25TH INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
7-8 SEPTEMBER 2023, ELISAVA UNIVERSITY SCHOOL OF DESIGN AND ENGINEERING, BARCELONA, SPAIN

SUSTAINABLE PROTOTYPING CHALLENGES IN DIGITAL FABRICATION DESIGN EDUCATION

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ABSTRACT
Education in digital fabrication design involves an active learning environment where ideas are transformed into prototypes. The way design activities are carried out and the kinds of outputs are all impacted by this environment. Knowledge concerning sustainability practices and how it affects students' learning and skill acquisition is scarce. Therefore, the main goal of this study was to examine and evaluate learners' sustainability practices and educational experience in a digital fabrication class. A seven-week first-year university course covered the fundamentals of design and digital fabrication, including electronics design, embedded programming, 2D design, and 3D design. Students were encouraged to create and implement their own ideas by designing and building a physical prototype that interacts with its surroundings. They worked in teams and were required to document their process on a weekly basis. The documentation and the final design prototype were the main deliverables of the course. Sustainability requirements were integrated as evaluation criteria, including the use of sustainable materials, reusing components, building instead of buying, and easy-to-reuse project components. Data collected from student documentation, surveys, and prototypes were analysed to identify sustainable practices and learning aspects. Findings showed that sustainability as a process and sustainability about the final prototype should be addressed differently. This requires timely actions on sustainability by both students and instructors. Intervention programs should be aware of sustainability issues in digital fabrication without compromising design education, iterative prototyping, and learning.

Keywords: Digital fabrication, prototyping, makerspaces, FabLab, sustainability practices

1 INTRODUCTION
Digital fabrication design education is defined by an active learning environment in which prototypes are created from concepts. This is a defining feature of this field of education. This environment (i.e., digital fabrication laboratories or FabLabs) has an effect not only on the method in which design activities are carried out but also on the content that is learned and the types of outputs that are produced [1,2].

Fundamental digital fabrication classes have been incorporated into the university curriculum, especially in design education (e.g., [3]). The context of digital fabrication has the potential to affect how design is taught in higher education [1,2,4]. This environment determines how design activities are conducted (e.g., [5]) and how knowledge is obtained (e.g., [6]), as well as the types of outputs that are feasible (e.g., [7,8]).

However, there is currently a lack of knowledge regarding sustainability practices and how they impact student learning and skill acquisition. Therefore, the objective of this research was to assess learners' sustainability practices and educational experience in a digital fabrication course.

2 SUSTAINABILITY AND DIGITAL FABRICATION DESIGN EDUCATION
Digital fabrication affords the possibility of digital do-it-yourself (DIY). Previously, the substitution of mass production with DIY practices based on a more sustainable model has been contested. In some instances, digital do-it-yourself is less sustainable because the manufactured object may be considered replaceable [9]. The substitution of mass production with localized digital fabrication has various

implications for digital do-it-yourself, such as the novel combination of readily available resources and materials [10] and the customization of objects [9]. These repercussions demonstrate that personal digital fabrication practices may have varying impacts and outcomes. The repair and reuse of existing objects [10] as well as the use of local and recycled materials in the production of new objects [9,11] have been pursued for their high environmental value.

As a tool for design education, digital fabrication impacts both the process and the outcome. This scenario of digital fabrication education must cope with varied criteria for digital fabrication abilities, design skills, and sustainability [12]. However, the design education context typically does not permit a great deal of sustainability-focused experimentation [13].

At the universities, digital fabrication is regarded a curricular component aimed at the development of specialized skills [3]. To strengthen design education inside the digital fabrication framework, it is vital to appreciate sustainability challenges and recommend intervention strategies. Despite the fact that digital fabrication courses and design studios share significant similarities [1,3,14], the development and implementation of sustainable solutions remain a challenge. Digital manufacturing spaces, such as FabLabs, offer innovative technology in a well-organized environment that is accessible to a broad variety of stakeholders, independent of their level of experience [15]. FabLabs are open environments where students may meet persons from diverse backgrounds working in the same field and be exposed to fresh ideas and fields of expertise, hence raising the likelihood of unforeseen synergies and creativity [16, 17]. Furthermore, these environments open avenues for synergy between research and education [18].

