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Sustainability Considerations in Digital Fabrication Design Education

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Abstract: Design education utilising digital fabrication is characterised by a dynamic project-based learning environment in which ideas are embodied in prototypes. This environment affects the way design and fabrication activities are taught, including sustainability considerations in the process and the outcomes. With the objectives of refining the sustainability indicators in the context of digital fabrication design education and identifying educational interventions for improving sustainability, we analyse the processes and outcomes of a digital fabrication course. We further develop a conceptual framework for sustainable prototyping based on the prototyping and testing stages in the design thinking model. The sustainability considerations in the prototyping process and outcomes in the design education context in FabLab are exemplified. The findings will help enhance sustainability and develop interventions in the context of design education.

Keywords: digital fabrication; design education; prototyping; FabLab; makerspace; sustainability education; sustainability indicators; environmental sustainability; economic sustainability; sustainable experience design

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1. Introduction

Design thinking entails generating ideas while addressing a design challenge and translating them into a solution. The design thinking paradigm refers to a well-established conceptual framework in which the creation of a solution results in a tangible product [1] and is generally applied in design education [2]. One possible standard solution might be the materialization of a prototype, which can be defined as "a concrete representation of part or all of an interactive system" that is a tangible artefact, not an abstract description that needs interpretation [3]. Prototyping is an essential step in the design thinking process; this is where digital fabrication plays an important role. Digital fabrication is characterised by the use of convenient techniques that facilitate the rapid creation of physical prototypes using CAD and CAM tools [4].

The use of makerspaces and digital fabrication laboratories (FabLabs) is rapidly increasing, particularly in design and engineering education [4,5]. The case of design education uses problem-based learning (PBL) approach employing technology-rich FabLab environments for prototyping [6]. Prototypes, as concrete representations of tangible artefacts, utilise various software, materials, and processes in digital fabrication laboratories [4], which can have extensive sustainability implications.

Distributed production in digital fabrication laboratories and makerspaces has been seen as a way to promote environmental sustainability [7]. Furthermore, digital fabrication can support sustainable economic development by promoting social sustainability and suitability, inclusiveness, usability, and accessibility [8]. However, sustainability and general environmental issues are rarely promoted in their own right in the digital fabrication context because environmental issues are intertwined with other ideological concerns of the maker movement [9]. In particular, the social, economic, and environmental sustainability of digital fabrication is not living up to this potential [10]. For instance, some studies examined the social aspects of digital fabrication for humanitarian development and develop a framework for the social sustainability of design implemented through digital fabrication [11,12]. A case study observed the effect of replacing traditional prototyping material in digital fabrication with biomaterial [13]. However, in experimental learning during the prototyping phase, the use of bio-based and biodegradable materials remains very limited [14].

The safety of digital fabrication laboratories is examined as an essential environmental responsibility of the users [15,16]. Furthermore, safety has been promoted as a social responsibility in the fabrication context incorporating sustainability concerns for monitoring and displaying the consumption of energy [17]. Behaviour change for sustainability is targeted to promote energy awareness in digital fabrication [18]. Typical recommendations include engagement with sustainability-oriented makers and other stakeholders in the digital fabrication context [9]. Moreover, scaffolding is highly recommended to engage robustly with central sustainability issues [9].

Nevertheless, systematic investigation of sustainability is often not the main focus, especially in digital fabrication classrooms. The existing efforts are constantly set into (1) distributed production and its impact on environmental sustainability; (2) mass customisation and personalisation, and assessment of sustainability [7]. The gap between different digital fabrication cultures in their sustainability focus has been acknowledged. This gap was identified between users interested in assessing environmental impacts and users interested in following the rapidly evolving new technologies and materials in digital fabrication [17]. The diversity of approaches within the FabLab context cannot be extrapolated to specific characteristic elements [19]; hence, the effects of sustainability and design education can be challenging to manage and change. Students' theoretical and empirical understanding of developments geared toward advancing sustainability is limited [20]. Therefore, sustainability is an essential topic to focus on in design education in the digital fabrication context.

