006). Further, chapter 4 showed how repair skills facilitated disassembly, including the phases of fault location, and fault isolation, supporting findings by Morris and Rouse, (1985). Knowing how to replace a component and having knowledge about the system is helpful for diagnosis. However, our results show that the design cues were insufficient to guide users, and that accessing components was difficult (chapters 3 and 4). Thus, in the case of household appliances, following a component-oriented route is a "difficult problem to solve" for end users. For an efficient diagnosis process, end users without training in repair or troubleshooting need guidance whether that is from the system itself or from some form of support.

In this thesis, we discuss two types of currently available end user support. We analysed the guidance provided in user manuals (chapter 5), and from technical repair forums (chapter 3). Guidance provided in user manuals only facilitates a cause-oriented route (chapter 5). Manuals rarely included other faults than those resulting from overdue maintenance or internal error state (for electronic systems). In forums, on the other hand, both diagnosis routes were addressed (chapter 3) and the instructions given led to a greater number of faults being diagnosed. In the forums, up to ten possible causes of failure were related to a symptom, whereas in manuals, a symptom was related to one or two possible causes of failure at most. The analyses of the forum and the user manuals also show that the most adequate route for diagnosis depends on the nature of the fault. The cause-oriented route makes most sense if two main conditions apply. First, there must be a strong coupling of symptom and cause. Second, correcting the malfunction is relatively easy and inexpensive. The component-oriented route, on the other hand, requires that faults need to be located and isolated which is necessary when there is no obvious or clear relationship between symptoms and cause. This might require appliance disassembly which can be time-consuming and (for relatively inexperienced users) challenging. Nonetheless, the findings suggest that both routes are necessary for the diagnosis of common faults in household appliances.

6.3. The influence of product design on the process of fault diagnosis

The second research question addressed in this thesis is: How does the design of an appliance influence the process of fault diagnosis for end users? We answered this question after gaining an initial understanding of the diagnosis process. Hence, steps and actions that end users perceived as difficult or easy were related to design features. The studies show that the design of appliances affects the diagnosis process in two ways. Design can: (1) affect the feasibility of the diagnosis steps, and (2) provide guidance to follow the diagnosis steps.

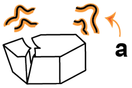
We found that the design of the appliances often impeded a successful fault diagnosis. In chapter 3, we show that design features hampered visual and manual access to components. As a result, fault location and fault isolation were difficult to perform. The observational study (chapter 4) showed similar results. Hidden snap-fits and deeply recessed fasteners hindered the disassembly process to the extent that many users required hints to continue. Some even stated that they would give up the process due to the frustration caused by difficult product disassembly. As a result, fault location and isolation were also difficult to perform. On the other hand, in the same chapter, we show that certain features could guide users through the diagnosis. For instance, textual feedback signals directed participants to a possibly defective component. However, the average time spent on the diagnosis exceeded 20min, which shows that guidance for diagnosis is uncommon. Moreover, the meaning of the feedback signals of some appliances was unclear for some participants at iFixit's forum (chapter 3).

Our findings support those from expert repairers and grassroot associations. The current design of products generally hampers repairs (iFixit, 2019; Repair Cafe International Foundation, 2020; Tecchio et al., 2016). We add that the design of household appliances also hampers the diagnosis process. For this reason, and the dearth of diagnosis guidelines, in chapter 4, we proposed the following set of guidelines:

a. Facilitate fault detection and symptom-to-cause deduction by giving timely and understandable feedback which does not require product specific knowledge
b. Facilitate navigating through the product's construction
c. Facilitate the inspection of product components
d. Minimise the need to disassemble the product
e. If product disassembly is needed, facilitate it

In chapter 5, we describe additional insights that motivate our guidelines reformulation and extension. Analysis of the user manuals showed both the cause-oriented diagnosis route and component-oriented route. The latter could be facilitated without disassembly. We anticipated that facilitating inspection without disassembly would greatly contribute to an easy diagnosis process. In chapter 4, we show that disassembly is a major barrier for diagnosis. Hence, we reformulated guidelines *c, d,* and *e* to distinguish between inspection with and without disassembly. As a result, in we propose four guidelines to ease the diagnosis process, taking all previous findings into account (see figure 6.2).