Especially in digital fabrication classrooms, a systematic examination of sustainability is rarely the primary focus. Existing initiatives continue to focus on distributed production and its influence on environmental sustainability, mass customization and personalizing, and sustainability evaluation [13]. It has been observed that digital fabrication cultures differ in their emphasis on sustainability. This gap was observed between users interested in assessing environmental implications and those interested in tracking the rapid evolution of new digital fabrication technologies and materials [11]. The multiplicity of approaches within the FabLab context cannot be extended to certain distinctive characteristics [19], making it difficult to monitor and alter the consequences of sustainability and design education. Hence, sustainability must be emphasized in design education within the framework of digital manufacturing.

3 RESEARCH METHODOLOGY

To investigate the integration of sustainability in design education, we implemented a method that introduced sustainability requirements as an intervention in a digital fabrication course. We collected data through documentation from the course, its outcomes, sustainability grades, and a series of self-reported subjective evaluations.

3.1 Course and context

This study targeted first-year students participating in a 5-ECTS (1 ECTS equals 27 hours of effective work) digital fabrication course offered by a European institution. In terms of requirements, intensity, duration, and load, the course's qualities are typical of the curriculum. The instructional language was English.

The seven-week BSc course was intended to help build design knowledge and skills. Although it was part of the bachelor's degree program in computer science, it was open to all university students. As a result, it attracts students from diverse backgrounds and academic areas. This course is intended to prepare students to develop interactive physical prototypes with mechanical, electrical, and software components. Designing and fabricating mechanical and electronic components and integrating software in a microcontroller are the major activities. The course is organized into two sections: a series of six lectures followed by guided project work. During the first two weeks of the course, six lectures introduce the primary aspects of design and digital fabrication, including an overview of FabLab, the design of physical objects, electronics design, embedded programming, 3D modeling and printing, and 2D design. Students were encouraged to conceive and realize their own ideas by designing and constructing a physical device (gadget) that interacts with its environment throughout the course of the subsequent five weeks. The device must meet the following requirements: (1) it must be primarily composed of mechanical and electronic components designed and manufactured in FabLab; (2) it must have moving parts that can be controlled by software; and (3) it must include at least one sensor and one actuator, with the software responding to the sensor's readings.

We employ various data streams, including students' documentation, final prototypes, course grades, and self-reported measures in surveys to analyse sustainable practices and learning in the context of the course.

3.2 Sustainability requirements

In this study, the course under investigation utilized specific and comprehensive sustainability requirements as part of its evaluation criteria. These requirements included: (1) reusing components, (2) choosing adequate and sustainable materials, (3) building instead of buying, and (4) selection of easy to reuse project components of the project. Reusability refers to utilizing previously disassembled components from prior projects or considering the potential for reuse in the current prototype. Reusing electronic components and their connections is a common practice.

Students were introduced to the sustainability in digital fabrication framework, which identifies categories of design, material, process, and de-assembly related to a set of sustainability indicators [12], such as recycling, reusability, transportation, energy consumption, waste reduction, emissions, and end-of-life considerations.

Individual student performance was evaluated by the instructor, with the sustainability criterion graded on a scale of 1 to 5, where 1 is low and 5 is high, and accounting for 5% of the final course grade. High performance on the sustainability criterion was achieved when all sustainability requirements were met. The sustainability grade was assigned per team.

3.3 Data collection: Documentation and prototypes

To support their learning, students were required to document their process on a weekly basis, with the online documentation and final design prototype serving as the primary deliverables for the course. Table 1 provides an overview of the two main sources of data, including their type, time, and relation to sustainability information.

