2023

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THE ART OF REPAIRING - OR HOW TO TEACH ENGINEERING STUDENTS SUSTAINABLE DESIGN PRINCIPLES

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Conference Key Areas: *Addressing the challenges of Climate Change and Sustainability, Innovative Teaching and Learning Methods*
Keywords: *sustainability, problem-based project learning, fostering engineering skills, student empowerment*

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ABSTRACT

Project-based learning bridges the gap between theoretical training and practical applications. The motivation of students to participate is increased especially by working out real-life problems. To provide this kind of practical learning experience, we are establishing a repair project for broken, otherwise discarded, lab equipment. It will not only help to reduce waste and save money by repairing research equipment, but will also encourage interdisciplinary collaboration and innovation. Providing a space to learn about the underlying functional properties of various often highly specialized lab instruments, students identify malfunctions, deepen understanding of vulnerable designs, and discuss and perform strategies for repairing them under guidance, while collecting credit points. Through gaining a deep understanding of how these instruments work, students may even invent new strategies to realize similar tasks or add new features. This project builds on the findings from a 2021 pilot study. We discovered that by offering a repair project, students were able to gain a deeper understanding of theoretical concepts, improve their self-confidence as well as their motivation in learning, and increase their awareness of sustainable design. In the following, we are presenting the transformation of the pilot study into a current course concept. With weekly mini-evaluations we are monitoring students' learning success towards their learning goals and share the results.

1 INTRODUCTION

1.1 Motivation

“Addressing the complexity of sustainability requires innovative practices for teaching and learning, leading to new methodologies that aim to develop the broad sets of competencies required from the students.” (Kunrath and Beliatis 2022)

The 12th goal of the Global Goals Agenda for Sustainable Development (“United Nations Development Programme” n.d.) demands responsible consumption and production. In this context, in addition to an improved process cycle and the reuse of components, the repair and preservation of existing equipment is an essential sustainability goal. These goals are gradually being enshrined in EU legislation. For this reason, the European Commission presented a proposal on the "Right to Repair" - consumers should be able to have defective "consumer goods", such as household appliances or home electronics, repaired more easily (European Commission 2023). These goals continue at the state level and are promoted in the German federal states. Technische Universität Berlin is also striving to integrate sustainability goals, ethics, and diversity into its curriculum. Since studies show that increasing awareness of sustainability leads to an increased integration into higher education (Sammalisto and Lindhqvist 2008), interdisciplinary projects may serve as a multiplier.

Similar to production-oriented and recycling-oriented designs, a shift towards repair- and maintenance-oriented designs for appliances is necessary in the medium term. Students must be taught the skills necessary to adapt to this change in the future work environment. Some of these design approaches are already part of the theoretical training, but they need to be deepened in practice. Just as the skills required for creating a design suitable for production are best acquired by gaining hands-on experience in manufacturing the components one has designed, developing a design that is suitable for repair also requires practical experimentation, including learning from negative examples.

In a preliminary teaching survey about students’ needs and course topic preferences, sustainability was ranked second highest, surpassed only by the inclusion of current research topics. The big majority indicated the development of hard skills being their main learning goal, with a preference of learning technical content through hands-on formats (compare results 3.2). Since the devices to be repaired are intended for scientific use and the project aims at an intensive exchange between students and device users to gain a deep understanding of the functional principles, the presented project can fulfil many of these wishes and also combine sustainability with insights into current research topics in an interdisciplinary manner. The survey results were confirmed during the first iteration of the repair project, where it was integrated as the practice part of an already existing engineering course. 75% of students chose the repair project from a selection of six various hands-on projects.