1



FACILITATE FAULT DETECTION AND SYMPTOM-TO-CAUSE DEDUCTION BY GIVING TIMELY AND UNDERSTANDABLE FEEDBACK

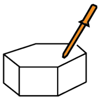
Designers can ease fault detection and symptom-to-cause deduction by providing audio and textual cues. For instance, designers can guide and educate end users on the sounds the appliances make during a working cycle. Moreover, text signals can communicate the process the appliance is executing, thereby providing guidance and understanding in case of a fault.

2

FACILITATE INSPECTION OF COMPONENTS WITHOUT THE NEED FOR DISASSEMBLY

Designers can avoid the need to disassemble the appliance by providing lids and doors to access the components. Including testing points in the components can also ease checking their condition. Moreover, making faults visible through the material's casing can also ease inspection without disassembly.

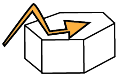
3



FACILITATE DISASSEMBLY AND REASSEMBLY IF NEEDED FOR INSPECTION

Designers can ease disassembly and reassembly by considering the fastener types and their access. For instance, fasteners would be preferable to adhesives. Fasteners prone to damage and breakage during removal should also be avoided (Pozo Arcos et al., 2018).

4



FACILITATE NAVIGATION OF THE PRODUCT'S CONSTRUCTION

Designers can help users navigate the appliance. In particular, the arrangement of components can guide users through different paths. For example, if components that are likely to fail are located on the surface, they can be quickly identified. Another possible arrangement could be one that guides the user through the input-output flow of materials. This would communicate existing relationship between components.

Figure 6.2 - Design guidelines for diagnosis.

Guideline 1 is comparable to guideline *a* from chapter 4. It is relevant for both diagnosis approaches: the component-oriented and the cause-oriented. This guideline aims to get end users to start the diagnosis on the right foot. The fault detection step highly influences subsequent actions in the diagnosis process. Hence, this guideline not only aims to ease fault detection, but also help users relate the symtpom to a cause or component. Design features like feedback signals can help fault detection and can direct users to thefault's location.

Guideline 2 is the result of amalgamating guidelines *c* and *d*. It aims to make the component-oriented route accessible to a greater number of users. Chapter 4 showed how product disassembly was perceived as a major barrier for fault location and isolation. Hence, by avoiding disassembly, the steps can be performed more quickly. Moreover, the need for repair skills will be reduced. Design features like testing points or doors to access components can help achieve this.

Guideline 3 acknowledges that, when following a component-oriented route, disassembly may be unavoidable for certain faults. This guideline is comparable to guideline *e.* If disassembly is needed for inspection, it should be easy and reversible. Thus, reassembly should be facilitated to ensure that products are reliable and can be used again after repair. The choice of fasteners and arrangement of the components are the design features relevant to achieving this aim. This guideline overlaps with guidelines for design for disassembly relevant for product repairs. An overview of guidelines for disassembly and reassembly can be found in Pozo Arcos et al., (2018).

Guideline 4 is comparable to guideline *b.* It aims to facilitate a component-oriented route. During fault location and isolation, users need to understand how the product works and is constructed. This helps them to deduce possible causes of failure and identify access points to the components. Design features can help achieve these aims. For instance, the arrangement of components can reveal how the appliance works and guide users through the disassembly process. For example, the position of fasteners serves as a cue to disassembly; providing visual cues for users to find their way through the product is an important aspect of a product's reparability (Flipsen et al., 2019).

These guidelines for diagnosis partly overlap with guidelines for repair. Design for disassembly is a common denominator of diagnosis and repair. As we have shown, for certain types of faults, disassembly may be needed for diagnosis. Nonetheless, guidelines for diagnosis, unlike guidelines for component repair, emphasize communicating the state of the product and its components to the user. The guidelines ease the process and reduce the time spent on diagnosis in order to avoid disassembly when possible.

These four guidelines have not yet been tested in practice. But we expect that they will help designers adapt or redesign consumer products to ease the diagnosis process. The guidelines have been related to specific design principles and design features from marketed appliances (chapters 3 and 4). Hence, the means to achieve an easy diagnosis should be familiar to design practitioners. Moreover, the number of guidelines has been limited to four to provide clear and simple directions. Furthermore, despite the studies' focus on household appliances, it is expected that these guidelines will be applicable for a broader range of consumer products. As long as the diagnosis process remains the same, and product features are comparable to those presented in the appliances, the directions provided in the guidelines should be applicable and relevant.