The objectives of this article are (1) to refine sustainability indicators in the context of digital fabrication and (2) to identify educational interventions for improving sustainability. To address these objectives, we performed a qualitative analysis of the processes and prototyping outcomes of a digital fabrication design education course.

In the following Section 2, we discuss the issues of digital fabrication design education and sustainability. In Section 3, we identify sources that can be used for sustainability information and assessment. Section 4 describes the methodology and the case of the digital fabrication design education course used in this study. The following Section 5 presents the results in terms of refined sustainability indicators. Section 6 discusses the findings, identifies potential sustainability impacts and interventions, and outlines the need for sustainable experiences with digital fabrication. The final section concludes the findings.

2. Digital Fabrication Design Education and Sustainability

Digital fabrication is an opportunity for a digital do-it-yourself (DIY). Previously, the substitution of mass production with a more sustainable model of DIY practices has been challenged. For example, in some cases, digital DIY is less sustainable because the fabricated object might be considered replaceable [21]. The mass production substitution with localized digital fabrication is presented with different implications for digital DIY, including the combination of resources and materials on hand in novel ways [22] and the personalisation of objects [21]. These implications highlight that personal digital fabrication practices might vary in their impact and consequences. High environmental value has been sought in the repair and reuse of existing objects [23], as well as in the use of local and recycled materials in the fabrication of new objects [17,21].

Digital fabrication design education ranges from brief topic workshops (e.g., [24–26]) to systematic programs spanning six months or more (e.g., [27]). In comparison to STEM digital fabrication education (e.g., [28]), digital fabrication design education is more extensive and skill-focused. These skills can range from teamwork or interpersonal skills to self-regulation, creativity, professional skills, problem-solving, technical skills, and critical thinking [29]. Creativity, professional/technical skills and teamwork are central in many cases [25,29]. In addition to these skills, empathy skills have been identified as developing global competencies in this context [30].

Recently, general digital fabrication courses have been part of university courses, particularly in design education (e.g., [25]). Digital fabrication environment has the potential to influence how design is taught in higher education [31–33]. This environment influences the manner in which design activities are carried out (e.g., [34–36]) and knowledge is acquired (e.g., [11,37,38]), as well as the sorts of deliverables and outcomes possible (e.g., [27,39]). It has been suggested that university-based digital fabrication spaces can provide significant growth experiences to a varied student group, which may be difficult for a single university department, program, or course [40].

Consequently, digital fabrication as a design education tool influences both the process and output. This case of education in digital fabrication has to deal with varying requirements in terms of digital fabrication skills, design skills, and sustainability requirements [4]. Furthermore, the design education case usually does not allow for much sustainability-oriented experimentation [9].

Creativity enhances environmental, social, and economic performance by fostering environmentally friendly outcomes and mechanisms [41]. Together with innovation, creativity is typically considered for design education and anticipated impacts on industry and society [4]; thus, it is a focus in digital fabrication design education. More importantly, creativity has been seen as the pivotal ability to produce innovative outcomes in FabLabs and makerspaces [42,43]. The positive role of makerspaces in leveraging creativity and developing innovative, sustainable, and viable products has been identified [42]. Development of such products requires sustainable knowledge co-creation founded on systemic transformation. In such transformation, student groups actively and creatively participate in knowledge co-creation while acquiring experience in learning, teaching, negotiating, and course redesign alongside teaching professionals [44].

At the university level, digital fabrication is considered part of the curriculum targeting specific skill development [25]. It is necessary to comprehend sustainability issues and suggest intervention programs to enhance design education within the digital fabrication framework. Although digital fabrication classes and design studios have certain commonalities [25,31,45–47], the creation and implementation of sustainability solutions remain a problem. Digital manufacturing spaces, such as FabLabs, provide advanced technologies in a well-organised environment accessible to a wide range of stakeholders, regardless of their experience [42,48,49]. FabLabs are open spaces where students may meet individuals from many backgrounds working in the same area and be exposed to new ideas and disciplines of expertise, thus increasing the potential for unanticipated synergies and innovation [42].

