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Designing for Safe Repairs—Identifying and Mitigating Repair Safety Risks in Washing Machines

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Abstract

Non-professional repairs could contribute to an increase in repairs, supporting circular economy goals, yet they raise safety concerns. While recent regulatory actions promote repair, they focus mainly on advancing access to professional repair, rather than enabling repairs by non-professionals, such as consumers and volunteers. This study investigates how product design can mitigate repair safety risks and contribute to safe non-professional repairs. In this exploratory research, a washing machine and a washer-dryer combo were analyzed through repeated disassembly and reassembly to identify mechanical, electrical, thermal, and chemical risks occurring during and after repair, as well as risk-inducing and risk-preventing design features and product architecture. Identified risk-inducing features include exposed components, vulnerable electrical and water connections, lack of reassembly guidance, and differences between disassembly and reassembly sequences. Based on the analysis insights, we developed a first version of a method for identifying, assessing, and mitigating repair safety risks. The method provides elements to visualize repair safety risks as an additional layer on disassembly maps and preliminary design recommendations to mitigate risk. The repair-risk mapping method aims to support designers in analyzing and anticipating repair safety risks and identifying relevant risk-inducing design features. Our findings show that relatively small design interventions, such as visual guidance, reusable connectors, robust connections, and enforced disassembly and reassembly sequences, can reduce risks and make repairs more accessible to non-professionals. Our research suggests that product design plays a crucial role in expanding repair opportunities to a broader range of users while maintaining safety.

Keywords: repair safety; right to repair; product design; design method; disassembly map; circular economy

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1. Introduction

The safety of repairs performed by non-professionals remains controversial. The debate focuses on who should be allowed to repair everyday products, the role of regulation, and how to balance the right to repair with consumer safety and manufacturers' interests. Although non-professional repair could contribute to an increase in repair, necessary to meet CE and sustainability ambitions [1], it also raises safety concerns. This paper addresses the issue from a product design perspective, focusing on how products can be designed to make non-professional repairs safe.

Design for repair is widely recognized as a key strategy for extending product lifetimes and advancing the circular economy [2,3]. The importance of advancing repair is reflected in evolving regulations. Most recently, the European Commission's Ecodesign for Sustainable Products Regulation [4] was introduced, which sets ecodesign requirements, including repair, for specific product groups sold on the European market. Its predecessor, the Ecodesign Directive [5], introduced repair provisions for ten product categories, including washing machines, refrigerators, and televisions, focusing on ease of disassembly, spare part availability, and repair information. Building on this, a European repairability scoring system was developed and first applied to smartphones [6]. From June 2025, manufacturers must display these repairability scores alongside energy labels in physical and online stores across Europe [7]. Similar requirements are expected to follow for other products. France has already implemented a similar approach through its Repairability Index, introduced in 2021 [8]. In parallel, the Directive on common rules promoting the repair of goods [9] aims to improve access to repair by obliging manufacturers to offer reasonably priced, timely repairs, and clear information on repair options and spare parts.

These regulatory actions, however, focus mainly on increasing access to professional repair, rather than enabling repairs by non-professionals. This has triggered debate over who should be enabled to repair products, and the implications of broadening the scope to non-professionals. For this research, we define non-professional repairers as people who are not recognized or classified as authorized repairers by manufacturers or regulation. This group includes different levels of skill and knowledge, from experienced volunteer repairers in Repair Cafés to occasional, inexperienced repairers at home and end users. The Right to Repair Europe coalition argues that consumers are largely excluded as potential repairers [10]. Studies likewise show that consumers face significant barriers to repair, including limited access to spare parts and repair information, lack of knowledge and experience, high repair costs, a tendency to replace rather than repair, and product designs that hinder repairability [1,11–13]. Manufacturers often reinforce these barriers by restricting spare parts and repair information to authorized repairers [10,14]. Restrictions on non-professional repairs are often justified on the grounds of consumer safety and liability, and manufacturers also cite economic and intellectual property concerns [1,10,15]. Further, safety aspects of transitioning to the circular economy, including repair, are increasingly addressed in regulation. The General Product Safety Regulation, for instance, specifies that consumer repairs should be considered only when they can be performed easily and safely [16]. However, terms such as "easily," "safely," and "professional repairer" remain undefined or vague in EU policy. As a result, the role of non-professionals in repair remains ambiguous, hindering the development of concrete support measures. Manufacturers control product design, which defines who can perform a repair and determines repair-related risks. This highlights the role of design in determining whether repair remains limited to professionals or can be safely extended to non-professionals [1,17].

Research on design for repair is expanding and explores diverse approaches, including, for example, methods to assess repairability and ease of disassembly [18–20], design guidelines for fault diagnosis [21], design aspects in repairability scoring systems [12,22], the effects of modular design in repair behaviour [23], the influence of design in repair and the experience of repair [24], and 3D printing of spare parts [25]. However, repair safety is rarely addressed, and when it is, it is only briefly considered. Dangal [22] points to a link between ease of disassembly and safety, and notes that some repairability scoring systems include factors such as protected batteries, safe working environments, skill requirements, and product warnings. This suggests that scoring systems consider certain safety aspects of the repair procedure but overlook, for example, the consequences of a faulty repair. Van Oudheusden [25] emphasizes the need to review the quality of 3D-printed spare parts

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to avoid safety risks, while Pozo Arcos [21] shows that built-in safety features, such as safety switches, can sometimes hinder correct fault diagnosis, suggesting potential tensions between safety and repairability. Overall, we observe a clear gap: repair safety has received little design attention, with no academic literature dedicated to studying repair safety aspects from a product design perspective.

Therefore, this research addresses the potential of product design to reduce repair safety risks in non-professional repairs, such as those performed by consumers. We aim to develop a method for identifying, assessing, and mitigating repair safety risks from a product design perspective, to ensure safe repairs by non-professional repairers. We build on previous exploratory work on Safe by Design and design-for-safe-repair, where we analyzed design aspects influencing repair safety in products, and proposed a preliminary design-based approach [26,27]. In this paper, we present an exploratory analysis of one washing machine and one washer-dryer combo to identify repair safety risks, risk-inducing and risk-preventing design features, and product architecture. Based on this, we (1) developed an initial version of a method for designers to assess and visualize repair safety risks, and (2) derived a set of preliminary design recommendations to address such risks. We conclude by presenting recommendations for further development of the method with regard to risk assessment, as well as for validation of the method and the preliminary design recommendations.

2. Materials and Methods

Below, we present the process that we followed to address our research aim. First, Section 2.1 presents the process to analyze the washing machine and the washer-dryer combo to identify repair safety risks in relation to the product architecture. Second, Section 2.2. outlines how we built previous work and applied the findings of the analysis to develop a method for designers to identify and assess repair safety risks [26,27]. Third, Section 2.3 explains how we derived design recommendations to address repair safety risks.

This research distinguishes between risks that occur during the repair process (referred to as *risks during repair*) and risks that may arise after the repair is completed (referred to as *post repair* risks). This distinction helps us identify specific product characteristics that contribute to risks to the repairer while performing the repair and potential risks to repairers, users, the product, and its surroundings resulting from a faulty repair (e.g., short circuits, fires, etc.). We also distinguish four different types of repair safety risks, as previously defined by Bolaños Arriola et al. [27]:

- Mechanical Risks: When a component or disassembly/assembly action can cause any sort of mechanical injury to the repairer/user (e.g., cuts or bruising) or mechanical damage to the surrounding environment of the product;
- Electrical risks: Risk of electrocution and electric shock during the repair procedure, as well as possible short circuits and consequences for the surrounding environment (e.g., fire caused by a faulty repair);
- Thermal risks: The risk of a component or a disassembly/assembly action causing burns to the repairer/user or fires/damage to the surroundings of the product;
- Chemical risks: The risk of contact (e.g., through skin or inhaling) between the repairer/user and hazardous substances caused by a component and/or a disassembly/assembly action.

