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ENGAGING STUDENTS IN THE CIRCULAR ECONOMY WITH PRODUCTIVE FAILURE

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ABSTRACT
Design for the Circular Economy often emphasizes business models and future visions, with less focus on practical application. Sustainability courses are generally seen as complex, attendance is often dropping, and the knowledge is minimally integrated into design projects.
In 2022, a new course on Repair was introduced. This course aligns with repair and with other R strategies like refurbishing, remanufacturing, and recycling. To engage students, the productive failure pedagogy was implemented in 8 weekly workshops. This method starts with an unsolvable exploratory problem, motivating students to learn the necessary knowledge. Workshops cover product architecture, disassembly documentation, part prioritization, legislation, directives, and human factors in repair design. The course, a master elective, has seen 25 to 50 students per run, working on client-based products to demonstrate improved circular economy fit.
This is the second IDE curriculum course using productive failure. Student evaluations (20 respondents) rated the course highly, with an overall grade of 8.5 out of 10 and a teaching, coaching, and feedback score of 4.68 out of 5. Students were highly engaged in making the circular economy actionable.
The paper will present the course, student outcomes, and qualitative learning experiences, focusing on the experiential learning aspect and the effects of productive failure on engineering courses.

Keywords: circular design, productive failure, engineering, autopsy, repair, design.

1 INTRODUCTION
Design for the Circular Economy often focuses on business models and future design visions. Most educational books emphasize analysis and theory, with less focus on the practical application of circular product design, from vision to action. In the bachelor program of the faculty of Industrial Design Engineering (IDE, TU Delft), three courses on sustainability are offered. Sustainable Impact focuses on the basics of sustainability like eco-design and LCA, Design for the Circular Economy focuses on circular business models and future design visions, and the Sustainable Transitions minor focuses on sustainable systems interventions. Although these courses score “more than satisfactory” on student evaluations (EvaSys), attendance is low and decreases over the course. Besides, coordinators of the parallel running design projects notice that students struggle with the integration of sustainability into the design solutions.
To make sustainability more applicable within our Integrated Product Design master, we developed a new elective related to design for repair, named Repair! (ID542/IDEM309), which was worth 3 European Credits and ran during the fall of 2023. The student population choosing this elective course consists for 70% out of bachelor IDE students and for 30% from other backgrounds like Industrial Ecology and Mechanical Engineering.
In this course we explicitly implemented the productive failure pedagogy [1-3] to increase retention of the knowledge taught and designed the course following the process as described in Persaud & Flipsen [4]. Productive failure flips the traditional learning process and starts with an explorative problem which students cannot solve without the right knowledge. This is followed by an instruction explaining the missing concept. This approach engages students in active problem-solving, with the goal to increase retention of the theoretical concepts and facilitate deep learning in a designerly way using the student’s curiosity obtained by “positively failing” at the start of the workshop.
In this paper, we will first present the course and its setup. The different workshops will be discussed shortly and one of the workshops will be explained more in detail. The experiential part of the course is described where students learn theory by doing, and the effects of the productive failure approach on

their learning. We qualitatively analysed the student's reflections on their learnings, their experience of the course, and the applicability of the course in future work, using NotebookLM from Google [5].

2 COURSE DESCRIPTION AND SETUP

In the Repair! course respectively 24 and 36 students participated over the past two years (Feb-Apr 2023 and Feb-April 2024). Students work on real-world client-based products consisting of companies designing and manufacturing electronic devices. Students work in teams of two and start out with one of the clients' products as a source for improvement, like a computer accessory (e.g. computer mouse), kitchen appliance (e.g. blender), or multimedia device (e.g. headset, figure 1). All products are electronic devices of high complexity which consist of more than 50 parts and many different types of connections. In the end each team delivers a demonstration model to validate their redesign and show the improved fit of the product within a circular economy. Next to the demonstrator a report is written which shows the application of the tools and methods taught during the course.

Figure 1. One of the results of student's product, improved on repairability (week 7).

The course is divided in seven weekly workshops and a final demonstration day. During the workshops, students are introduced to physical attributes of product architecture, such as documenting disassembly's and prioritizing parts, legislation and upcoming directives, and human factors in design for repair.
During the weekly four-hour workshop sessions students are experiencing the weekly concepts through a case-study, the computer mouse. We start the workshop with a quiz reflecting on the knowledge of last week. After the quiz, the student's brain is challenged by a problem they cannot solve without the right concept. Next they are instructed on the tools and methods applied during the second hour using several sprints with alternating assignments related to taught concepts. In the rest of the workshop time, they are guided in applying their acquired knowledge to the client-based project. The rest of the week the student teams work on their project and finish that week's tasks for which they have 6-8 hours.
Table 1 gives an extended overview of the weekly content and an impression on the Productive Failure pedagogy by presenting the weekly morning starter exercise. The course starts with a teardown in week 1 covering disassembly mapping [6], followed by week 2 where students define the key repair obstacles and locating critical parts using Hotspot Mapping [7,8]. In week 3 students deep dive into optimizing their project with redesign strategies and learn to improve the design on durability, diagnosis, maintenance, and repair [9-10]. Week 4 gives students space to continue with the disassembly mapping and come up with redesign solutions for observed hotspots using sketches and prototyping. In week 5 the influence of legislation, directives, and repairability indicators are discussed, and how this influences design [11-13]. During week 6 students learn about emotional, functional, social, epistemic, and conditional values influencing users to do repair [14]. Week 7, like week 4, gives students space to finish the report, prototype their redesign, and prepare their work for the demo day in week 8.