In addition to the development of skills for the creation of repair-oriented designs and equipment, this teaching method offers the opportunity to further deepen theoretical and practical knowledge, to bring existing knowledge into the application and to support interdisciplinary exchange. In order to achieve these learning objectives efficiently, didactic methods and safety principles are required. Many common factors such as lack of goal clarity, low motivation, disorganized thinking, or mood swings can affect academic performance. Goal setting in particular plays an important role in social-cognitive learning models of academic achievement. According to psychological models, successful performance is associated with positive feedback loops between self-efficacy and goal commitment. When a student achieves a goal successfully, self-efficacy increases, which in turn increases commitment to the goal and mobilizes self-regulation of cognitive and motivational resources to facilitate further achievement (Morisano et al. 2010). For this reason, individual learning goals are developed in collaboration with mentors at the beginning of the project. These are continuously queried and reflected upon in the form of control loops.

1.2 Repairing: A way to strengthen sustainability learning goals?

Repair practices represent technical skills that allow designers to gain competencies in circular design (Terzioğlu and Wever 2021). Initially, students gain hands-on experience in troubleshooting and problem-solving, which effectively strengthens their critical thinking abilities. Repairing equipment also requires an understanding of the operating principles of the equipment, which encourages students to apply acquired theoretical knowledge to practical challenges. In addition, repairing scientific equipment promotes a deeper understanding of the importance of maintenance and sustainability in mechanical engineering. Students learn how to extend the life of equipment and reduce the environmental impact of industry by repairing and reusing equipment rather than replacing it. This is in line with the growing demand for sustainability in engineering and allows students to contribute to this important issue while developing their skills. Finally, repairing scientific equipment gives students a sense of accomplishment and pride in their work. Successfully repairing a piece of equipment provides a tangible result of their efforts and boosts their confidence and motivation to continue learning and growing in their field.

2 METHODOLOGY

2.1 Project organization procedure and didactic approach

Course assignment as repairing scientific equipment mandates a didactic approach that methodically guides students through the semester. The concept is mainly divided into two phases (compare Fig. 1): In the first phase, students are guided by mentors to independently acquire essential knowledge about the device and its operating principles. This phase also involves the development of a semester-long plan tailored to each student's individual learning objectives. During the second phase, students apply their existing and newly acquired domain knowledge, reflect on their current understanding, and expand it as needed. They also define and monitor their learning objectives, ensuring a more targeted learning experience. Mentors are available for the relevant phases, and experts are identified and involved as necessary. These can include students from other specifically required disciplines. Depending on necessity and availability, the involvement takes place on site, either online or hybrid. The mentors also assist in recruiting the experts or company members of the equipment manufacturers who contribute expertise. To deepen knowledge and integrate the interdisciplinary approach, students have the opportunity to also benefit from expert knowledge offered in various workshops. For example, problems arising from electrical engineering can be discussed and solved independently, with the help of experts, in the so-called "Soldering Lab" at Technische Universität Berlin.