Table 1. Sources of data collection regarding sustainability of the digital fabrication course

Sources	Type	Time Frame	Sustainability information
Documentation	Introduction, Weekly records, Summary	Week 1, Weeks 2-7, Week 7	Alternatives considered, Iterations and their number
Prototypes	Final presentation and demo	Week 7	Implemented solutions

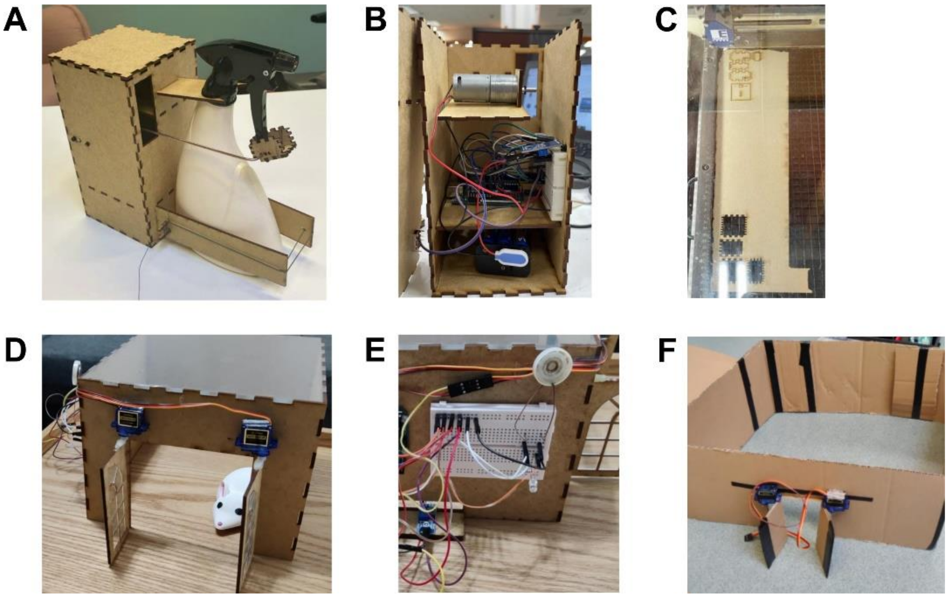

Figure 1. Examples of two prototypes and their sustainability characteristics: Refresher gadget prototype (A), its inner structure and electronics (B), laser cutting of some of the of its parts (C), and Mouse trap prototype (D), the electronics on its side (E), its early iteration made of cardboard (F)

Figure 1 showcases two prototypes and various aspects of their sustainability. The first prototype (Figure 1A) is a refresher gadget that detects high ambient temperatures and passing people to spray water. This mechanism is adaptable to different-sized bottles and considers de-assembly (Figure 1B). However, the production process is not optimized for minimal material use (Figure 1C), resulting in large spaces of unused material. The second prototype (Figure 1D) is a mouse trap that closes trap doors when detecting an object entering the space. This prototype also considered de-assembly (Figure 1E) and used materials with lower environmental impact for early iterations (Figure 1F)

3.4 Data collection: Survey

We gathered demographic information from the students and collected their post-course subjective evaluations of their experiences. The survey included four psychological dimensions, including perceived (i) skills, (ii) confidence, (iii) motivation, and (iv) enjoyment, which were represented by five technological dimensions: (a) 2D design, (b) 3D design, (c) electronics, (d) programming, and (e) use of tools and devices in digital fabrication. The survey utilized a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Out of the 96 students who completed the course, we collected 84 valid responses from the survey.

4 RESULTS

This section focuses on the relationship between the sustainability grades and the post-course subjective measures. Out of 84 students, 42 received a sustainability grade of 5, 27 received a grade of 4, and the remaining received a grade of 3.

We examined the correlations between the grades and the post-course subjective measures of skills, confidence, motivation, and enjoyment in each of the five technological dimensions of 2D design, 3D design, electronic prototyping, programming, and use of tools and devices. Out of all the skill measures in the five technological dimensions, only experience in 3D design and modeling showed a significant negative correlation to the sustainability grade ($r = -.296$; $p < .01$). There were no significant correlations regarding motivation measures in any of the five technological dimensions. Similarly, out of all the confidence measures in the five technological dimensions, only experience in 3D design and modeling showed a significant negative correlation to the sustainability grade ($r = -.266$; $p < .05$). Finally, out of all the enjoyment measures in the five technological dimensions, only experience in 3D design and modeling showed a significant negative correlation to the sustainability grade ($r = -.243$; $p < .05$). Overall, no relationships between the sustainability grade and post-course subjective evaluations of 2D design and modeling, electronic prototyping, programming, and use of tools and devices were observed.