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2.1. Analysis to Identify Repair Safety Risks

2.1.1. Selection of Products for Analysis

A washing machine and a washer-dryer combo were selected as cases to analyze repair safety risks (AEG Electrolux front-loading washing machine, and Hisense washer-dryer combo). Washing machines were considered a suitable product category due to several characteristics: they operate with several systems (i.e., electromechanical system, water and electrical system combination, parts that move at high revolutions, and heating system), have a high complexity, are heavy, and are typically difficult to handle, all of which showcase a variety of potential repair safety risks (e.g., electrical, mechanical, thermal, and potential combinations). Furthermore, washing machines are typically repaired by professional repairers, and repair and service information is rarely available to the public. The washer-dryer combo was also selected due to the presence of additional heating components, adding to the complexity. Both machines were analyzed independently and later compared as described below.

2.1.2. Documentation of the Disassembly and Reassembly of Each Washing Machine

Each machine was completely disassembled and reassembled a total of three times. In this study, disassembly refers to the process of dismantling a product in its entirety, while reassembly refers to the process of reconnecting all components to restore the product to its original form. Figure 1 shows the setup used to perform the analysis. The first and second disassembly and reassembly processes were video recorded with a wide-angle lens camera positioned to provide a top-down perspective. An operating area was marked on the floor to avoid stepping out of the shot while manipulating the products, which were placed on top of a moving plate to ease the process (Figure 1).

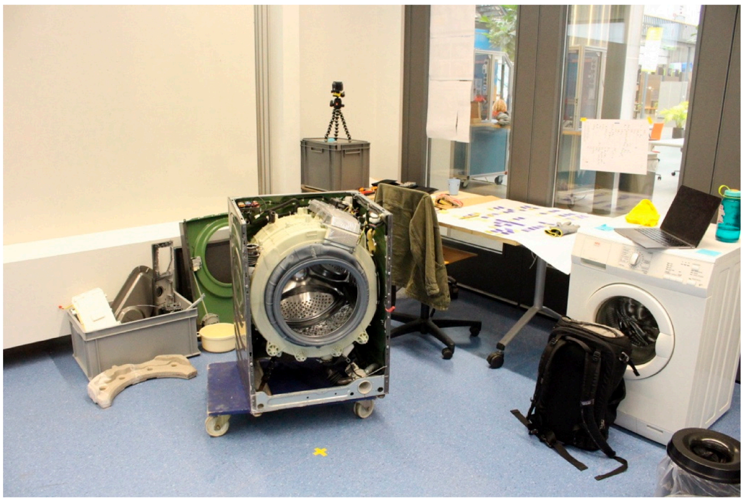

Figure 1. Experimental setup for the disassembly and reassembly of the washing machines.

During the disassembly process of each washing machine, all disassembly sequences and actions were documented in an adapted version of the Disassembly Map, developed by De Fazio et al. [18]. The Disassembly Map is a method for visually assessing the ease of disassembly of a product, indicating the set of necessary actions (sequences) required to reach a specific component. Video recordings were used to verify observations and derive the final disassembly maps of the washing machine and washer-dryer combo.

The disassembly, reassembly, and documentation of these processes were performed by the corresponding author, who has previous experience in repair research and the disassembly of consumer products. As safety measures, the appliances were unplugged prior to any disassembly, and working gloves were worn.

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Figure 2 shows the adaptation made to the Disassembly Map for the purpose of this study. We simplified the visualization of tools to two shapes (hand and tool) instead of the three shapes in the original map (hand, spudger, screwdriver). We also reduced the number of colours used to represent force intensity from six to three, using a street-light system (green, yellow, red). These adaptations retain the capacity to represent disassembly actions and their characteristics, while reducing potential visual cluttering. This was done to improve readability in conjunction with repair safety mapping elements.

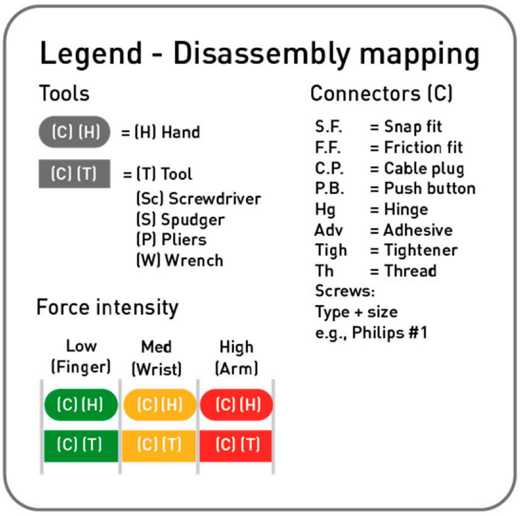

Figure 2. Disassembly mapping elements to indicate disassembly actions and sequences. Adapted from De Fazio et al. [18] for the purpose of this study.

2.1.3. Identification and Documentation of Repair Safety Risks, Risk-Inducing Design Features, and Risk-Inducing Architecture

During the disassembly and reassembly of the machines, we observed and documented potential repair safety risks and their associated design features and product architecture. In this study, design features refer to specific product characteristics that enable certain functions or qualities, while product architecture refers to the overall organization and interrelation of components. To structure the analysis, we first established an observation checklist (Table 1). This was created based on the definition of risks proposed by Bolaños Arriola et al. [27], the repair and industrial design experience of the researcher, and inspiration from publicly available washing machine repair guides (e.g., iFixit and YouTube).

We employed an Excel table to document our observations, and photographed all relevant design features and architecture. Table 2 shows the elements we considered to describe each potential risk in detail. This resulted in a list of risks for each washing machine. We then clustered the identified risks according to their similarities to develop a single summary of identified risks in both machines.

We analyzed the documented disassembly and reassembly sequences to also identify any risks considering the product architecture, hypothetical behavioural factors, and contextual factors. These were documented and described under aggravating factors (Table 2). The following aspects were analyzed:

- Differences in disassembly and reassembly sequences caused by the product architecture. If the disassembly sequence to get to a component differs from its reassembly sequence, it could lead to errors in the repair process, which could lead to risks.

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- Potential shortcuts performed by the repairer. The potential of a repairer deviating from the intended disassembly sequence to reach a component. Shortcuts could lead to unintended exposure to risky components or to errors in the repair process.
- Contextual factors that could influence disassembly/reassembly sequences. Repairers may be forced to use alternative disassembly or reassembly sequences due to contextual restrictions, such as limited mobility due to the positioning or installation of the appliance.

Table 1. Observation checklist that includes examples of risk-inducing design features and architecture. The checklist was used to support the identification and documentation of repair safety risks.

Type of Risk	Risks During Repair	Post Repair Risks
Mechanical	• Features/architecture causing exposure to sharp edges or features in which body parts can be hit or trapped. • Interaction with heavy components.	• Features/architecture leading to mechanical failure such as loose or broken components.
Thermal	• Features/architecture causing exposure to heating systems, or to hot water. • Features/architecture leading to fire, such as punctured batteries.	• Features/architecture leading to overheating, fire, or malfunctioning of heating components, such as faulty connections.
Chemical	• Features/architecture causing exposure to hazardous substances, such as punctured batteries, gases, or fumes.	• Features/architecture leading to the release of hazardous substances, such as punctured components or faulty valves.
Electrical	• Features/architecture causing exposure to electrified components. • Features/architecture leading to short circuits, such as water leakage.	• Features/architecture leading to short circuits, or fire, such as faulty connections. • Features/architecture leading to water leakage.

Table 2. Elements considered for the documentation and description of observed risks, risk-inducing design features, and risk-inducing architecture.

Description of risk and related risk-inducing design features and architecture	Image of risk-inducing design features/architecture	Related components	Risk type Mechanical, Electrical, Thermal, Chemical	Disassembly/Reassembly	Risk during repair/Post repair risk	On person/on product	Aggravating factors yes/no (Context, fixed installation, positioning, necessary help, sequences)	Description of aggravating factors

The repeated disassembly and reassembly of the appliances served to confirm some of the observations, revise the logic in the documented disassembly sequences, and identify any additional, previously overlooked risks.