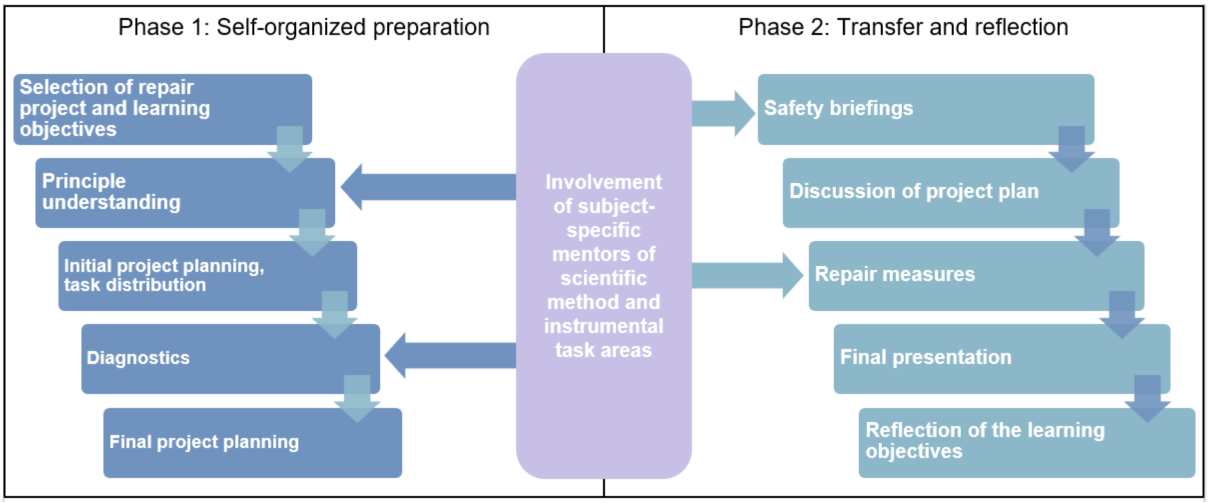

Fig. 1 Draft of didactic approach

To provide equipment, a call was launched via an existing interdisciplinary network within the university. As a result, several well-suited devices with complex operating principles were identified and collected for the repair project. Depending on the equipment, the involved departments agreed to make reusable subcomponents of the devices available to a student pool for equipment development if repair is not possible, in the interests of sustainability. Repaired devices are reintegrated into the scientific activities.

<u>Learning objectives</u>

In addition to promoting a sustainable mindset and providing a course to teach advanced engineering skills, we also support students in gaining and strengthening competencies such as teamwork, conflict resolution and leadership skills. As individual learning goals tend to have a positive impact on learning outcome, we ask students to elaborate their learning objectives in terms of soft and hard skills that they aim to achieve during the project. The elaboration of those goals is supported by the addition of a psychological online test, addressing “Past and Future Self Authoring” (Morisano et al. 2010) and discussions with the mentors at the beginning of the course. The test consists of two stages. Stage 1 involves writing a positive personal vision and a negative counter-vision in order to undergo the past authoring phase. Stage 2 involves analyzing and organizing the positive vision developed in the first stage as well as formulating a detailed plan for implementation and self-monitoring. Participants are required to title and rank-order their individual learning goals and to justify each goal from a personal, familial, and social perspective, to consider potential obstacles and strategies to overcome them, and to formulate a personal progress monitoring process. The goals are monitored and reflected on with the mentor.

<u>Preparation phase (Phase 1)</u>

Students select a repair project from the available science equipment that matches their area of interest, their area of knowledge, and their personal learning goals. A student group that is as interdisciplinary as possible allows for division into diverse learning objectives that are linked to one another. Students will try to understand the structure and (measurement/function) principle of the device on their own and discuss the results in their team. A mentor will help with the team discussion. The aim is to understand the device well and find out what additional knowledge is required. After that initial research phase, the teams develop a working plan for the semester, which includes the definition of team and individual learning objectives. Each team member is assigned a different area in which he or she is to become an "expert". This also results in different specific tasks for each team member, which are to be documented. In order to increase motivation in achieving individual goals, a continuous exchange with the mentor is encouraged to reflect on whether their choice of methods during the project phase offers promise of success (Morisano et al. 2010). Next, the most time-consuming step of phase one starts and requires the students' independent organizational skills. Together with the mentor, the student teams examine the device, identify defects and malfunctions and, consequently, learn more about the device. This may also result in new learning content, which must be assigned as a task. The step requires a problem hypothesis, a plan for testing, and, depending on the outcome, an iteration, a new hypothesis and an adapted plan for testing. Now that the problem is known, the teams finalize project planning, taking into account the repair measures, timing, methodology and necessary equipment. In the process, tasks are distributed according to the areas of expertise defined earlier. To ensure an even workload, adjustments may need to be made to the arrangements documented in their working plan.

Transfer and Reflection (Phase 2)
After determining what needs to be done, the practical implementation takes place. Since active manipulations of the equipment now begin, mentors provide mandatory equipment- and task-specific safety briefings. Especially with regard to electrical interventions, entitled expert mentors are important. We involve in-house electrician trainees for these activities. Before starting the practical work, students present their project (instrument, problems, and repair plan) to the other teams. In doing so, they learn from each other, identify possible commonalities and discuss their approaches to solve the problems. Next, the most time-consuming step of the second phase takes place. Using the test methods developed before, students implement the planned repair measures and test whether the repair was successful or not. During this process, mentors remain available as needed. Towards the end of the project, students present the results and reflect on their success or failure in a (hopefully) lively discussion. Especially in the case of failure, it should be discussed whether further work by a new group of students in the following semester may have a chance of success if building on the current results. Finally, the students summarize their results in a report and meet with their mentor to conclusively reflect on the implementation of their learning objectives and the experience gained in a mutual feedback discussion.