6.4. Fault diagnosis for stimulating repairs

In this thesis, I set out to understand the fault diagnosis process that end users follow when appliances breakdown and how product design affects this process. Both aims were set in view of stimulating product repairs and to support the transition towards a circular economy. Based on the insights gained, it can be concluded that the process of diagnosis is one of the initial steps in the repair of a product, but currently for end users, it is difficult to perform without guidance. The design of the appliances makes the process difficult to perform. Accessing the components for fault location and isolation is difficult and requires repair skills. Moreover, users lack guidance to deduce possible causes of failure related to frequently occurring faults. The official guidance provided in manuals is generally limited to facilitating a cause-oriented route. Hence, the only faults that are easy to diagnose are those due to overdue maintenance. Nonetheless, both diagnosis routes are needed to diagnose frequent faults in the appliances.

In the case of household appliances, facilitating both routes to diagnosis makes sense. Household appliances are more likely to be replaced due to a functional failure than due to a novelty trend (Jaeger-Erben et al., 2021). Hence, providing users with insights into the nature of the fault, as the diagnosis process does, could potentially translate into more repairs. A transparent diagnosis would allow users to estimate the cost and time needed, and the expected lifespan after the repair. It would enable them to make an informed decision on whether to repair an appliance or not. However, how end users can best be facilitated to perform a successful diagnosis remains a question. Here we present four possible ways.

Facilitating fault diagnosis could become a reparability requirement in Ecodesign Regulations. For example, manuals could instruct both routes to diagnosis so that end users would be able to diagnose common faults. This would be in line with the European Commission's aim to empower consumers to repair products and the shift towards a circular economy (The European Commission, 2020). Ecodesign regulations have been amended in view of increasing product reparability, however facilitating the diagnosis of common faults is not yet a requirement (see washing machines Ecodesign Regulation (The European Comission, 2019). Nonetheless, fault diagnosis could be a valuable addition to reparability policy given that it provides transparency to the repair process. This would in principle allow end users to follow both diagnosis routes.

Another way to help end users with the diagnosis process would be to adapt peripherals to guide the diagnosis. Recent studies have investigated how to adapt digital systems, e.g. smartphones and/or augmented reality, to ease the diagnosis of appliances (Baek et al., 2020; Müller et al., 2013). This opens up additional means to ease the diagnosis for end users. Products are becoming increasingly connected, automated, and integrated. They are starting to resemble monitored systems, hence, this alternative could be potentially easy to adopt.

Diagnosis would also be easier for end users if they were educated on how to diagnose and repair. This is in line with recommendations provided by repair associations (Repair Cafe International Foundation, 2020). They suggest teaching repair skills at schools to overcome the lack of repair knowledge they see in their visitors. They also recommend incentivising maintenance practices through public campaigns. Educating consumers is also in line with recent findings on consumer attitudes towards product care. Ackermann, (2020) reported on the declared lack of knowledge on product care by some of the participants, suggesting this could be overcome if companies shared the responsibility of product care with consumers. For example, companies could provide tutorials or workshops to increase end users' ability to care for their products. Furthermore, public campaigns could help increase awareness of the importance of taking care of the appliances and repairing them to reduce waste.

An additional way to ease the diagnosis would be to rethink the design of products. This could be especially relevant for small household appliances given the low rates of maintenance and repair (Harmer et al., 2019; Pérez-Belis et al., 2017; Stamminger and Hennies, 2016). Ackermann (2020) proposed a number of design-related strategies to incentivise better product care. Similarly, products could be redesigned to make fault diagnosis easier and increase repair rates. Based on recent research on consumer attitudes towards repair, e.g., Berge et al (2021), Jaeger-Erben et al. (2021) and Terzioğlu, (2021), a design that increases repair rates should be perceived as requiring low effort, little time, and low skills. These are technical barriers commonly perceived by consumers when deciding on whether to repair. However, fulfilling these three requirements might be difficult to achieve for certain faults. Thus, for a majority of users, design for diagnosis should focus more on enabling a conscious decision regarding repair than on self-repair.