2.2. Visualization of Repair Safety Risks—Method Development

To develop the repair risk visualization and assessment method, we used the adapted version of the disassembly map (Figure 2) [18] as a base to visually represent the entire product architecture. Repair safety risks were then presented as an additional layer to position over the disassembly map.

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We created a set of mapping elements to represent the different identified repair safety risks. These were developed following our observations during the disassembly and reassembly of the washing machines, and expanding on what was previously proposed by Ingemarsdotter et al. and Bolaños et al. [26,27], who performed disassembly analyses in blenders, coffee makers, radios, and washing machines, among others. The elements were developed iteratively, by visualizing all identified risks in the washing machines as an additional layer on their corresponding disassembly maps. We collaborated with design experts to gain input on the clarity of the mapping elements. The mapping elements were developed to indicate risks and their characteristics (Table 2), for instance, if they occur during the repair or post repair, their type, relevant components, and potential aggravating factors.

2.3. Developing Design Recommendations—Risk Mitigation Strategies

We developed a set of preliminary design recommendations for designers to address repair safety risks, focusing on the risks identified in the washing machines. To do this, we first created a summary that clustered the risks identified in both machines. We then developed design recommendations to address each risk cluster. These combine an element of ideation from the researchers' industrial design and repair expertise, ideation from the findings obtained during the mapping of risks, inspiration from educational design projects involving repair safety, and observed risk-preventing design features in the washing machines.

Identifying Risk-Preventing Design Features

During the disassembly and reassembly of each washing machine, we observed and documented risk-preventing design features and architecture. To guide the analysis, we used a similar approach to the observation of risks and risk-inducing features and architecture. However, the observation checklist in Table 1 was applied in an opposite manner, for example, identifying features preventing exposure to sharp edges or preventing faulty connections that lead to electrical or mechanical malfunctions.

Again, we employed an Excel table to document our observations and photographed all risk-preventing design features and architecture. Table 3 shows the elements we considered to describe the prevented risk in detail. The observation of these features informed the identification of risk-mitigation strategies and the development of the preliminary design recommendations.

Table 3. Elements considered for the documentation and description of observed prevented risks and their related design features and architecture.

Description of the prevented risk and risk-preventing design features and architecture	Image of risk preventing design feature/ architecture	Related components	Risk type Mechanical, Electrical, Thermal, Chemical	Disassembly/ Reassembly	Risk during repair/Post repair risk	On person/on product

3. Results

The results are presented in three parts. The first part presents the risks identified during the analysis of the washing machines. The second part introduces the developed risk-mapping elements and illustrates their application in visualizing the washing machine findings. The third part focuses on risk mitigation, presenting the preliminary design recommendations derived from the analysis and mapping.

3.1. Identified Repair Safety Risks and Their Related Risk-Inducing Design Features

We identified 44 repair safety risks and their associated design features and architecture in the washing machine, and 54 in the washer-dryer combo. Table 4 summarizes and clusters these findings into 20 risk-inducing design features. The complete list for each machine is provided in Supplementary Material S1. We categorized the identified features to describe them according to the characteristics listed in Table 2.

Table 4. Summary of risk-inducing design features and architecture identified in the washing machine and washer-dryer combo. For each identified risk-inducing feature or architecture, we indicated the type of risk they generate, if the risk is related to specific components, if it affects a larger zone in the product architecture (marked with an *), whether it is generated in a disassembly or reassembly sequence, if there are aggravating factors present (marked with an *), and if these are related to differences in sequences (marked with an *). Risk types: electrical (E), mechanical (M), thermal (T).

Description of Risk-Inducing Design Feature/Architecture	Components	Risk Type	During Post Repair	Disassembly Reassembly	Agg. Factors	Risk Zones	Sequ.
R1. Exposure to non-insulated electrified components. Risk from remaining charge or the appliance remaining plugged into the electrical supply.	PCB, capacitor, heating element, inlet valve, motor, pump, top, back, and front panels.	E	During	Disassembly		*	
R2. Exposure to non-insulated cable plugs. Risk from remaining charge or the appliance remaining plugged.	PCB, capacitor, heating element, motor.	E	During	Disassembly		*	
R3. Water-related components and hoses are located near high-voltage components.	Outlet hose, tub, pump.	E	During Post	Disassembly Reassembly			
R4. Lack of information or affordances for the correct grounding of appliances.	Capacitor, motor, metal housing.	E	During Post	Reassembly			
R5. Lack of information or affordances for the correct reassembly of cable plugs.	Motor, pump, heating element, capacitor, PCB, lock, inlet valve.	E	Post	Reassembly			
R6. Lack of information or affordances for the correct routing and fixing of cables.	Cable harness, metal housing.	E	Post	Reassembly			
R7. Loss of mechanical integrity in electrical components and cable plugs, due to low quality or lack of information or affordances.	Capacitor, metal housing, power cable.	E	Post	Disassembly Reassembly			
R8. Differences between disassembly and reassembly sequences that can lead to errors in reassembly.	Rubber ring, concrete ring.	E	Post	Disassembly Reassembly	*		*
R9. Specialized tools required for reassembly that can lead to errors.	Rubber ring, spring.	E	Post	Reassembly			
R10. Lack of information or affordances for the correct reassembly of hoses and water-related components.	Hoses, tub, inlet valve, soap module.	E	Post	Reassembly			

Table 4. *Cont.*

Description of Risk-Inducing Design Feature/Architecture	Components	Risk Type	During Post Repair	Disassembly Reassembly	Agg. Factors	Risk Zones	Sequ.
R11. Water-related components with shallow connections that lead to incorrect reassembly and vulnerable connections.	Rubber ring, inlet hose (tub), outlet hose (tub).	E	Post	Reassembly			
R12. Limited mobility and visibility for disassembly and reassembly which can lead to errors.	Motor brushes, motor, dampers, tub, heating element, pump, inlet hose (tub), outlet hose (tub).	E, M, T	Post	Disassembly Reassembly	*		*
R13. Exposure to sharp edges and corners.	Front and back frame, back panel.	M	During	Disassembly Reassembly	*		
R14. Heavy products and/or components that require a lot of manipulation during disassembly and reassembly.	Entire machine, levelling elements, tub, motor, concrete ring.	M	During	Disassembly Reassembly	*		*
R15. Exposure to moving components.	Motor, drive wheel, tub.	M	During	Disassembly			
R16. Lack of information or affordances to prevent injury-inducing disassembly actions or sequences.	Tub, dampers.	M	During	Disassembly			*
R17. Loss of mechanical integrity of mechanical-related components and fixtures.	Concrete ring, damper holders.	M	Post	Disassembly Reassembly			
R18. Loaded components and disassembly actions that require high forces.	Screws, spring ring.	M	During	Disassembly Reassembly			
R19. Exposure to non-insulated hot components.	Heating element, motor.	T	During	Disassembly		*	
R20. High complexity that leads to incorrect reassembly.	Heating element.	T, E	Post	Reassembly			

Figures 3–5 illustrate risk-inducing design features and clarify our terminology to describe risks and their characteristics. Figure 3 shows that after removing the back panel, the repairer is exposed to sharp edges, electrified parts, and moving components. We can observe what we define as risk zones, in this case, exposure to electrical risks from the motor and its cable connectors when the appliance is not disconnected from the electrical supply prior to the repair. What we denominate as aggravating factors are also observable, in this case originating in the product architecture: limited mobility and visibility for the motor disassembly, increasing the likelihood of injury or reassembly errors. Figure 4 shows a shallow, vulnerable connection, with minimum overlap between the tub outlet and its hose, which, despite using a reusable connector, can result in faulty reassembly or leakage. This is an example of what we denominate risk steps; if the reassembly of the hose is not done correctly, it can lead to post repair risks. Architecture related risks are also observable, as the vulnerable connection sits above the pump, an electrified component, potentially leading to electrical risks. Figure 5 shows the disassembly of a heavy component that requires assistance from another person, which may not always be available, thereby increasing the risk of injury. We denominate these situations as an aggravating factor originating in both the product architecture and the context.

