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ORIGINAL PAPER

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

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Abstract
Product repairs are at the core of sustainable consumption and user manuals can play a relevant role in facilitating them. They are the accredited source of product information for end users and are therefore sought as an important means for the diagnosis and subsequent repair of household appliances. However, 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. 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 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 a 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.

Keywords Troubleshooting · Fault diagnosis · Design for repair · Circular economy · Product design · Sustainable consumption

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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 [9]. 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 [2]). Repairs have a low environmental impact, and in the case of small household appliances, tend to be a better option than replacement. Extending the life of products requires little energy and few resources [7] and contributes to a reduction of energy associated with new productions [31]. 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 [31]. Hence, the societal, economic, and environmental impact of repairs makes them not only a circular economy strategy, but also a sustainable choice [21].

The process of fault diagnosis is important to facilitate repairs in a circular economy. It is "the action to identify and characterise the fault" (IEC, 192–06-20, [12]). In other words, it reveals what needs to be repaired in a product. It 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 [14, 19, 22]. 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 [5, 18, 29, 30]. 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 [13, 16, 33].

Guidance during the diagnosis process procures a more effective outcome [14]. A recent study showed that, for end users, guidance is decisive in successfully diagnosing the faults in malfunctioning appliances [24]. 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 [34], and dishwashers in [36] 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 [35] are expected to include similar requirements. Likewise, reparability analysts and researchers have indicated that manufacturers should provide diagnosis information to facilitate repairs [27, 32]. They concur that user manuals can better support the diagnosis process if they, at least, provide sufficient information to diagnose common faults [3, 8]. Moreover, product safety standards recommend that manufacturers provide diagnosis information in user manuals. [37] 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) [17] recommends that manuals include information to correct potential product failures. Hence, manuals should facilitate the diagnosis and correction of potential product failures to facilitate product repairs.

However, up to now, far too little attention has been paid to analysing which common product faults are included in the manuals, and how their diagnosis and correction is facilitated.

Previous academic studies on the content of user manuals examine topics like the usability and accessibility of manuals [6], their effect on customer satisfaction [11], how the content should be developed for optimal product use [26], or how alternative media such as virtual and augmented reality can be used to present the manual's information [10, 20]. 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 [4, 24, 29]. Therefore, it remains unclear how much support manuals provide to end users regarding the diagnosis of malfunctioning appliances. To date, no studies have examined this claim in detail.

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 (the "Method" section), we describe the method we employed for the analysis. In the "Results" section, we report the results of our analysis. In the "Discussion" section, we discuss the results; and in the "Conclusions" section, we present our conclusions.

Method

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

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).

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, and 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

Table 1 Criteria to select the 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's 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

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

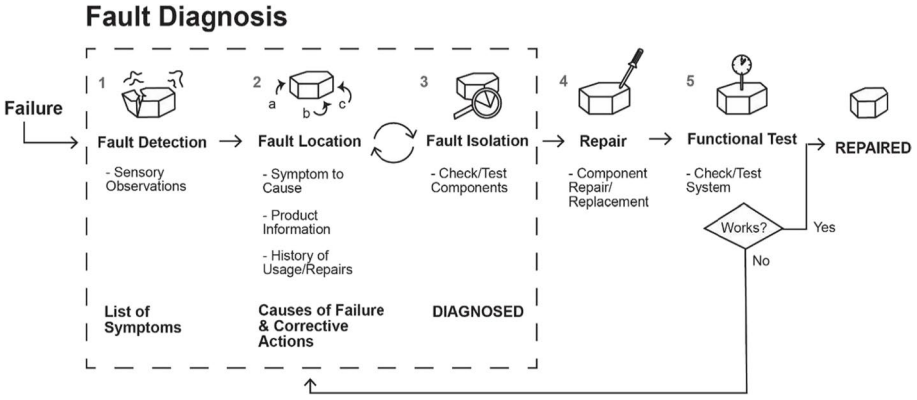

Fig. 1 Framework of the diagnosis process performed by end users

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.

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. [25] (see Fig. 1). We selected this framework because it is the most accurate representation available of the diagnosis process by end users of a household appliance. It is based on a literature review and has been refined and validated with 24 participants during an observatory study (Ibid).

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.

A manual that facilitates the diagnosis process would be expected to guide the user through these consecutive steps. Hence, 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 [25]. 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.

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 [24, 32], and reports from consumer and repair associations like Test ankoop, Which?, and the Repair Cafe [3, 27]. 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]".

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,

Table 3 Criteria for the analysis of user manuals

Criteria for analysing the guidance provided by 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

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 ($N=19{,}000$) Which? 2015 ($N=637$) Repair Monitor 2020 ($N=699$)
	Hose	
	Engine	
	Power cable and plug	
	Rewinding mechanism	
Washing machines	Electronics	[32] ($N=9492$)
	Shock absorbers and bearings	
	Door	
	Carbon brushes*	
	Pumps	
	Engine*	
	Drain system	
Refrigerator	Electronics	[24] ($N=117$)
	Condenser coils	
	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. [32],some components reported as frequently failing are no longer embodied in modern washing machines. These have been marked with an asterisk. 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

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 [28].

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.

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).

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).

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 electronic 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).

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).

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.