In principle, all these options are technically feasible and could be adopted. Facilitating the diagnosis of common faults seems a sensible first step to stimulating repairs. Yet, simply enabling diagnosis may not translate to more repairs unless users accept and adopt the practice, as suggested by research into consumer behaviour where studies show there are stigmas associated to repairs. For example, some people associate repair with financial struggle (Terzioğlu, 2021). Moreover, some consumers negatively perceive products that are easy to repair, associating them with shorter lifespans (Berge et al., 2021). Thus, actions that lead to a changed user attitude on repair are also needed. Moreover, manufacturers and policymakers need to ensure adequate repair infrastructures, otherwise, repair becomes impracticable (Jaeger-Erben et al., 2021).

In conclusion, in this thesis, I present two approaches to diagnose household appliances. Both have their merits and drawbacks, but both are needed for diagnosis. Hence, a component-oriented route should be better supported. I show that there are different ways in which diagnosis can be facilitated for end users, however that technically enabling fault diagnosis may not necessarily lead to more repairs. Actions for consumer acceptance and adequate infrastructure also need to be in place. Future research must explore the impact of the adoption of different measures in user behaviour towards repair. Furthermore, the impact of facilitating diagnosis in available repair infrastructures should also be investigated.

6.5. Contribution to scientific knowledge

This thesis contributes to research in the fields of end user (consumer) repair practices and to design for diagnosis. Consequently, it also contributes to design for repair and product life extension. Earlier research on consumer repair practices has examined barriers and motivations repair products, but not the repair practice itself. The user perspective between the occurrence of a failure in an appliance and the actual decision to repair remained unexplored. Hence, it was unclear whether users could know what was wrong with their appliance when a failure occurred i.e., fault diagnosis.

Likewise, research on design for repair assumed that repairers knew which component needed to be repaired. The studies were geared towards understanding how to ease component replacement, however how design can affect the process of diagnosing an appliance was not considered. Thus, the main contributions of this thesis are twofold: (1) a novel framework of the fault diagnosis process followed by end users when diagnosing a household appliance (depicted in figure 6.2.); and (2), empirical evidence on the difficulties set by design for end users during the diagnosis process. In this way, our findings support the user's perspective from failure to actual repair and provide insights to how design can ease the diagnosis process for end users.

6.6. Implications for design practice

A central topic in this thesis is the influence of product design on the fault diagnosis process. Apart from contributing with scientific knowledge, we aim to provide guidance for designers aiming to design repairable products. We have developed a set of guidelines that ease fault diagnosis (figure 6.2). Its implementation needs to be tested, but they serve as a preliminary guidance on key aspects that need to be easy to perform in products. They will help product conceptualization and can be relevant when redesigning product to increase its reparability. Facilitating diagnosis can bring products a step closer to an easy repair. Moreover, we also contribute with a schematic representation of the diagnosis process presenting two routes to diagnosis (figure 6.1.). The framework can help designers understand the process users take from failure to diagnosis thereby providing guidance for the diagnosis.

The findings in this thesis reveal that diagnosis is currently insufficiently supported. Initial efforts to better support diagnosis should start by facilitating the diagnosis of the five most common faults.

6.7. Implications for policy

Currently, European sustainable product policy aims to empower consumers to take part in circular practices. The Circular Economy Action Plan presented in 2020 by the European Commission gave directives towards a new ‘Right to Repair’ for consumers. In 2019, after the adoption of the CE working plan, eco-design regulations of washing machines, dishwasher, electronic displays, and refrigerators were amended to include reparability requirements. Moreover, the same year, France announced the adoption of regulations on the mandatory display of a reparability score in products. Since 2021, this has been applied to five products: smartphones, laptops, televisions, washing machines, and lawnmowers.

The Ecodesign regulation is currently the tool to establish circular economy requirements in products. In particular, material efficiency requirements refer to the implementation of a circular economy. Current Ecodesign requirements focus on spare part availability and on information on maintenance and repair. The regulation distinguishes between the type of information available to users and to professional repairers. For end-users, it stipulates that user manuals should include maintenance information e.g., correct installation and care of products, and identification of errors, their meaning, and corrective actions.

In chapter 5, we describe the content of user manuals of products available on the market on January 2021. New eco-design regulations had not yet been enforced. Nonetheless, the eco-design requirements on user manuals are already being fulfilled. They instruct users on how to perform maintenance tasks and identify errors codes from the machine. In this way, they facilitate a cause-oriented route. However, as chapter 5 also shows, this would be insufficient to facilitate the diagnosis of the five most common faults in appliances. Hence, the user would still be unable to rely on the manufacturer’s information to diagnose their appliances. This is evidence that current regulatory requirements are insufficient to ensure a transparent diagnosis for end users. Therefore, we recommend that with a view to empowering consumers in their right to repair, to include the facilitation of the diagnosis of common faults as a reparability requirement.

