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Insights for design**

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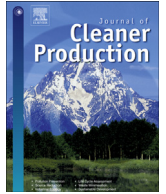
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Practices of fault diagnosis in household appliances: Insights for design

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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.

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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 Commission, 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

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(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.

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; Mostia, 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 (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 (Fig. 1).

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 cited 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 (1990) 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.

Fault Diagnosis

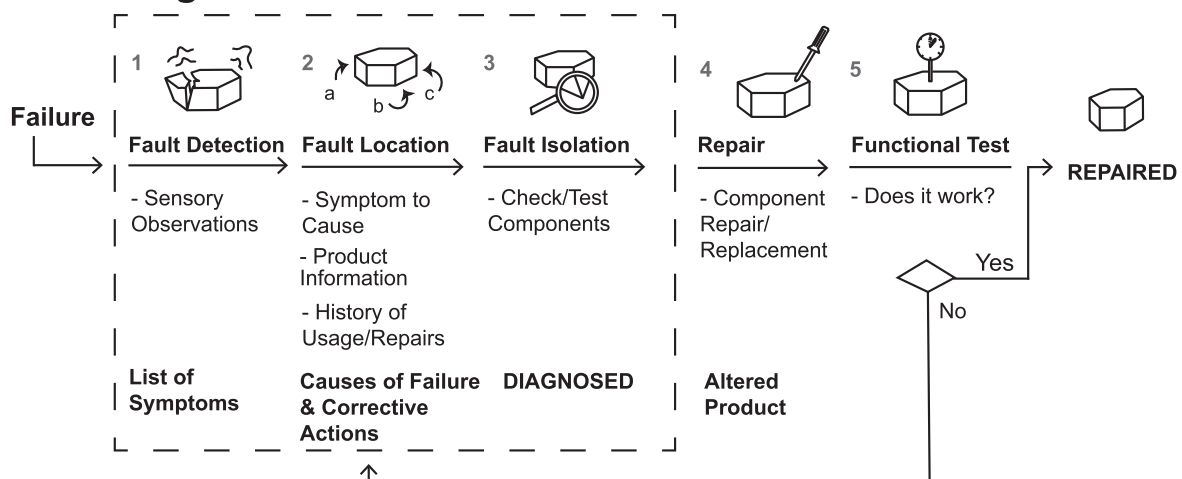


Fig. 1. Conceptual framework of the process of fault diagnosis.

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.

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.

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.

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.

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 under-performance; (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.

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

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 (Fig. 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

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		—

codes and categories of each case are presented in the results section.

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.

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.

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

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 ^a
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)

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

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.

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 under-performance, 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

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

Fault Diagnosis Observation (Condensed Description)	Feature coding	Category	Impact On Diagnosis ^a
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)

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

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.

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 under-performance 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.

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.

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.

6.1. 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

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

Fault Diagnosis Observation (Condensed Description)	Feature coding	Category	Impact On Diagnosis ^a
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)

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

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

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.

6.2. 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 (Tables 3 and 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.

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.

	(1) Fault Detection [Symptom Observation]	(2) Fault Location [Symptom to cause deduction]	(3) Fault Isolation [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			–

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 when 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.

6.3. 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.

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.

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.

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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Beatriz Pozo Arcos: Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **Conny Bakker:** Conceptualization, Supervision, Writing - review & editing. **Bas Flipsen:** Resources. **Ruud Balkenende:** Conceptualization, Supervision, Writing - review & editing.

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