Discussion

In this study, we aimed to analyse to what extent user manuals facilitate the diagnosis of the most 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. The manuals only facilitate the diagnosis and correction of faults caused by a lack of maintenance, or that are due to an internal

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 cause of failure: 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. One manual referred to a defective sensor as the possible location of the fault
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 faults 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	Demagnetised 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

state failure of electronic components. 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, and instead referred to the most likely cause of failure in the appliance, e.g. limescale. Last, we observed that the fault isolation step 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. Therefore, 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 Fig. 2).

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).

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 failing components in vacuum cleaners are the filters, the hose, the engine, the power cable and plug, and the rewinding mechanism. All the manuals recognised 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 recognised 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 cylinder 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			

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 failing components are electronic components: shock absorbers, bearings, door components, and the pumps, including water circulation and the drain pump. The defects described in the manuals 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 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, and 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			

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 failing components are 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 recognised 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

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

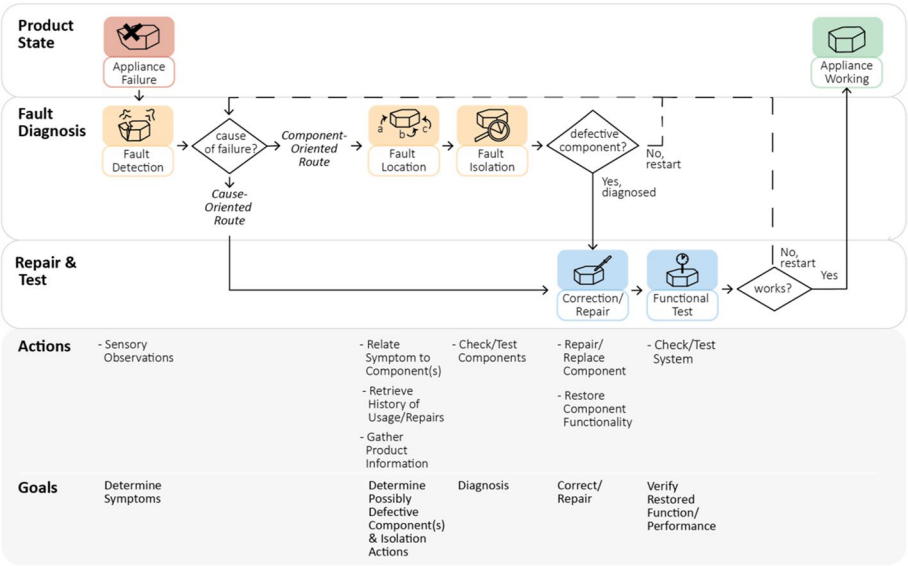

Fig. 2 Expanded framework of the process of fault diagnosis in consumer appliances

From the perspective of manufacturers, limiting the diagnosis information to faults due to lack of maintenance and only facilitating the cause-oriented route makes the diagnosis and troubleshooting process relatively risk-free and safe for end users. 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 also 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 be valuable information for manufacturers and designers [15, 23]. Moreover, the current approach in user manuals may drive up sales and profits, as consumers who cannot diagnose and fix their appliances may be inclined to replace them instead of having them repaired, especially when the appliances are inexpensive. The inconvenience and complexity associated with a repair are well-identified barriers for repair practices [13]. At the same time, providing a limited amount of diagnosis information could cause dissatisfaction among a subset of consumers who want to be able to fully diagnose and repair their products. This may damage the brand's image, as exemplified by iFixit's campaign about low reparability scores of certain brands of smartphones. Moreover, Raihanian Mashhadi et al. [17] found that repair convenience can influence future repurchase decisions or recommendations to other product users of a certain product or brand. In addition, limiting the diagnosis information available in manuals could drive up costs for manufacturers. 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 current approach in user manuals provides 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 Tables 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. Another advantage of the current approach is that the manuals educate 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). At the same time, the lack of provision of diagnosis information in manuals hampers 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. Moreover, 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, Terzioğlu [33] found that the required knowledge, skills, and efforts to take on a product repair are some of the perceived technical barriers experienced by users. Furthermore, limiting diagnosis information in user manuals may lead to a further erosion of consumers' "product literacy" [15]. 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.

Overall, our findings indicate that both routes in the fault diagnosis process, the component-oriented and the cause-oriented route, are needed for the diagnosis of household appliances by end users and should, therefore, be considered during the design of products for easy fault diagnosis. The framework of the diagnosis process presented here (Fig. 2) can be useful to that end. Based on the results of this study and previous findings on the perceived difficulties during the diagnosis process by end users [25], we also 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 Tables 5 and 6). Moreover, the use of augmented reality and other digital support systems like smartphones is currently being explored in practice [1, 10, 20] and may open up interesting avenues to facilitate the diagnosis of household appliances. 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 the "Introduction" section, 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, and a potential good addition to repair policy requirements such as product reparability scoring systems aimed at informing consumers on the ease of product repairs and incentivising design for repair.

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 their top 5 occurring faults, 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 of the fault diagnosis process by end users. 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 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. Our study also provides an original contribution to literature on design for repair and user repair practices. The findings of the study show the support for diagnosis currently provided by manufacturers in user manuals. Hence, it contributes to a better understanding of the fault diagnosis process by end users, and expands our understanding on the end user's perspective upon a product failure. 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.

Future studies should investigate other types of consumer products to further validate the framework of the diagnosis process. Fault diagnosis might be different for other widely adopted consumer products such as fully electronic consumer products. Future research might also explore 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. 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.

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Data Availability Supplementary material has been provided.

Declarations

Conflict of Interest The authors declare no competing interests.

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