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Designing products that facilitate easy and intuitive repair, an implementation in product design education

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Abstract: When considering circular economy, reuse, refurbish and repair of products is key in many circular business models. Both efficient and intuitive disassembly and assembly are crucial facilitators for these strategies, impacting feasibility, cost and economic viability. Thus, product designers and product design educations should focus on how to design products for easy and intuitive disassembly and reassembly to facilitate repairability. The focus from design educations on these specific processes is however very limited. This paper elaborates on the outcomes of a project-based learning course for design engineering students. The students redesigned an electric device (power tool or household appliance) with special attention to design for repairability strategies. Necessary frameworks and tools were offered to first analyze the disassembly and assembly process of the product and secondly redesign for repair. Unlike many other methods that are about assessing assembly and disassembly processes in terms of the time needed to perform them, here special attention was paid to the interactions, both cognitive and physical, during repair. This premise aligns better with the context of end-user repair where time is less relevant but where interactions need to be easier and more intuitive. Through case studies, it was investigated whether this focus generated valuable results and was feasible to implement. The paper is especially relevant for those concerned with circular product design, the assembly and disassembly of products linked to circular strategies such as repair and the integration within design engineering curricula.

Introduction

Product design plays a crucial role in facilitating circular economy and reducing environmental impact. Designing products for a circular economy is about maintaining product integrity over multiple use cycles (e.g. by facilitating repair), and closing the loop (e.g., through recycling) in combination with economically viable product–service systems (Bocken et al., 2016). This circular approach contrasts with traditional linear models of take-make-use-dispose and selling artifacts to generate profit.

Many design educations consider it fundamental to prepare future designers for a circular economy, resulting in many educational courses and projects aiming to integrate circular economy in product design education (Ramirez, 2006; Lilley & Lofthouse, 2009). However, as highlighted by Terzioğlu & Wever (2021), few courses and projects focus on design for repair or even more specifically on competencies or skills linked to design for disassembly and reassembly. These processes are however crucial facilitators for many R-strategies such as repair. Moreover, when considering research into these processes, researchers focus mostly on time measurements (i.e., from existing products) or on anticipations of time (e.g., calculations based on product features).

Important efforts have been made to anticipate time using predefined reference values, see e.g., the work of Sodhi et al. (2004) on the U-effort (unfastening-effort) for fasteners. A quantitative indication of time by calculating the time needed for disassembly and reassembly is then again given by the ease of Disassembly Metric (eDiM), see Vanegas et al. (2016). The reference times used in eDiM are from MOST (Maynard Operation Sequence Technique) which was developed to have standardized times for different working steps, see Zandin (2002) on MOST. Another method, the Philips

ECC is working with dismantling times defined through time measurements of real disassembly processes (Boks et al., 1996). The database is linked to product categories, which poses limitations to extend the method towards other categories (Ritthoff et al., 2023). Desai & Mital (2003) developed the disassembly design method which uses five factors to calculate disassembly time (i.e., disassembly force, material handling, requirements of disassembly tools, accessibility of joints as well as tool positioning). Kroll & Carver (1999) developed a method which calculates the required disassembly time based on manual disassembly trials on computers, keyboards, monitors and printers. It uses difficulty levels which can be seen as more subjective (Ritthoff et al., 2023).
Many methods, each having limitations to apply them in every repair context (e.g., non-ideal situations in which operators lack experience, have limited tools or instructions available).

Nevertheless, the anticipation of disassembly and assembly time is relevant, especially when considering priority parts. Priority parts are mainly defined by the frequency of becoming defective, functional importance and economic value (Ritthoff et al., 2023). The steps and time needed to reach these parts are impacted by the product architecture (i.e. how the product is arranged in components and subassemblies which is linked to the functions of the product) and by the complexity of the interactions (physically and cognitively). The disassembly map, see De Fazio et al. (2021), is a tool which allows the analysis of disassembly properties of products in relation to these identified priority parts and the product architecture, which is valuable to facilitate repair.

Although time to repair a product is an important element due to the impact on cost (e.g., repair in the factory or by professionals), we could state that in some contexts time has less economic impact (e.g., repair by the consumer, repair in repair cafés, etc.). Here, ease and intuitiveness of both the disassembly and assembly processes are important as the people repairing are potentially not trained and lack instructions. Therefore, product designers should be aware of how people construct meaning during interactions and how product design impacts complexity of both disassembly and assembly in relation to human interaction during repair.