6.8. Future studies and recommendations

This thesis contributes by providing a framework of the diagnosis process and a set of design guidelines for diagnosis. These open up the opportunity for future research to (1) extend the scope of the framework to other types of products, (2) other types of repairers, to (3) test and examine the use of guidelines for diagnosis in practice, and (4) to examine the influence of the diagnosis process in subsequent repair steps. Hence, we propose the following research topics:

Investigate diagnosis process for electronic products. The studies in this thesis examined the diagnosis process in electromechanical appliances. However, the diagnosis process for electronic products may be different, for example being highly reliant on software and need peripherals. This approach was out of the scope of this thesis, nonetheless, it is important to understand it given the increasing number of electronic products. Facilitating diagnosis could facilitate reusability and upgradability of electronics.

Investigate the diagnosis process by professional repairers and whether it affects the design of household appliances. In this thesis, we focused on end users with low repair skills. Professional repairers were not included. Nonetheless, understanding how repairers act may provide relevant insights for designers on how to make diagnosis more efficient. Do they follow the same diagnosis process? Do designers consider ‘professional’ diagnosis in their appliances? Moreover, given the reliance on software for diagnosis and the increasing adoption of electronics, the findings could be relevant in view of facilitating diagnosis of electronics.

Investigate the implementation of design guidelines. In this thesis, we propose a set of four design guidelines for diagnosis however, these have not been used in practice. Hence, the usability and validity of the guidelines still needs to be tested. Can these guidelines be used in practice? Do they result in easier to diagnose products? To what extent can the diagnosis process be facilitated following these guidelines? For instance, it would be relevant to know whether some should be prioritized over others. And, how this would affect the diagnosability of the product for end users and professional repairers?

Examine the influence of fault diagnosis in the repair-or-replace decision-making process. The process of fault diagnosis opens the door towards more transparent repairs. However, we did not study how this would influence the end users’ repair or replace decision. It would therefore be relevant to gain a better understanding of these issues to provide guidance for designers and stimulate more repairs. For instance, would end users be keener to repair if they knew which component failed?

References

Ackermann, L., 2020. Design for Product Care. TU Delft Univ. https://doi.org/10.4233/uuid:9fe0a3cd-a7f7-4d29-bb44-6dc78575a2e8

Angeli, C., 2010. Chapter 4: Diagnostic Expert Systems: From Expert's Knowledge to Real-Time Systems, Advanced Knowledge Based Systems: Model, Applications & Research. Jones & Bartlett Learning.

Baek, J.M., Ji, S.H., Koo, J.C., 2020. A cost effective on-site fault diagnosis method for home appliance rotor failures. Microsyst. Technol. 9. https://doi.org/10.1007/s00542-020-04892-9

Bereiter, S.R., Miller, S.M., 1989. A Field Based Study of Troubleshooting in Computer-Controlled Manufacturing Systems. IEEE Trans. Syst. Man Cybern. 19, 205–219. https://doi.org/10.1109/21.31027

Berge, R. Van Den, Magnier, L., Mugge, R., 2021. A poorly educated guess : c onsumers ' lifetime estimations , attitudes towards repairability , and a product lifetime label.

Davidson, H.L., 2004. Troubleshooting and Repairing Consumer Electronics- 3rd edition. TAB electronics.

Flipsen, B., Huisken, M., Opsomer, T., Depypere, M., 2019. IFIXIT Smartphone Reparability Scoring: Assessing the Self-Repair Potential of Mobile ICT Devices. PLATE Conf. 2019 18–20.

Harmer, L., Cooper, T., Fisher, T., Salvia, G., Barr, C., 2019. Design, Dirt and Disposal: Influences on the maintenance of vacuum cleaners. J. Clean. Prod. 228, 1176–1186. https://doi.org/10.1016/j.jclepro.2019.04.101

iFixit, 2019. Repair Market Observations: iFixit's testimony to the FTC.

International Electrotechnical Commission, 2015. 192-06-20.