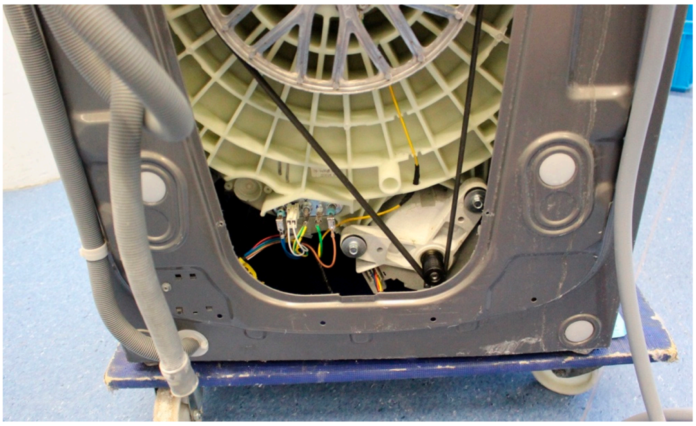

Figure 3. Back opening of the washing machine, showing a number of potential repair-related risks. Immediately after removing the back panel, the repairer is exposed to sharp edges, electrified parts, and moving components. Aggravating factors, such as mobility and visibility issues, to perform repairs that require the disassembly of the motor, are also evident.

Figure 4. Shallow connection with minimum overlap (approx. 5 mm) between the tub outlet and its corresponding hose. Shallow connections can be vulnerable or cause reassembly issues despite the reusable connector, potentially leading to leaks. In this case, a leak from the tub outlet hose could cause a short circuit since it is positioned directly on top of the pump.

Figure 5. Disassembly of the tub requires support from an additional repairer due to its weight and fixture type. The manipulation of heavy products and components can lead to injuries if the repairer does not have help available.

3.2. Mapping Repair Safety Risks on the Disassembly Maps of the Washing Machines

Figures 6 and 7 show the disassembly maps for each machine, outlining the product architecture and displaying all identified risks (Section 3.1, Supplementary Material S1). The risks are mapped as an additional layer on the disassembly map, using the mapping elements developed, to distinguish different risks from a design perspective. Below, we explain each of the mapping elements in detail, supporting the interpretation of the maps.

3.2.1. Risk Zones

We identified what we denominate risk zones during the disassembly of the washing machines. These constitute sets of disassembly sequences in which the repairer is exposed to risk. The objective of mapping risk zones is to denote high levels of risk in case precautions are not taken prior to the repair, such as unplugging a device, allowing the device to cool down, or emptying water systems. We identified risk zones relevant to electrical and thermal risks that occur during repair. Risk zones are represented in the disassembly map by enclosing all disassembly actions for which the repairer is at risk (Figure 8). Thermal risks are represented in purple; electrical risks are represented in orange. Each risk zone is defined by an entry point and a limit boundary. An entry point constitutes the removal of a component after which the repairer is exposed to the risk (e.g., the removal of a housing component after which electrified components are exposed). The limit boundary or "end" of the risk zone is defined by the operation or set of operations after which the repairer is no longer exposed to the risk (e.g., the removal of power plugs from a PCB). A disassembly sequence and/or component can be a part of more than one risk zone simultaneously. To differentiate risk zones, we use colour and the notation Z1, Z2, Z3, etc.

In the disassembly maps (Figures 6 and 7), we can observe that both machines present thermal (in purple) and electrical (in orange) risk zones. In both machines, repairers are exposed to potentially electrified and hot components immediately after disassembling the back or top panels. Removing one or several panels is necessary to be able to perform repairs on almost any other component, hence the importance of guaranteeing the removal of the electrical connection and the cool down of the products prior to repair. For the washer-dryer combo, the thermal risk zone is considerably larger than for the washing machine. This is due to the presence of a potentially hot motor and a heating element that lies deep in the disassembly sequence. The electrical risk zones in both machines are generated by a number of components (i.e., capacitor, motor, pump, etc.), all of which must be disconnected to "exit" the risk zone. The disassembly depth of some of these components results in an increase in the risk zone area.

3.2.2. Disassembly and Reassembly Risk Steps

We identified the need to highlight disassembly and reassembly steps that lead to risk. We denominate these as *risk steps*, and annotate them in the disassembly map as A1, A2, A3, etc., attached to disassembly steps/actions (Figure 9). Specifically, we noted risk steps that can lead to post repair risks. According to our observations, post repair risks are commonly related to mistakes made during reassembly, or to damage caused to components during disassembly and/or reassembly. Examples include reconnecting cable plugs incorrectly, breaking fasteners, damaging a component, or reassembling connectors incorrectly. One risk step can be associated with multiple risks. Additionally, the penalizations for *non-reversible connector* and *uncommon tool*, as already indicated in the disassembly map De Fazio et al. [18], are considered to potentially lead to incorrect reassembly or damage during disassembly.