The construction of intuitive interactions during manual assembly is key within the Design For Assembly Meaning framework (DFAM), see the work of Parmentier et al. (2020, 2021). This framework builds upon affordance theory (i.e. action possibilities) [see, Norman (1988, p 9) and You & Chen (2007) on affordances] and on product semantics [see, Krippendorff & Butter (1984)] as the building blocks of interaction during manual assembly. Therefore, DFAM was considered valuable for the interactions during a repair process and to redesign the product accordingly. Following, both the disassembly map by De Fazio et al. (2021) and the DFAM framework from Parmentier et al. (2020) were considered valuable for the course.

However, considering repairability of products, many elements [i.e., on a system level (e.g., business model, logistics, strategies for spare parts, etc.), on a product level (e.g. product architecture, interfaces, connections and on an interaction level (ease and intuitiveness of interactions, tools, manipulations, etc.)] play a role.

In this paper we discuss how frameworks and tools (e.g., to map and visualize interactions during repair) were used by design engineering students and whether the use of these frameworks and tools generated valuable results. In the following sections we explain how students engaged both on a system and product level to design for repair, and we discuss the results of their redesign efforts.

Methodology

Course and student description

The course was planned for the second semester of the academic year 2023 - 2024. The participants were third year students from the Bachelor of Science (BSc) program in Industrial Design Engineering Technology at Ghent University. Twenty-five students (22 male and 3 female) received 20 hours of lectures during a total of 12 weeks. The rest of

the 180 hours were spent on the project to redesign a product focusing on repairability.
The kick-off of the redesign project was given in week 4. The students selected an electric household appliance or power tool and iteratively redesigned it in the following weeks of the project. The students were guided with individual feedback (critiques) which is typical in Project Based Learning (PBL) (Brosens et al., 2022).

Framework

Repairability of products is defined by the design (product and interaction level) and by the repair context (e.g. tools, information, availability of spare parts, cost, etc.). Following, the students were offered insights, methods and tools looking at the system level (strategies for e.g. spare part, logistics, costs, etc.), the product level (i.e., the architecture, function mapping, priority parts, subassemblies) and the interaction level (interactions over the different disassembly and assembly steps), illustrated in Figure 1.

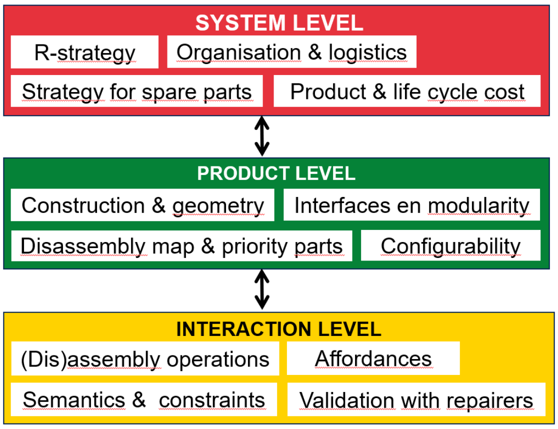

Figure 1: overarching framework offered to the students.

Although insights were given on a system level (red box in Figure 1) and considered during trade-offs (i.e., to weigh design decisions), the focus was mainly on a product level and interaction level (green and yellow boxes in Figure 1).
Students received courses on the DFAM framework [i.e., based on the work of Parmentier et al. (2020, 2021) and papers to read on the disassembly map (De Fazio et al., 2021), product architecture and modularity (K. Ulrich, 1995) and product architecture and platforms (Muffatto & Roveda, 2002). They received information on the French repairability index (French Government, 2021) and suggestions for improving repairability scores based on the work of Rodríguez et al. (2023). They also received the example of Rodriguez & Favi (2024) on a methodology to improve the repairability of mechatronic products.

Constraints and design approach

Functionality, end-user interactions and aesthetics had to remain the same in the redesign. Despite these constraints, they were not bound by the existing architecture, subassemblies or component designs. They could completely redesign the products, focusing on repair while respecting functionality and overall appearance.

Product Autopsy was used to gain understanding of the design decisions made in the original product [see Milton & Rodgers, p. (2013, p. 33) on Product Autopsy]. Priority parts were defined based on available information (e.g., from online forums, or known to be subject to wear) combined with insights from the product autopsy.