Figure 1 presents the original framework for digital fabrication based on sustainable design and prototyping developed by Soomro et al. [4]. The sustainability considerations and details of digital fabrication software, materials, and processes are further specified under “Digital Fabrication” (see Figure 1).

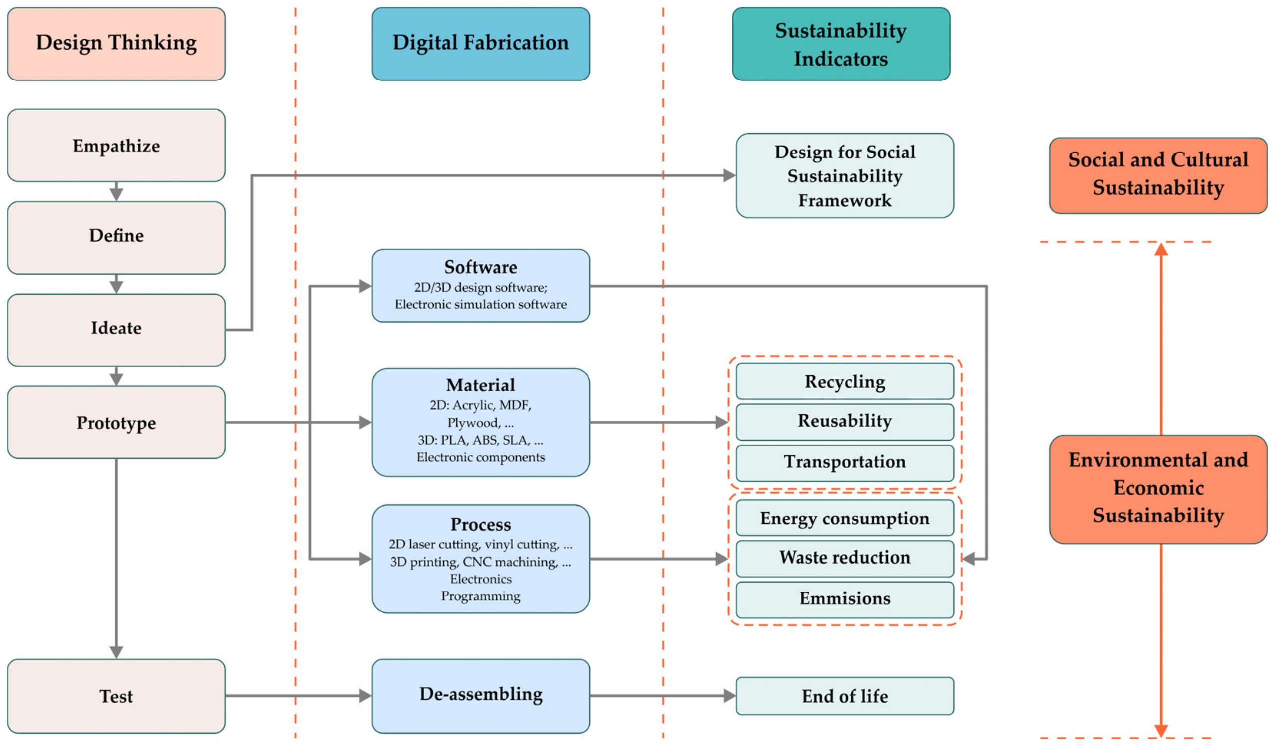

Figure 1. The original framework for digital fabrication-based sustainable design and prototyping (adapted from [4]).

3. Sources for Sustainability Information and Assessment

Sustainability can be evaluated based on different sources of information. Digital fabrication laboratories incorporate a wide variety of activities, many of which cannot be formally recorded. For example, documenting one's own activities might represent a challenge [50]. The time needed to document such activities properly might interfere with digital fabrication activities. Therefore, various approaches exist to facilitate written or spoken documentation [50], automate parts of the activity such as picture capturing [51–56] and facilitate students' assignments and instructors' feedback for students' progress [50].