Jaeger-Erben, M., Frick, V., Hipp, T., 2021. Why do users (not) repair their devices? A study of the predictors of repair practices. J. Clean. Prod. 286, 125382. https://doi.org/10.1016/j.jclepro.2020.125382

Jonassen, D.H., Hung, W., 2006. Learning to troubleshoot: A new theory-based design architecture. Educ. Psychol. Rev. 18, 77–114. https://doi.org/10.1007/s10648-006-9001-8

Khaksari, G., 1988. Expert Diagnosis System, in: First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems. pp. 43–53.

Kluge, A., Termer, A., 2017. Human-centered design (HCD) of a fault-finding application for mobile devices and its impact on the reduction of time in fault diagnosis in the manufacturing industry. Appl. Ergon. 59, 170–181. https://doi.org/10.1016/j.apergo.2016.08.030

Morris, N.M., Rouse, W.B., 1985. Review and Evaluation of empirical research in troubleshooting. J. Hum. Factors Soc. 27.

Mostia William L., J., 2006. Troubleshooting - A Technician's Guide (2nd Edition). ISA.

Müller, L., Aslan, I., Krüßen, L., 2013. GuideMe: A Mobile Augmented Reality System to Display User Manuals for Home Appliances. pp. 152–167. https://doi.org/10.1007/978-3-319-03161-3_11

Patrick, J., 1993. Cognitive aspects of fault-finding training and transfer. Trav. Hum. 56, 187–209.

Pérez-Belis, V., Braulio-Gonzalo, M., Juan, P., Bovea, M.D., 2017. Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment. A Spanish case study. J. Clean. Prod. 158, 261–275. https://doi.org/10.1016/j.jclepro.2017.04.143

Pozo Arcos, B., Balkenende, A.R., Bakker, C.A., Sundin, E., 2018. Product Design for a Circular Economy : Functional Recovery on Focus 2727–2738.

Repair Cafe International Foundation, 2020. Repair Monitor - Analysis Results 2019.

Stamminger, R., Hennies, L., 2016. An empirical survey on the obsolescence of appliances in German households. Resour. Conserv. Recycl. 112, 73–82. https://doi.org/10.1016/j.resconrec.2016.04.013

Tecchio, P., Ardente, F., Mathieux, F., 2016. Analysis of durability, reusability and reparability - Application to dishwashers and washing machines, EUR 28042 EN. https://doi.org/10.2788/51992

Terzioğlu, N., 2021. Repair motivation and barriers model: Investigating user perspectives related to product repair towards a circular economy. J. Clean. Prod. 289. https://doi.org/10.1016/j.jclepro.2020.125644

The European Comission, 2019. Commission Regulation (EU) 2019/2023 laying down ecodesign requirements for household washing machines and household washer-dryers. Off. J. Eur. Union L 315/285.

The European Commission, 2020. A new Circular Economy Action Plan For a cleaner and more competitive Europe. Commun. FROM Comm. TO Eur. Parliam. Counc. Eur. Econ. Soc. Comm. Comm. Reg.

About the author

Beatriz Pozo Arcos has made sustainable living a practice and a life purpose. Since she was a child, her family has instilled in her a love and respect for nature. Repairing and caring for the world around her is still one of her core values and a philosophy of living. In 2009, she started her studies in Industrial Engineering at her hometown university, the University of Castilla-La Mancha in Ciudad Real, Spain. She spent a year abroad at the Institute National des Sciences Appliques (INSA) in Lyon, France. She followed a program focused on the Design and Development of Mechanical Products. She finished her Master Thesis back in her hometown with a project on the redesign of the injection nozzle for industrial explosion-suppression systems.

Beatriz gained professional experience taking up an internship position as a buyer in the product development team of a multinational sports wear firm. She also worked doing an assistantship at Beijing Foreign Studies University, Beijing, China. Upon its completion, she turned her professional interest towards positions in the field of sustainability. She applied for a PhD position on the topic of design for a circular economy with the aim to contribute to a more sustainable world. She started her PhD candidature in November 2016 as part of the Marie Sklodowska-Curie Innovative Training Network. In particular, she followed the CircEUit program. During her PhD, she published several journal articles, attended international conferences, and was involved in coaching activities with design students. Next to her PhD, she volunteered at the Repair Café in Rotterdam, repaired Technics SL1200 record players, and deepened her love for movies, yoga, and ramen.