During the redesign, the students followed a basic design process, going through the stages of discover (i.e., analysis of the existing product and systems by means of the DFAM framework and the Disassembly Map), define (i.e., problem definition and methods to tackle these problems), develop (i.e., to develop concepts, solutions) and deliver (i.e., to finalize the designs).

During the define stage (mainly the analysis of the existing product), they had to construct a function diagram (Figure 2), an assembly (Figure 3) and disassembly diagram (Figure 4), the disassembly map (Figure 5) and finally analyze the interactions during disassembly and assembly by using the DFAM framework (e.g. by considering whether the action possibility is desired or undesired, possible or obstructed, triggered or not).

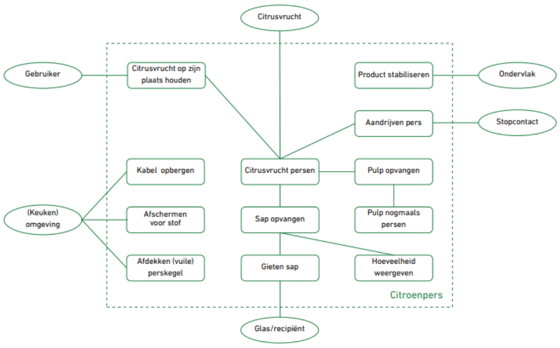

Figure 2. Function diagram made by a student for a citrus juicer

The disassembly and assembly process were then analyzed onto the level of affordances and product semantics. Affordances (i.e., action possibilities) and product semantics (i.e., meanings associated with the product, feature, texture, …which can trigger the action) define the interactions. The students were also registering the time needed to discover and resolve errors.

As pointed out, the interaction level is mainly linked to the DFAM framework in which affordances (desired or undesired), constraints (which limit affordances on a physical level) and semantics (which could trigger the action) are considered. Considering whether the affordance was desired or undesired, triggered or not, obstructed or not, is crucial within the DFAM framework. Focus on ease and intuitive interaction is important when considering non-availability of repair instructions and repair by non-professionals.

The students delivered a final report on the process (documented during the project) and the use of the frameworks and tools, describing the different iterations and the final redesign of the product. The process was weekly observed by researchers during the design critiques.

Results

25 products were redesigned within the categories of household appliances and power tools, see Table 1 for an overview.

Household appliances		**Power tools**	
Coffee grinder	1	Sanding Machine	2
Blender	5	Jigsaw	3
Ice crusher	1	Multitool	2
Slicing machine	1	grinder	1
Coffee maker	2	Glue gun	1
Waffle Iron	1	Electric screwdriver	1
toaster	2	Electric scraper	1
Citrus juicer	1		

Table 1. Products which were redesigned

In this section we explain the results by highlighting one of the redesigns (i.e. a Citrus juicer, see Figure 6) which exemplifies the other cases. We discuss the process of the redesign of the product which was documented by the student.

Process and redesign

Discover phase: The students made an analysis of the product by means of the DFAM framework and the Disassembly Map. The product was disassembled and reassembled by the students to gain understanding of the product (4 times in case of the citrus juicer). Pictures were taken and used to map the product architecture. As reported by the student, several problems on the level of affordances and (product) semantics were discovered when 5 people who had no prior knowledge or technical backgrounds disassembled and reassembled the product. These interactions were filmed and used as a benchmark to validate or compare the redesigns.

After these initial steps, a function analysis of the product was made (see Figure 2) and the components were mapped on these functional elements. Defining how components interact to achieve and maintain functionality is crucial.