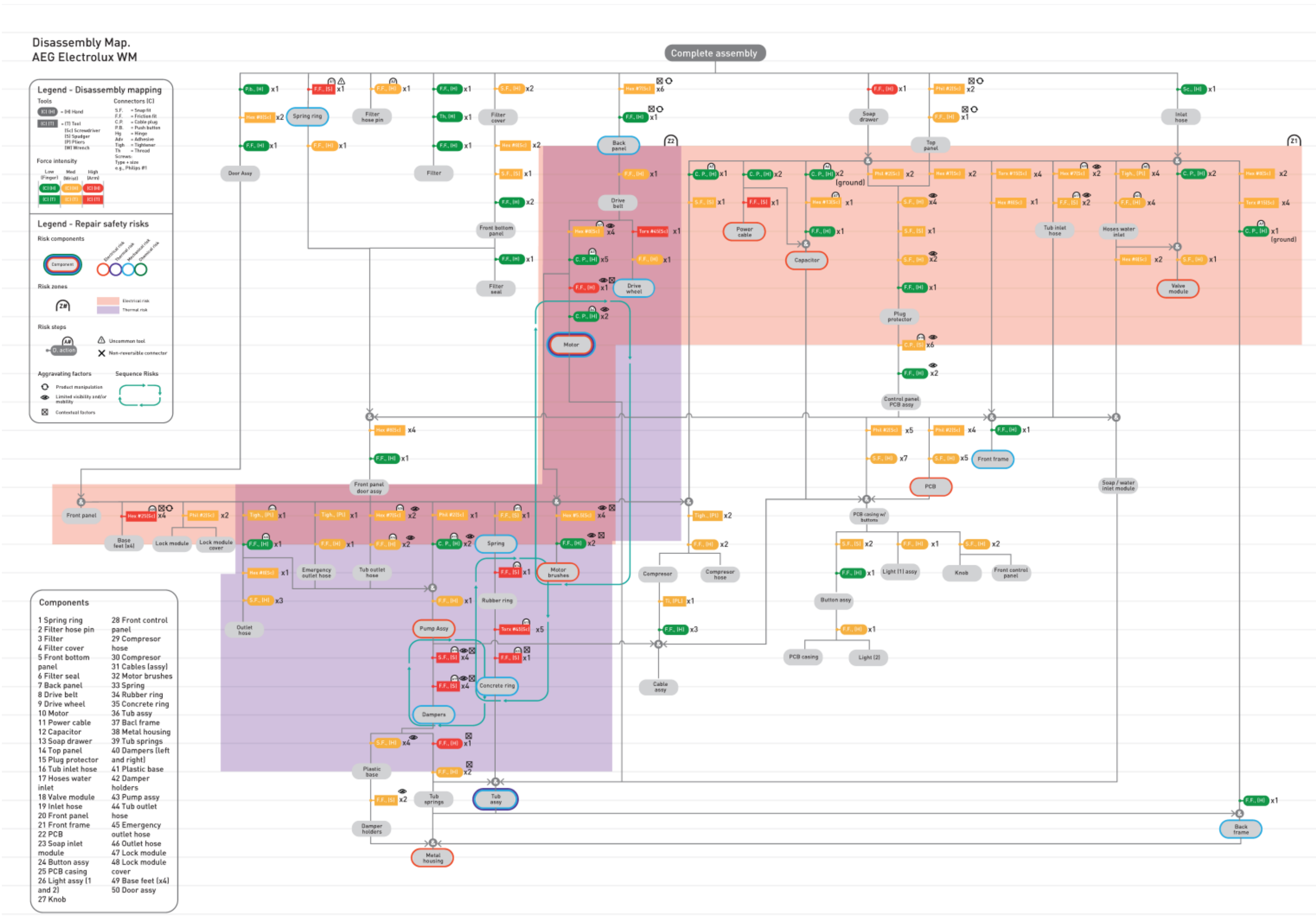

Figure 6. Disassembly map and visualization of risks of the washing machine. The risk mapping elements indicate the presence of thermal and electrical risk zones originating after the removal of panels. Thermal, electrical, and mechanical risks associated with components such as the capacitor, the motor, and the tub are highlighted. The 26 risk steps indicate potential post repair risks due to reassembly issues. Sequence risks highlight differences between the disassembly and reassembly of the rubber ring, and potential shortcuts to reach the motor brushes. A high-fidelity version is available in Supplementary Material S2.

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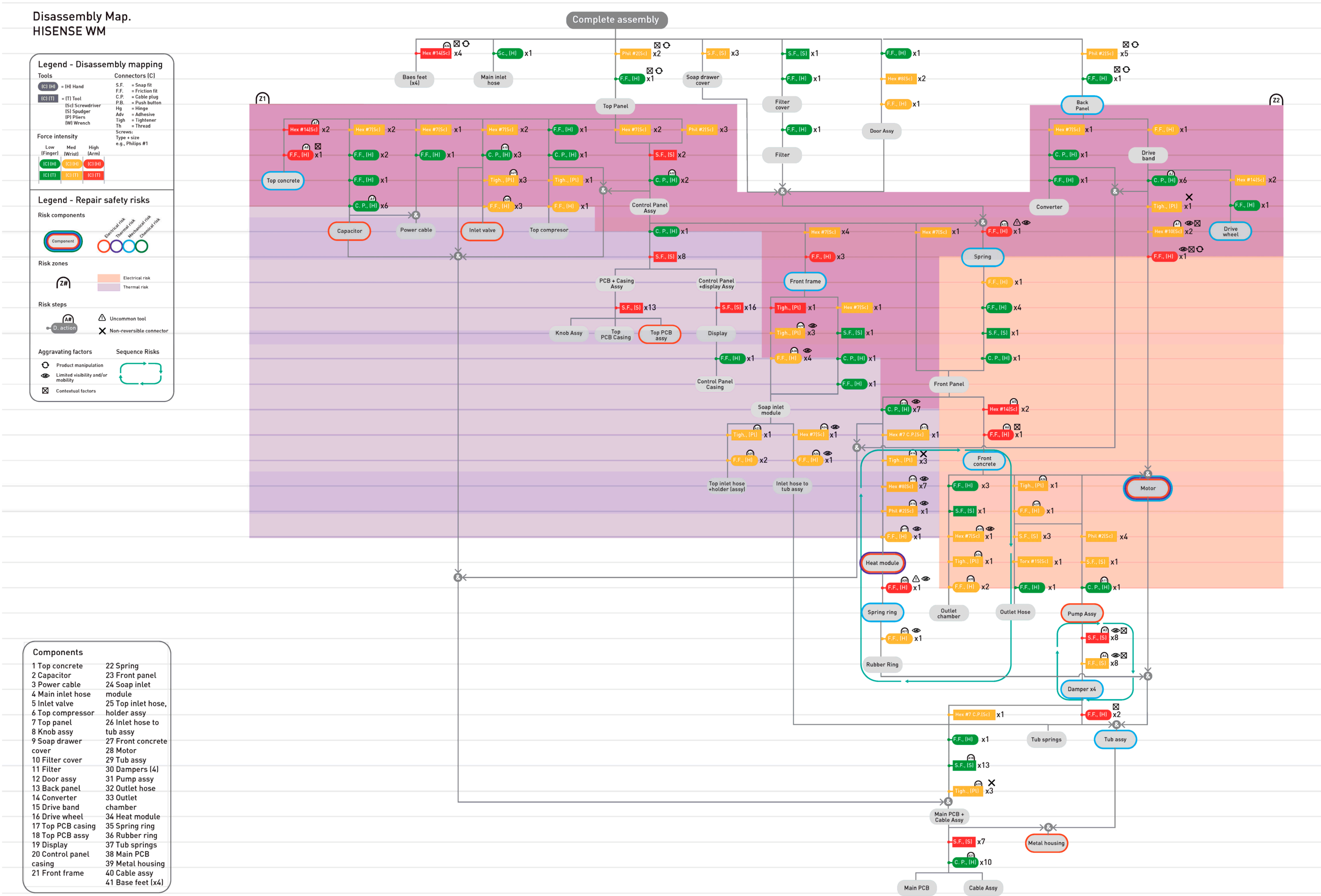

Figure 7. Disassembly map and visualization of risks of the washer-dryer combo. The risk mapping elements indicate the presence of thermal and electrical risk zones originating after the removal of panels. Thermal, electrical, and mechanical risks associated with components such as the capacitor, the motor, and the heating element are highlighted. The 35 risk steps indicate potential post repair risks due to reassembly issues and several non-reusable connectors. Sequence risks highlight differences between the disassembly and reassembly of the rubber ring. A high-fidelity version is available in Supplementary Material S2.

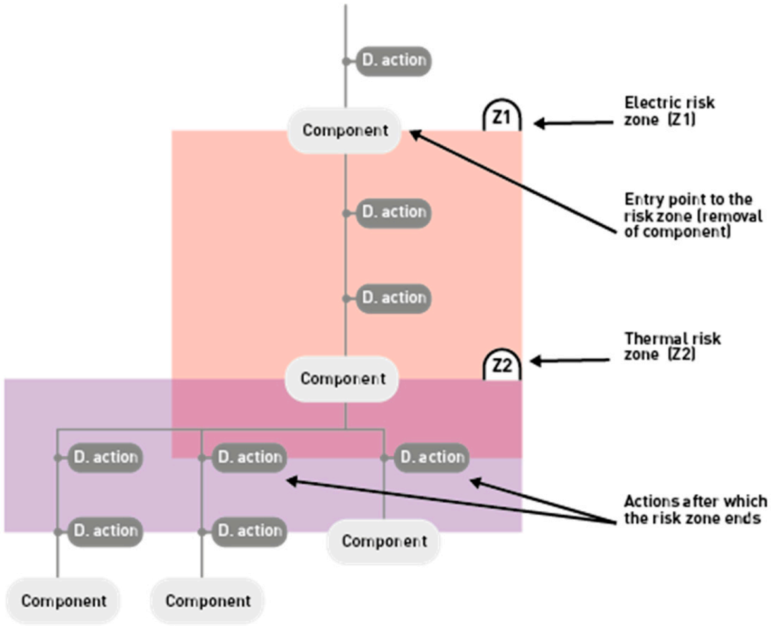

Figure 8. Visualization of two risk zones, Z1 electric risk zone and Z2 thermal risk zone. The coloured areas indicate the start and end of the risk zone, while enclosing all components and disassembly actions affected by it. The colours are given opacity to show any overlaps of the zones.

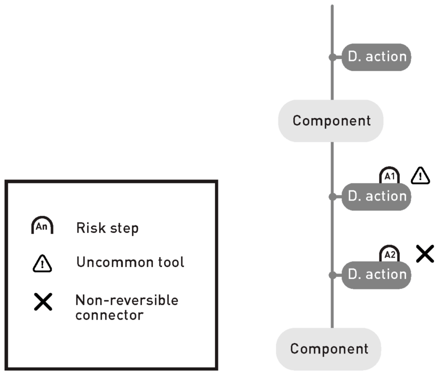

Figure 9. Visualization of risk steps in a disassembly sequence and the "non-reversible connector" and "uncommon tool" penalizations. The risk step indicators are numbered (i.e., A1, A2, A#) to differentiate and quantify them. Risk step indicators are always located in the top right corner of their relevant disassembly action.