2.2 Numeric evaluation of teaching/learning preferences

In Winter 2022/23 we used our Moodle based learning platform to conduct a survey with the goal to learn about students' teaching and learning preferences. It was divided into several sub-areas with different relevance to different projects offered. In addition to demographics, data was collected on the use of courses and teaching media, the desire and opportunity to participate in the design of teaching topics, learning types and learning behaviors, learning goals, and about the support offered for the achievement of learning goals. Furthermore, students were asked about the relevance of topics such as sustainability and society in education, as well as motivational modalities. The aim was to compare students' desired educational experience with what they experience in university. For this purpose, point systems (1-5 points for not relevant to very important) as well as binary answer options and free-text areas were used.

2.3 Numeric evaluation of learning success

To assess participants' learning progress, we have designed a series of surveys that students complete anonymously at regular intervals. Throughout the semester, the current status of their personal learning goals (hard and soft skills) is reflected weekly via a scalar query (0 for no experience - 100 for expert).

2.4 Use case examples of systematic lab equipment refurbishment

The project aims to provide scientific devices from as diverse a range of disciplines as possible: precision mechanics, optics, fluidics and electronics. In the following, the explained procedure is illustrated by the case study of an optical device. The system chosen by the student is a special surface interferometer. The applied teaching content correlates with a master course for micro-optical systems.
First, an analogy model of the optical components was built on a breadboard in order to understand the principle and the influences. The learning objective of this methodical preparation was to build up a basic understanding of interferometry. This preparation also included an independent literature research to understand the operation of a special component used in this interferometer to reduce the so-called spatial coherence. The learning objective was to understand spatial and temporal coherence and how they affect the system. At this point, a mentor from the field of optical simulation and optical metrology was involved to realize a virtual model of the system and a mathematical analytical description that would simplify the failure analysis. It became apparent that the replacement of defective optical components and the sensor technology was necessary. The sensor replacement in particular required the development of further specific knowledge, since a low-cost open source solution was to be used. This required programming a custom software for the sensor readout, as well as introducing the open source software for data analysis. The learning objectives were an understanding of the necessary quantum sensor technology, LabView programming (laboratory software standard) and the regulations of open source software. After integrating the new components and sensor technology, a successful validation was achieved through measurement on known reference components. The whole project was documented in a final report.

3 RESULTS

3.1 Lessons learned from the case study

We interviewed the student who repaired the optical instrument featured in the case study. They shared very positive experiences during the process and expressed a strong sense of pride in the successful restoration of an otherwise lost instrument, thereby contributing to sustainability at the university. They also mentioned that they learned even more than they expected initially and explained that the didactic schedule required them to first gain a thorough understanding of the physical principles of the instrument; by using an analogy model, many of the theoretical concepts that they had only partially learned before now really made sense to them. Furthermore, they even developed ideas to improve its accuracy, showing the project’s potential to boost creativity through a hands-on high-level understanding of high precision instruments. They also underlined that having access to a supportive mentor helped them to not lose track during the project and to ultimately reach their learning goals. Not having repaired a device of any kind before, the project lowered their inhibition threshold, and they now regularly opens malfunctioning instruments and tries to repair them. This demonstrates that the project has the potential to support students in developing a sustainable mindset.

3.2 Results of preliminary survey about teaching/learning preferences

In the teaching survey about students' teaching and learning preferences (n=21), students indicated the following: In ranking the importance of course topics, sustainability was ranked second highest (3.7/5), surpassed only by the inclusion of current research topics (4.4/5). 83% of students indicated learning objectives, with hard skills being the most important to the vast majority (76%). This was also confirmed when asked about reasons for choosing courses, with a value of 4.1/5, technical content was the highest rated reason. Having a value of 4.2/5, learning through practical activities was the most highly rated form of teaching. Also with respect to hands-on formats, hands-on activities with a sustainability focus were ranked second highest with a value of 3.7/5.