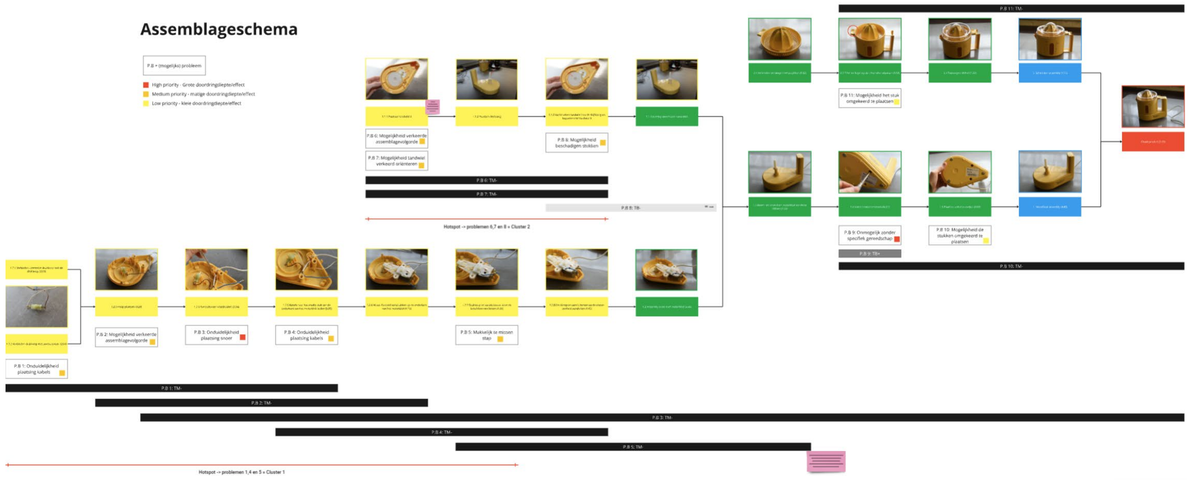

Figure 3. Assembly diagram made by a student (citrus juicer)

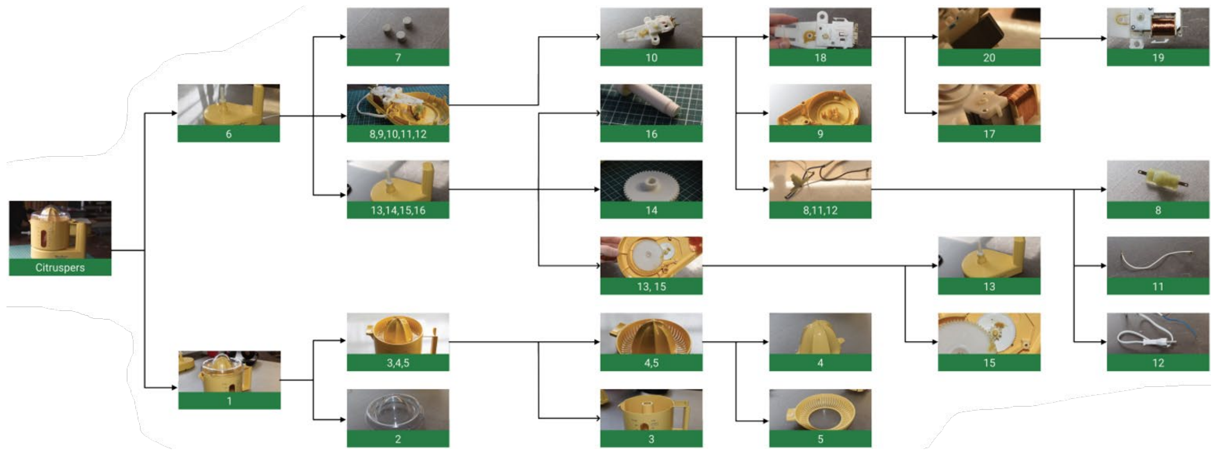

Figure 4. Disassembly diagram made by a student (citrus juicer, numbers are linked to figure 5)