Table 1: weekly scheduled content and the related first Productive Failure exercises.

Wk	***Subject description***	***Productive Failure Exercise***
1	**Disassembly mapping:** the student is introduced to the course, the background reasoning, and the logistics of the course. They will teardown their case product and document it by using video recording and generating the disassembly map.	**Assignment 1:** Instructions are very important to make products more accessible and easier to repair. We have several computer mouses, and we want you to develop an instruction manual for others to use to assemble the computer mouse. You have 30 minutes to produce a manual, you can make use of photos, drawings, videos, and text to make the manual attractive and usable.
2	**Hotspot mapping:** the student uses their video recording and disassembly map to find the critical parts and activities in the product architecture. In combination with the disassembly map this will give a visual insight of the product architecture and the location of priority obstacles.	**Assignment 2:** After charting the product architecture in a disassembly map, the next step is to determine our focus. Specifically, we need to identify which parts require urgent replacement and which ones are most critical. You have 30 minutes to brainstorm strategies for prioritization. Your task is to disassemble the computer mouse and arrange all its parts in order of priority.
3	**Redesign strategies:** the student deep dives into optimizing their case product using redesign strategies like clumping, trimming, and surfacing. They are introduced to strategies improving physical durability, diagnosis, maintenance, and ease the process of repair.	**Assignment 3:** Let's turn the mouse in a Rubics cube and speed up the disassembly. How can you improve the design of the computer mouse to speed up the process of accessing with a factor of 2.
4	**Redesign:** the student has time to get by on the disassembly and hotspot mapping and come up with redesign solutions for hotspots indicated. In this phase students redesign and experiment by prototyping.	
5	**Legislation and context:** the student is informed about context-related aspects like existing and upcoming EU legislation, and country specific approaches like the French Reparability Index (FRI). The student will assess their product on the FRI and make redesigns for improvement.	**Assignment 5:** The EU wants more sustainable products and therefore want to score them. Produce 5 requirements to score the Repairability or Recyclability of the computer mouse.
6	**User aspects:** the student learns that product replacement is not only based on rational decision making, but also emotional, functional, social, epistemic, and conditional values. They are informed how these aspects influence the trade-offs that consumers make whether to repair their product or not. Several strategies are discussed that can increase the owned product's values and stimulate product retention.	**Assignment 6:** We all know the Fairphone series, and we all know how easy they are to repair! But why is it so easy to repair? Wander around this building in search for products and product features which facilitate and stimulate product care, inspection, and maintenance of the product.
7	**Remake and validate:** the student has time to finish the project with a report and a demonstrator. In this phase students validate their hypotheses by prototyping and experimenting.	
8	**Demo day:** the student teams pitch their work in front of the class and for the client making predominantly use of their demonstrator. The students prototyped new parts and connections and remade the original product into a more reparable demonstrator. During this 10-minute session the client is available online.	

3 WEEK 2 WORKSHOP EXAMPLE

Each week consists of a four-hour workshop, where we reflect on previous weeks by means of a quiz and deep dive immediately into an activity concerning the concept, the starter exercise as described in table 1. After their first exercise, the students are instructed on the specific week's content (tool or method). The didactical concept is based on the Productive Failure (PF) pedagogy [1] which has been formalized by the authors into a didactical method to develop workshops implementing this [4]. The Repair course is one of the courses where this methodology was successfully implemented.

As an example of how this was implemented, in week 2 students are introduced to Hotspot Mapping [7], where they learn about the concept of "critical parts" and "critical activities" which are challenging in the disassembly process. Critical parts are those parts in the product architecture which are important due to its functionality and failure/maintenance rate or are valuable due to the economic material value or the invested environmental impact. When these critical parts are reached or captured in an easy way and in a low number of activities this will cater for the ease-of-disassembly and the product's circularity. Therefore, the process of reaching these parts is also very important in the facilitation for the different R-strategies. Important aspects in these activities are time-to-disconnect and the difficulty of access described by the force, tools needed, and the accessibility of the fastener. To identify the critical parts and the critical activities the students will use Hotspot Mapping (HSM) where they document their disassembly process in a rigorous way using a spreadsheet tool to document every single step in the disassembly process.