5 DISCUSSIONS

5.1 Quantitative analysis of grades and post-course subjective measure survey

The negative correlations between sustainability grade and 3D design and modeling skills, confidence, and enjoyment in digital fabrication design education suggest that there may be trade-offs between the sustainability of a prototype and the level of expertise and enjoyment that students have in using 3D design and printing. These findings can be interpreted in two directions.

The first direction suggests that 3D design, and printing may not be the most sustainable alternative for digital fabrication prototyping in design education. Using alternative techniques such as 2D laser cutting or a combination of laser cutting and 3D printing might be more sustainable, which aligns with previous studies [12]. While 3D printing is an innovative and exciting technology that enables designers to create complex shapes, it requires a notable amount of energy and materials, and often produces waste. In contrast, laser cutting might be a more precise and efficient process that produces less waste and requires less energy. By using a combination of 2D laser cutting and 3D printing, students can achieve the best of both worlds - precise, efficient prototyping with minimal waste.

The second direction suggests that investing too much time and effort into 3D design might divert attention from actual hands-on resolution of sustainability issues. While 3D design and printing can be valuable tools for designers, they should not be the sole focus of a digital fabrication course. Sustainable design principles and practices should be integrated into the curriculum and emphasized throughout the design process. Students should be encouraged to consider the environmental impact of their designs and to explore alternative materials and processes that minimize waste and energy consumption. By prioritizing sustainability in the design process, students can develop the skills and knowledge needed to create innovative and sustainable solutions to real-world problems.

5.2 Qualitative analysis of sustainability

Results showed that the high-scoring design outcomes produced by the students included sustainability elements based on the use of materials and processes available in the digital fabrication laboratory. Students were concerned with the assembly and disassembly of reused components, as well as the reduction of generated waste and emissions, which was found to be critical for effective and sustainable digital fabrication practices. Sustainability, in terms of recycling and energy usage, relates to waste and emission reduction. Waste refers to excessive material use (see Figure 1C), and the initial ideation provides a crucial opportunity to reduce waste [20]. Design education interventions can optimize the prototyping process, mostly in the ideation phase (see Figure 1F), and eliminate wasteful iterations, mainly in the prototyping stage.

In general, the findings showed that sustainability as a process and sustainability about the final prototype should be addressed differently. This requires timely actions on sustainability by both students and instructors. Intervention programs should be aware of these sustainability issues affecting digital fabrication design, without compromising design education iterative prototyping and learning.

In addition to the reduction of environmental impact in prototyping and small series production provided by digital fabrication manufacturing, the final product designs have substantial environmental impact [11,13,20]. This perspective has implications for design education, and the findings of this study represent only a small part of the overall environmental implications.

5.3 Implications

Overall, educational interventions require timely actions on sustainability by both students and instructors. In terms of technology and methods, educational interventions should emphasize the understanding of a variety of possibilities and alternatives for materializing prototypes. Depending on the concept for the prototype, using a new digital fabrication process for the complete prototype construction could have a favourable effect on sustainability. Alternatively, decomposing the prototype's structure and materializing various components using various digital manufacturing techniques can also have a positive impact on sustainability. The focus of education should be on comprehending the characteristics, purpose, and sustainability consequences of numerous design iterations. Early design iterations, which are intended for learning, can be realized with low-fidelity materials that are leftover, salvaged, or repurposed (as shown in Figure 1F).

6 CONCLUSIONS

Our study of a digital fabrication design course revealed the importance of using specific materials and processes for different design iterations to achieve effective and sustainable digital fabrication practices. Intervention programs in higher education institutions aimed at digital fabrication courses in design may benefit from considering our findings. These will help to improve design education in suitability, particularly regarding aspects such as waste, emissions and reuse of components. Furthermore, our findings have implications for implementing sustainability in digital fabrication prototyping, particularly in small teams and startups engaged in product development. By incorporating sustainable practices in the design process, such as the use of sustainable materials and reducing waste, startups can reduce their environmental impact while also improving the overall quality of their products.

ACKNOWLEDGEMENTS

This research was funded by the Academy of Finland 6Genesis Flagship grant number 346208, and by the Erasmus+ project “Bridging the creativity gap” (agreement number 2020-1-UK-01KA202-079124).

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