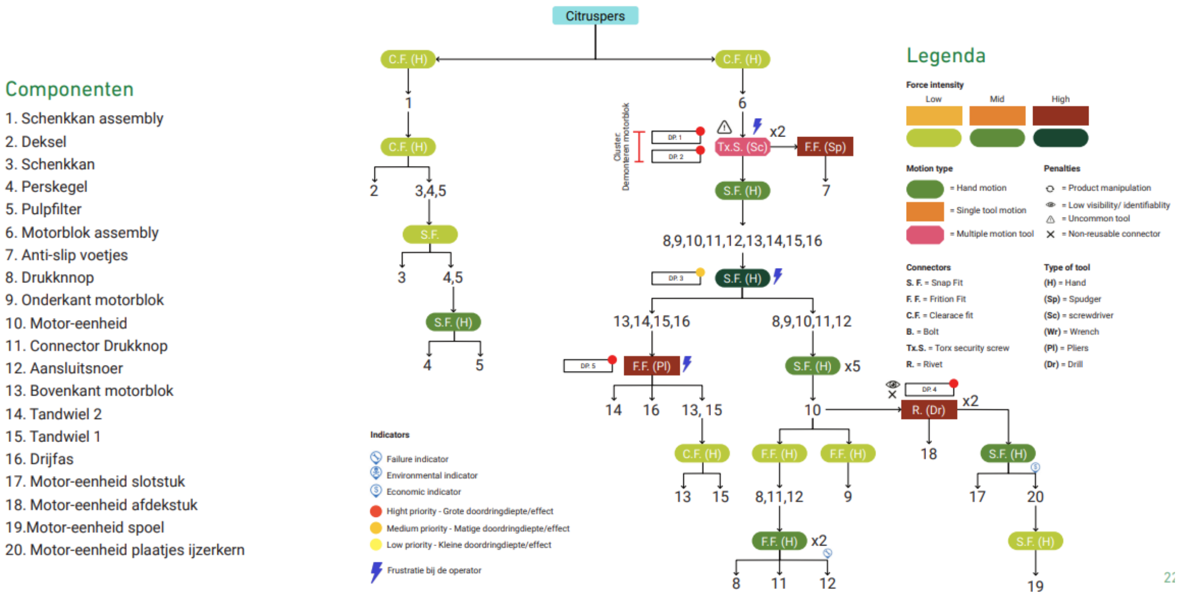

Figure 5. Disassembly map made by a student (citrus juicer), based on De Fazio et al. (2021)

Figure 6. The citrus juicer which was redesigned

Define phase: By conducting a product autopsy, the student was able to construct the assembly diagram (Figure 3), the disassembly diagram (Figure 4) and the disassembly map (Figure 5) for the existing product. The assembly diagram was used to map the problems which were discovered and to identify clusters of problems. The disassembly diagram and the disassembly map from De Fazio et al. (2021) were then used to map the structure and indicate uncommon tools, non-reusable connectors, low visibility, etc. The DFAM framework was used to define the problem on a level of affordances, defining the root cause of a problem (e.g., whether selection of the appropriate tools, and linking it to the different interactions during an assembly step). The combined use of these tools proved especially useful to define and map the problems within the existing product architecture.

Develop phase: Students iteratively developed solutions, build prototypes, and tested different concepts until finding a final solution for the problems found in previous phases**.**

Different solutions, on different levels, were developed in the citrus press case (i.e., on an interaction level by adding and removing physical constraints or by changing the product semantics). Changing physical constraints and product semantics are inherently part of the DFAM framework. Semantic solutions were, e.g. implemented to trigger correct tool use (Figure 7) or by indicating in color how the cables should be installed (Figure 8).

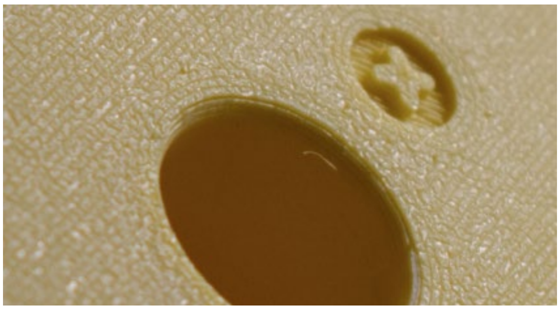

Figure 7. 3D printed part with a semantic addition illustrating the type of screwdriver.

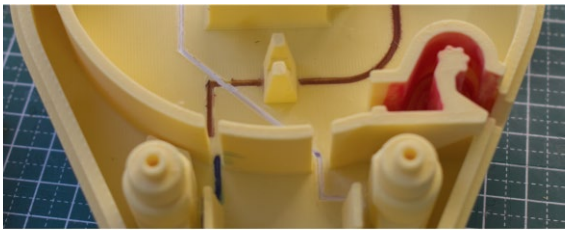

Figure 8. 3D printed part illustrating how the cables should run.

The gears and associated interactions were redesigned by adding numbers, highlighting their correct position and assembly sequence (see Figure 9), or by changing the shape of the axis into a tapered shape which makes the incorrect positioning of the gear impossible (i.e., by adding constraints).

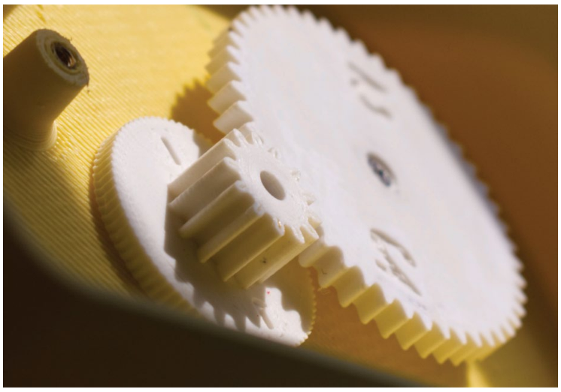

Figure 9. Numbers indicating the correct position and sequence.