3.3 Transformation to a repair project

Based on the learnings derived from the case study, we developed the repair project as a practical course concept and measured the learning success towards their learning goals (compare section 2.1). The learning goals are freely selectable and are taken into account when choosing the appropriate device for repair. The only requirement is that each student defines at least one hard and one soft skill. The specific learning objectives are known only to the mentors. In the surveys, a distinction is only made between soft and hard skills to ensure anonymity. The top three hard skills selected by students themselves included learning new programming languages, working with electronic components and understanding new manufacturing methods. The development of understanding within their learning objectives was reflected weekly, as described in section 2.3. At the submission of this conference paper, nine weekly surveys had been conducted. The data from students who regularly completed the survey (n=3) is summarized in Fig. 2.

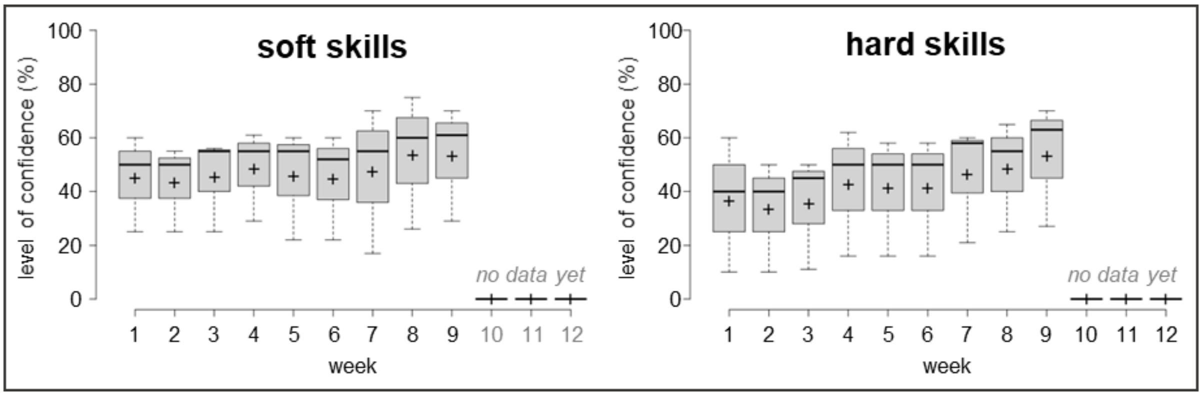

Fig. 2 Boxplots of the weekly evaluations about the development towards their hard and soft skill learning goals (scale: 0=know nothing at all, 100=feel like an expert). The mean of all answers for each students' individual learning objective is displayed with a "+". Please note that the last three evaluations are yet to be carried out at the time of this submission.

The data suggest that students' perceived confidence levels improved over the weeks, a trend that is corroborated by the mentors. Intriguingly, the mean decreases after the the fourth week, which was the week preceding the students' presentation

of their projects in front of their peers and scientific staff. This drop could be attributed to the students being faced with new details and deep questions. Another notable change occured in the seventh week when the students commenced their practical reparations.
Student feedback named the project format as instructive, and motivating for self-learning, and encouraged its continuation. The lessons learned from this first iteration will be used to further improve the didactic concept.

4 SUMMARY AND FUTURE DIRECTIONS

The presented project is designed to be emulated, as it provides a great learning opportunity for students while increasing the sustainability of a university as a whole. We are planning to integrate it into the curriculum and are already in contact with other self-organized repair workshops to establish a university-wide repair campus. By joining forces and competencies, we expect to create a momentum, strong enough to transform our university into a role model for repair friendly environments. Observed by the public, we expect to inspire other organizations, companies and even citizens to adopt more sustainable practices. Together with the engineers we train, we aspire to become ambassadors for circular production and repairable products in order to promote sustainability and contribute to a more sustainable world.

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