A total of 26 risk steps were identified in the washing machine (Figure 6) and 35 in the washer-dryer combo (Figure 7), suggesting a number of post repair risks. In both machines, most risk steps stem from vulnerable hose connections and the lack of affordances to reconnect cable plugs correctly. A number of disassembly actions require high forces, which could result in injury or reduced mechanical integrity of components. The washer-dryer combo presents additional risks due to the heating element, which lacks reassembly affordances and involves a larger number of hoses and non-reversible connectors. For instance, zip-ties are used in hose connections and cable harnesses. Finally, both machines require an uncommon tool for the correct reassembly of the rubber ring, a component that requires disassembly to access other parts.

3.2.3. Risk Components

We identified that additional elements are necessary to link risks to their source. We define *risk components* as product components (e.g., heating element, PCB) that are sources of risk. Visualizing the associated risk types of a component provides design-specific insights concerning safety. Different types of risk can be indicated for a single risk component, as shown in Figure 10.

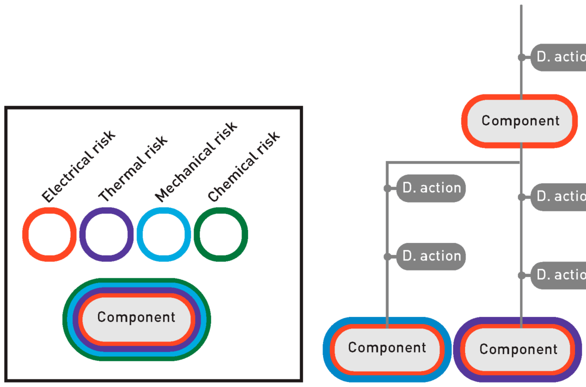

Figure 10. Visualization of risk components in a disassembly sequence. The top component has an associated electrical risk, while the two components at the bottom are associated with electrical and mechanical, and electrical and thermal risks, respectively.

Several *risk components* were highlighted in the disassembly maps (Figures 6 and 7). For the washing machine, the capacitor, motor, PCB, and pump all pose electrical hazards due to residual charge. In the washer-dryer combo, however, the main PCB was not marked as risky since it is insulated and does not require direct access for most repairs. Moving components (motor and drive wheel), panels with sharp corners, and heavy components (concrete ring and tub) have been marked as mechanical risks. These are either exposed after removing one or more panels or must be disassembled to reach other parts, increasing risks. It is important to highlight that the disassembly depth of a component shown on the maps should not be confused with the proximity of touching. For example, the motor appears deep in the map sequence since several steps are required for its disassembly; however, in reality, repairers are physically exposed to it immediately after removing the back panel.

3.2.4. Sequence Risks

We also identified the need to indicate potential risks in disassembly sequences (i.e., sets of steps required to reach a specific component). During the analysis of the washing machine, we observed that differences between disassembly and reassembly sequences can lead to risk due to errors. For example, in Figure 11, the disassembly of component A can be done without disassembling component B first. However, the correct reassembly of component A does require component B to be disassembled. Furthermore, we observed that the disassembly sequence represented in the disassembly map may not necessarily be the disassembly sequence conducted by the repairer. A repairer could choose a different disassembly sequence as a shortcut or due to contextual restrictions, which could lead to risks. Designers should then consider if alternative disassembly or reassembly sequences are possible and visualize those that could lead to risk. We denominate these as *sequence risks*, and they are represented in the disassembly maps as indicated in Figure 11.

In both the washing machine and the washer-dryer, the disassembly and reassembly of the rubber ring have been marked as *sequence risks* (Figures 6 and 7). The rubber ring can be disassembled without first removing the concrete ring. However, the correct reassembly of the rubber ring requires that the concrete ring be disassembled. The incorrect reassembly of the rubber ring could lead to leakage and electrical risks as a consequence. Similarly, the disassembly of the dampers poses a risk of injury if they are removed without first securing the tub. When all dampers are detached, the tension from the upper springs can cause the tub to spring suddenly upward. In the washing machine (Figure 6), the disassembly of the motor brushes was flagged as a sequence risk, since attempting to remove them without disassembling the entire motor can lead to incorrect reassembly, which could lead to electrical risks.

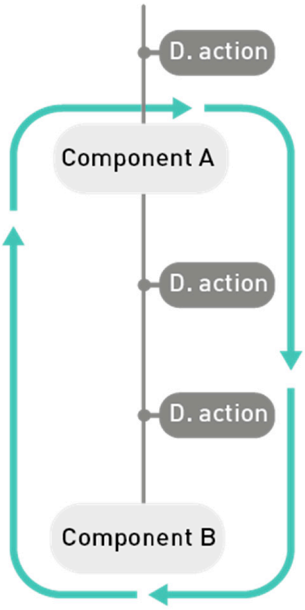

Figure 11. Visualization of sequence risks, i.e., differences between disassembly and reassembly sequences and/or potential changes in sequences due to contextual factors. The sequence risks are indicated by arrows that surround all components involved. The arrows are meant to indicate a potential "reverse" order or alteration to the sequence.

3.2.5. Aggravating Factors

Finally, we observed the need to indicate additional sources or aggravators of risk (Figure 12). For example, if the repairer must work with limited space or visibility during disassembly or reassembly, this could lead to errors and risks. These aggravating factors may originate in the context (e.g., built-in installations) or stem from the product architecture (e.g., limited visibility of components).

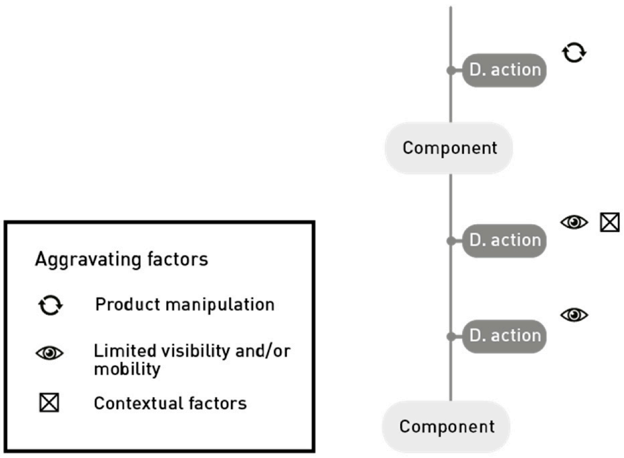

Figure 12. Visualization of aggravating factors. Product manipulation and limited visibility/mobility can originate in the product architecture and/or the context. Additional contextual factors can also be indicated, such as necessary help to perform a disassembly action.

De Fazio et al. [18] proposed penalizations in the disassembly map that can be used to describe product characteristics that lead to, or aggravate, risk: *limited visibility* and *manipulation*. We propose to use both for risk mapping to represent what we denominate as *aggravating factors* that originate in the product design or architecture. We modified the original *limited visibility* penalization to also include *limited mobility* (i.e., lack of space to perform disassembly or reassembly actions correctly, or without incurring harm). We maintained the original *manipulation* penalization to describe cases where the product design forces the repairer to move the product (e.g., tilt, flip) in a specific way to access a component or perform an action.

We also identified aggravating factors originating in the context. For washing machines, these may result from fixed or built-in installations that restrict access to several components. Such factors can include additional mobility and/or visibility issues, the need for additional manipulation, or reliance on support from another person. To indicate these, we propose an additional penalization that we denominate *contextual factors*.

Both disassembly maps show indicators of contextual aggravating factors (Figures 6 and 7). If installed in a way that blocks access to the back or top panels, the entire machine must be moved for repair, which is problematic since most disassembly sequences require removing these panels. Both machines show indicators of contextual factors for heavy components (e.g., tub, concrete ring) that likely require assistance to be handled safely. Aggravating factors stemming from the product design and architecture can also be observed in the maps, including limited space and visibility for the disassembly and reassembly of the motor, dampers, tub hoses, and heat module.