Additionally, solutions were explored at a product level. As reported by the student, it was for example impossible to disassemble the drive axis and gear in a non-destructive way (due to a press-connection). By redesigning the connection (Figure 10), physical constraints were removed which prevented disassembly.

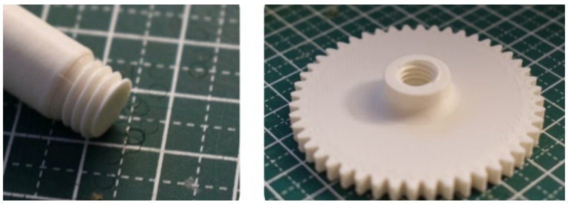

Figure 10. Drive axis and main gear connected by a new integrated thread connection.

Furthermore, the design was reconsidered on a system level (e.g. by. considering the availability of tools in a DIY context). In the original product it was not possible to use a screwdriver with an interchangeable bit. Moreover, a safety-torx was used, which is not very common. Following, the casing was redesigned to facilitate the use of a screwdriver with interchangeable bits and the screw was changed to a commonly found Philips Pan Head Screw. Semantics were added to highlight the type of tool to be used, see Figure 7.

Considering the spare part availability, the student opted to 3D print the replacements. The original product was redesigned to facilitate 3D printed replacements (e.g. the form of 3D printed and injection molded parts might differ, yet both parts need to fit the casing). As reported by the student, insights on the design specifications for these printed parts were gained through iterative testing and prototyping of 3D printed parts.

Deliver phase: During the deliver phase, the designs were finalized (i.e., final iterations on prototypes, detailing, testing) and were validated.

The results in this section were presented by some examples of 1 case study. However, the process, tools and methods used were identical for all case studies and consequently similar results were observed in other case studies.

Discussion and Conclusions

As highlighted by Terzioğlu & Wever (2021), few courses focus on design for repair and on competencies or skills linked to design for disassembly and reassembly. However, in this course this was the very focus.

The case studies' focus was on potential redesigns by manufacturing companies, yet not necessarily for these companies to facilitate the repair service. The case studies focused more on repair in a DIY context where users repair their own product or bring it to a repair café. This differentiation is important to understand the focus on simple and intuitive operations in which time measurement was more considered an indicator for complexity. Therefore, reduction of time was not the primary focus as in different other methods described in the introduction. Following, time anticipation techniques were not offered to the students. Instead, frameworks were offered to make them consider the structure of the product, the use of the tools and the complexity of the interactions (both cognitive and physical) during repair.

Insights were also provided on a system level by offering them insights on e.g. the French repairability index, the availability of spare parts, the availability of instructions etc.

The results (also illustrated by means of the presented case study) illustrate the ability of the students to use the tools and frameworks and to redesign a product focusing on repairability. Conducting a product autopsy, constructing a function diagram, assembly diagram and disassembly diagram clearly helped them to understand the structure of the product, the interactions between the components, the functionality of the components and the sequential nature of both the disassembly and assembly processes. Constructing the disassembly map helped them to consider the priority parts, uncommon tools, non-reusable connectors, low visibility, etc.

The weekly critiques with the students revealed that the offered tools helped students visually map and cluster the difficulties, allowing them to identify the core of the problems. Triggering students to analyze the affordances and product semantics (during disassembly and reassembly processes, (also with non-technical profiles)) proved very valuable. Considering the interactions during repair facilitated easier and more intuitive solutions. Moreover, DFAM helped them to delineate the problem and select appropriate solution strategies.

The presented case study illustrates that students were able to develop and validate solutions at different levels (interaction, product and system). Moreover, it was observed that the students (familiar with 3D printing), very quickly engaged in printing parts to use them as replacements for a defective component. Consequently, companies could adapt their product designs to facilitate the replacement of parts by 3D printed parts of which the files can be shared online, for example in cases where spare parts are unavailable (as was the case for the citrus press). In a DIY context, repair cafés or makerspaces could facilitate the 3D printing of these spare parts.

The premise of this course was to increase the competencies of design engineering students to redesign a product focusing on the repairability by end users. The results illustrate the use of the frameworks and the value of zooming in on a system, product and interaction level to find appropriate solutions. We therefore hope this can be an inspiration for other design education programs.

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