Instead of instructing them on the tool, students are first challenged to dismantle a computer mouse and prioritize the components (figure 2). Without knowing how, they need to brainstorm their own strategies for prioritization, e.g. based on mass, volume, or difficulty of access. This step helps in activating their brain and related prior knowledge. While students fail to generate the correct solution, curiosity and a need-to-know develops. Only after this failing and struggling, they are introduced to the method of hotspot mapping where it is explained to prioritize activities based on time and difficulty of disassembly, and prioritize parts, based on failure rate, and its intrinsic economic and environmental value. For this they need to document the disassembly process in a rigorous way, noting down every step and its attributions while slowly peeling of parts and subassemblies from the main assembly.

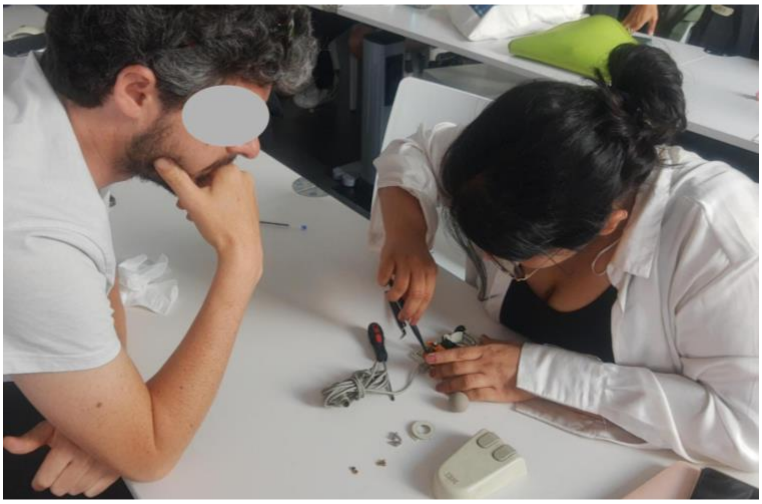

Figure 2. Dismantling a computer mouse and prioratisation parts and activities (week 2).

4 STUDENT EXPERIENCES

For quality control of the different courses, we use EvaSys surveys [5,15] which are sent out to our students who can grade the course on delivery, feasibility in time, quality of teaching, organization, amount of challenge, and expectation for success. The results of the student's evaluation (20 respondents) for the first run are very high and graded 8.5 out of 10, which is qualified as "very good".

"Why is this not a standard mandatory course in the IDE bachelor programme???"
[Noa, 2023]

Throughout the course, students were highly engaged in making the circular economy more actionable. Every week most students attended the course's workshops. To get a grip on their understanding and motivation we asked both cohorts of students to reflect on their project and their own learnings. We analyzed in total 60 written reflections from two cohorts, using NotebookLM [3] to generalize, group, and summarize their work. We anonymized all reflections before the data was uploaded in the online tool. The student's reflections were analyzed on (1) their learnings within the course, (2) the experience of the course, and (3) the applicability of the course content in future work:

(1) Learnings: students gained valuable insights into the multi-faceted nature of repair, going beyond simply "making things repairable". They gained a deeper understanding of product architecture through hands-on disassembly activities. The course highlighted the importance of considering the user's perspective in repair, emphasizing the need for clear instructions, accessible designs, and available spare parts. Additionally, students learned about the influence of policy and legislation on repairability, recognizing its potential to drive systemic change.

(2) Course Experience: students consistently praised the hands-on, practical approach of the course. Disassembling and analyzing real products provided valuable learning experiences and sparked curiosity about repair. Some students found the disassembly process initially daunting but ultimately rewarding. The interactive workshops and use of tools like disassembly maps and hotspot mapping facilitated their understanding of repairability.

(3) Future Applicability in Design: students expressed a strong intention to incorporate their learnings into future design practices. They recognize the importance of designing for repairability from the start, integrating user-centered considerations, and balancing repairability with other design factors. Some students plan to explore specific areas further, such as user engagement in repair, policy implications, and the integration of repairability with other circular economy strategies.

The course scores high already from the first run, but there is still room for improvement. Students would appreciate more time for deeper investigation into specific product aspects and potential improvements. They also found the user perspective and legislative aspects of repair very important and suggested to incorporate user testing of their redesigns to gain better insight in the actual user repair experience. While the legislative aspects were touched up with the Right-to-repair bill, students expressed a wish for a deeper dive into its practical implications like for instance how companies deal with logistics of spare parts. Lastly, while tools like the Disassembly and Hotspot Mapping were found to be useful and insightful, some students found the process of creating detailed maps tedious or challenging, especially with high-complex products.

CONCLUSIONS AND FUTURE OUTLOOK

The course scores high compared to other courses, demonstrating its effectiveness and appeal. Students are well engaged and gain substantial knowledge on design for repair and the ease-of-disassembly. The productive failure pedagogy proves successful in motivating students to acquaint them with the class content. In the fall of 24/25, we ran the course for the third time and introduced design for recycling [14] as a new concept. Students are introduced to Recycling Mapping and explore the discrepancies between design-for-recycling and design-for-repair. To improve the course experience, we are currently working with spreadsheet-based tools and are investigating the development of software to support and automate the process of making detailed Disassembly and Hotspot Maps. This continuous improvement ensures the course remains relevant and impactful for future learners.

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