3.3. Mitigating Repair Safety Risks—Design Recommendations

Based on the analysis and mapping (Figures 6 and 7), we developed preliminary design recommendations to address risks. The first set of recommendations indicates how designers can respond to the insights obtained from the map: *Risk zones* can be eliminated by forcing precautionary actions before repair or minimized by surfacing disassembly actions that remove the risk source. Alternatively, strategically maintaining disassembly sequences of specific components outside *risk zones* can prevent exposure. *Risk steps* can be mitigated by avoiding high-force actions, non-reusable connectors, and the need for specialized tools. Risks may also be prevented by avoiding sequence dependencies where the disassembly of high-risk components is necessary to reach others. *Risk components* can be sequenced strategically, either deeper to restrict access or earlier to eliminate risks quickly. Differences between disassembly and reassembly sequences should be avoided. Sequences can be defined and enforced by design to enhance safety. *Aggravating factors* can be mitigated by accounting for contextual conditions such as limited visibility or mobility, reducing the need for additional repairers, and minimizing unnecessary manipulation. Finally, products should be designed to provide sufficient space and visibility for safe and correct disassembly and reassembly.

In addition to the recommendations above, which are based on the map observations, we developed a set of preliminary design recommendations by compiling several findings, including the identified risk-inducing features (Table 4), insights from the disassembly and reassembly, and the observation of risk-preventing features in the machines. Table 5 presents a preliminary set of strategies, practical recommendations to apply them, and the risk they are intended to mitigate.

We identified 16 risk-preventing design features and architecture in the washing machine, and 18 in the washer-dryer combo. The complete list for each machine is provided in Supplementary Material S1. Examples of these features include visual affordances that support the repairer in reassembling cable connectors correctly, deeper, more robust hose connections, and disassembly sequences that force the repairer to empty the water system before the disassembly of the bottom panel.

Table 5. Preliminary design recommendations for repair risk mitigation based on observations from washing machines and the mapping of risks.

Risk Mitigation Strategy	Preliminary Design Recommendations for Risk Mitigation	Related Risk
A. Prevent repairers from coming into contact with electrified components.	1. Design components in a way that forces the power to be removed before disassembly. 2. Provide guidance for the repairer to remove power before disassembly. 3. Cover or insulate live components. 4. Provide warnings on risky components. 5. Position electrical risk–inducing components deeper in the disassembly sequence. 6. Facilitate access to frequently failing components without contact with risk–inducing parts. 7. Separate high-voltage PCBs from user-interface PCBs. 8. Reduce the need for manual testing. Or allow testing without disassembling. 9. Insulate cable plugs.	R1, R2.
B. Prevent electrical components from coming into contact with water.	1. Position high-voltage components and cable plugs away from water-related parts. 2. Provide repairers with guidance to empty water systems before disassembly. 3. Design components and sequences to ensure water systems are emptied prior to access. 4. Ensure electrical components that may contact water are watertight.	R3.
C. Ensure the correct and safe grounding of the appliance.	1. Provide indicators or guidance to ensure correct grounding. 2. Design components that ensure a correct grounding. 3. Design cable plugs and electrical components for robustness to prevent loosening or loss of mechanical integrity. 4. Provide reusable, durable cable fasteners. 5. Avoid conducting materials for the product casing.	R4, R7.
D. Ensure the correct reassembly of electrical wiring.	1. Provide indicators or guidance to ensure correct connection of all electrical components. 2. Provide guidance for correct cable routing. 3. Reduce wiring complexity and avoid visually cluttered layouts.	R5, R6, R20.
E. Ensure the correct, watertight reassembly of hoses and water-related components.	1. Provide guidance for the repairer to follow safe disassembly and reassembly sequences. 2. Prevent differences in the order of disassembly and reassembly sequences. 3. Avoid non-reversible connectors. 4. Avoid the need for specialized tools, especially for reassembly. 5. Provide indicators to reconnect hoses and water-related components correctly. 6. Ensure sufficient contact area in hose connections; avoid shallow connections. 7. Design water-related components for robustness to prevent loosening or loss of integrity.	R8, R9, R10, R11.

Table 5. *Cont.*

Risk Mitigation Strategy	Preliminary Design Recommendations for Risk Mitigation	Related Risk
F. Provide sufficient visibility and mobility to disassemble and reassemble components safely and correctly.	1. Provide sufficient visibility and space to perform disassembly and reassembly actions. 2. Consider the context and accommodate potential mobility and visibility limitations.	R12.
G. Prevent repairers from coming into contact with injury-inducing components or performing risky actions.	1. Avoid sharp edges on surfaces and components that may contact the repairer. 2. Design sequences that minimize product manipulation or handling of heavy components. 3. Provide configurations that aid component repositioning and reduce the need to carry heavy parts during reassembly. 4. Prevent the activation of moving components during repair. 5. Provide information or warnings in the product to indicate risk actions. 6. Cover, block, or isolate moving components. 7. Place mechanical risk–inducing components deeper in the disassembly sequence. 8. Enable access to frequently failing components without contact with risk–inducing parts. 9. Provide guidance for the repairer to follow safe disassembly and reassembly sequences.	R13, R14, R15, R16.
H. Ensure the correct reassembly of mechanical components.	1. Design for robustness to prevent mechanical components from loosening or losing integrity. 2. Provide guidance to prevent actions that damage components or their connectors.	R17.
I. Avoid disassembly actions that require high forces or highly loaded components.	1. Provide warnings of high-force actions or loaded components. 2. Provide fastening mechanisms that require less force to disassemble. 3. Use fasteners whose tension can be adjusted.	R18.
J. Prevent repairers from coming into contact with potentially hot components	1. Design to ensure the repairer allows the appliance to cool before repair. 2. Provide guidance for the repairer to allow the appliance to cool before repair. 3. Cover or insulate hot components. 4. Provide warnings on risky components. 5. Move thermal risk-inducing components deeper into the disassembly sequence. 6. Facilitate access to frequently failing components without contact with risk–inducing parts. 7. Reduce the need for manual testing. Or allow testing without disassembling.	R19.

4. Discussion

The analysis of the washing machine and the washer-dryer combo demonstrates that repair safety risks are closely linked to product design. In both machines, repairers were exposed to electrical, mechanical, and thermal risks, particularly from heavy, moving, and exposed electrified or high-temperature components. We also identified significant post repair risks arising from differences between disassembly and reassembly sequences and design features such as vulnerable electrical and water connections and the absence of reassembly indicators. The disassembly maps revealed not only these risks but also that many repair actions can be performed safely, and that most risks during repair can be mitigated through precautions that eliminate risk zones, such as unplugging the device, allowing it to cool, or emptying water systems before disassembly. In addition, we observed risk-preventing features and product architecture showing how relatively small interventions can reduce risks during and post repair, including insulating cable plugs, using reusable fasteners, providing visual reassembly guidance, and enforcing disassembly sequences. Our results highlight the role of designers in making products safe to repair, while providing a method to address repair safety in the design process.

The repair-risk mapping method proved effective for visualizing design-related risks and provides a structured approach to anticipating hazards and identifying design interventions. However, several aspects of repair safety remain insufficiently captured. Risk steps could be differentiated more precisely by distinguishing between lack of affordances, loss of mechanical integrity, and damage to vulnerable components. Risks related to component positioning are also not yet represented, such as the tub water outlet placed directly above the pump. In addition, the specific design features or product architecture causing the identified risks cannot yet be detailed. For instance, a vulnerable hose connection can be identified as a risk step, but its degree cannot be illustrated. Introducing a mechanical risk zone could highlight hazards from moving components if the appliance remains plugged in during repair, while a marker for heavy components could clarify risks related to product and component handling.

This study was limited to two case products, a washing machine and a washer-dryer, and therefore may not capture the full range of repair safety risks within the washing machine category or across other product types. Consequently, the proposed design recommendations cannot yet be generalized, although they may be transferable to other complex household appliances. Future research should test the preliminary design recommendations across a broader range of products and models to validate their applicability and determine whether the proposed mapping elements are sufficient or require further expansion. Although the framework includes chemical risks, none were observed, indicating the need to assess chemical risks in other product groups and refine their representation. We recommend the analysis of cases with components that may generate chemical risks by exposing the repairer to hazardous substances. For example, products with batteries and products that contain refrigerant gases (potential risks of puncture and leakage).

The method currently identifies risks without assigning probabilities or severity, treating all risks as equally important. Integrating quantitative assessments that combine severity and probability [26] could provide a more comprehensive evaluation of repair safety and provide indicators to prioritize identified risks. In order to assess the probability of risks during repair, future research could focus on analyzing exposure scenarios and estimating exposure frequency based on the analysis of repair sequences of “common” repairs, and the potential exposure to components identified as high risk. To assess the probability of post repair risks, future research could analyze scenarios based on the complexity of reassembly sequences and actions. Furthermore, failure and incident databases from manufacturers could support such analyses, as well as further understanding of differences in skills and knowledge of non-professional repairers, and how these may influence probability. However, we consider that estimating probability accurately would be challenging given the diversity of products, their specific designs, and the specific circumstances of the repairer. We therefore recommend future studies to prioritize and incorporate severity assessment of repair-related risks, based on existing guidelines, such as Safety Gate (formerly known as RAPEX) [26,28]. Finally, the method has only been applied by the researchers in the described cases for development purposes; the method

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has not yet been validated. Further development of the method should involve product designers to test the method in real cases and evaluate its usability and effectiveness.

Our preliminary design recommendations indicate that repair safety can be integrated into existing design-for-repair principles. Table 6 presents the design-for-repair features and principles proposed by Dangal [22] and illustrates how these principles can be adapted to better address safety based on our findings. While many principles apply both to repair safety and repairability, such as connector removability and reusability, visibility, ease of handling, and guidance, our findings add specific safety considerations. Four design-for-repair principles are not related to safety and were therefore not addressed in this research (Table 6).

Table 6. Addition of repair safety considerations to existing design-for-repair features and principles [22]. The safety considerations are based on the preliminary design recommendations presented in Table 5. The relevance of the design principle to repair safety is marked by an X.

Design Features and Principles Empirically Shown to Drive Repairability [22]	Relevance to Repair Safety	Addition to Address Repair Safety Risks
Disassembly	X	Disassembly sequences to access (or prevent the access to) components can be defined and enforced by design to prevent risks.
Reassembly	X	Guaranteeing the correct reassembly of a product to its original configuration can prevent post repair risks.
Fastener removability and reusability	X	Preventing the damage of fasteners and connectors, and guaranteeing their reusability, can support correct reassembly, preventing post repair risks.
Fastener visibility	X	Fastener visibility and the provision of visual cues support correct, safe disassembly and reassembly.
Modularity	X	Encapsulating risk zones or risk components into modules can prevent contact with the repairer, reducing risks during repair.
Diagnosis	X	Facilitating diagnosis and testing without exposing the repairer to risk actions or risk-inducing components.
Health and Safety	X	Minimize or eliminate safety risks by design. Increase confidence in repairers either through fail-proof design features or by providing guidelines and information.
Standard parts and interface		Not applicable
Information accessibility	X	Guidance on the repair process should emphasize potential risks during disassembly and provide information for a correct, safe reassembly.
Design simplicity and complexity	X	Product and component simplicity, and simplicity of disassembly and reassembly sequences can contribute to a correct, safe repair procedure.
Adaptability/upgradability		Not applicable

Table 6. *Cont.*

Design Features and Principles Empirically Shown to Drive Repairability [22]	Relevance to Repair Safety	Addition to Address Repair Safety Risks
Ease of handling	X	Potential risks from product manipulation should be considered, especially in the case of fixed product installations and heavy products and components.
Interchangeability	X	The mechanical integrity and correct reassembly of components should be guaranteed during their replacement to prevent post repair risks.
Robustness	X	Preventing the wear and breakage of components during disassembly and reassembly can prevent post repair risks due to failure.
Redundancy		Not applicable
Firmware reset		Not applicable

We argue that incorporating safety considerations into design-for-repair principles can enhance repair process safety and expand the range of repairs that non-professionals can perform. The proposed design recommendations may also address barriers faced by non-professional repairers, through increased repair confidence through risk reduction, improved ease of disassembly [12], and improved product robustness [11]. However, the validity and effectiveness of these recommendations require further investigation across different scenarios to ensure that design-for-safe-repair aligns with the requirements and characteristics of the intended user group. For non-professional repairers, this entails understanding their existing knowledge, skills [29], access to repair information, and contextual constraints (beyond fixed installations). Prior studies show that self-reported repair experience significantly influences repair success among non-professionals and that access to repair information can guide repairers through safe procedures, reducing risk and improving the overall experience [23,30]. Future iterations of the method should explicitly consider these factors and further specify the competences and requirements for designing for non-professional repairers.

Our results show that design interventions that improve repair safety can also create tensions with ease of disassembly, repairability, and product complexity. These tensions arise because safety measures often introduce additional physical or procedural constraints that affect how a product is accessed and taken apart. As a result, they may also increase costs and environmental impacts. For example, positioning high-risk components later in the disassembly sequence reduces exposure but increases the number of steps required to access them. Such risk-mitigating strategies may be suitable for components that do not require frequent repair or maintenance, whereas different approaches are needed for components that do, to avoid negative effects on ease of repair. Similarly, protective enclosures around electrical or hot components can reduce risk but may require additional disassembly steps and components, introducing economic and sustainability trade-offs, impaired repairability, or even reluctance to repair. Modularity could encapsulate risk zones or components that could prevent exposure and minimize reassembly errors. However, it may also increase costs, product complexity, and challenges related to fault diagnosis and disassembly [11,21,23]. Modularity could also lead to the replacement of materials or components that would not otherwise require repair. Design decisions should therefore balance safety requirements with other functional, economic, repairability, and sustainability requirements, while considering the intended repairers and the severity and probability of the risks they are exposed to (professional versus non-professional). Further research is needed to better understand how different safety interventions affect repairability, product complexity, and sustainability outcomes across product types.

5. Conclusions

This research explored how product design can reduce repair safety risks in non-professional repairs. We aimed to develop a method for identifying, assessing, and mitigating these risks from a product design perspective. To achieve this, we analyzed one washing machine and one washer-dryer combo, identifying risks during and post repair, as well as risk-inducing and safe design features and architecture. The analysis revealed a number of mechanical, electrical, and thermal risks, resulting from risk-inducing design features and architecture, including exposed components, vulnerable electrical and water connections, lack of reassembly guidance, and differences between disassembly and reassembly sequences. Based on these results, we developed the first version of a method for mapping repair safety risks as an additional layer to the disassembly map [18], visualizing risks across the product architecture. The repair-risk mapping method aims to support designers in systematically analyzing and anticipating repair safety risks, while identifying relevant risk-inducing design features and architecture. The preliminary design recommendations derived from the analysis of the machines and risk-mapping observations provide initial guidance to address repair-related risks. We provide recommendations for further development of the method, particularly with regard to risk assessment, and for validation of both the method and the preliminary design recommendations. This work advances the field of design-for-repair by explicitly integrating repair safety into existing principles and providing a practical approach for incorporating safety into the design process.

Our findings suggest that design interventions, many of them relatively small, such as visual guidance, reusable connectors, robust connections, and enforced disassembly and reassembly sequences, can reduce risks and make several repairs accessible to non-professionals. This indicates that product design can play a critical role in expanding repair opportunities to a broader range of users while maintaining safety.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su18136424/s1, Supplementary Material S1: complete set of identified risks, as well as the risk-inducing and risk-preventing design features and architecture observed in the washing machine and washer-dryer combo, supported by descriptions and images and an overview of the resulting design recommendations based on the insights derived from the analysis. Supplementary Material S2: High-fidelity versions of Figures 6 and 7.

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