Table 1 systematises possible sources of sustainability information that might be useful for determining and assessing sustainability in the context of digital fabrication. Curriculum-based design education in digital fabrication typically falls into the first category of formal educational activities. The typical time frame ranges from a few weeks (a period) to an entire semester. Examples of such education include degree courses and programs [25,35,57–59], intensive workshops [6,24] or separate degrees [27]. The larger time frame and the larger scale, in particular cases, represent challenges for identifying and analysing sustainability information. The challenges can be summarised as follows:

- A larger time frame creates a diversity of instances of information. For example, this can be various outputs, types of documentation, self-reports, or whether the particular setting allows monitoring of the generated waste.
- A larger scale creates challenges due to the scale of the information—for example, the number of outputs, documents, and reports.
- Digital fabrication education interweaves with other activities in typical universally used digital fabrication spaces. For example, this is the case with digital fabrication in a designated FabLab (hence, a member of the FabLab network), where various activities can occur in the same physical and social space and time.

Typically, such information can be obtained using direct and indirect sources. These can be part of the requirements of formal education. In this particular case, formal education and personal digital fabrication activities might be easier to follow using direct sources.

Table 1. Sources of sustainability information in digital fabrication used in the sustainability assessment. Sources indicated in italics are challenging to monitor or inquire about.

Activities in Digital Fabrication Context	Time Frame	Direct Sources	Indirect Sources
Formal education (for example, degree courses)	Typically, medium to medium-long time frame	Outputs or prototypes, *(monitored) generated waste*	Documentation, self-reports
Informal education (for example, dedicated events)	Typically, a short time frame	Outputs or prototypes, (monitored) generated waste	Inquiries, *self-reports*
Personal digital fabrication activity	Time frame varies	Outputs or prototypes, *(monitored) generated waste*	*Inquiries*

4. Methodology

4.1. Context of a Digital Fabrication Course

We examined a course on the principles of digital fabrication to analyse the considerations of sustainable design and prototype methods in digital fabrication. The primary aim of the course is to promote the development of design skills and knowledge through the digital manufacturing process in a FabLab environment while fostering the practice of sustainability. The teachers on design and prototype development methodologies gave the students a series of six lectures at the beginning of the course. These talks emphasised the primary components of the framework, such as design awareness and environmental responsibility. The primary objective of the lectures was to enhance the theoretical and practical underpinnings of digital manufacturing methods and techniques, as well as their application in the process of turning ideas into concrete prototypes. In the second major part of the class, students were tasked with applying the knowledge they gained from the lectures to a practical activity known as design prototyping. During this part, teachers and other professional team members offered feedback on design ideas for prototypes, alternative solutions, materials, and the use and reuse of product components to promote the development of the best possible solutions. Students received detailed and specific instructions on how to obtain the best possible results from the digital manufacturing process using the resources at their disposal. Some of the electrical components (e.g., motors and microcontrollers) of the prototypes were recycled for use in the following classes—an integral element of the course. The design assignment for this course required students to make an interactive 3D prototype, create basic electronics, implement control logic for an open hardware embedded board, design mechanical components for the prototype, and cooperate with their classmates on a group project.

Making a prototype of a physical interactive device was one of the training goals, as was designing mechanical components with the help of solid modelling software, assembling the proper electronics, and integrating software with a microcontroller, among other things. The class was a requirement for students seeking a Bachelor of Science degree in computer science; however, participation was open to those pursuing degrees in other disciplines as well. Students collaborated in groups of three or four members each. They were free to choose to materialise the kind of idea they wanted as a group project. However, the production of the design prototype required employing technologies associated with digital fabrication. Students were given until the end of the seventh week to finish their projects. After that, the instructors assessed the design process and the final prototype based on the quality of the design prototypes, signs of digital fabrication and sustainability, and the outcomes specified in the suggested framework.

4.2. Documentation of the Digital Fabrication Process

Each team must keep a journal documenting the development of its concept. For this, a dedicated blog-based website was used (Figure 2). The documentation included descriptions of the ideation, design process, and outcomes, supplemented by pictures and videos. Both the students and the instructors were able to see and comment on the weekly submissions posted. Reflection on the process of creating the prototype was another prerequisite of the course. This was done so that students could hand in a list of all the difficulties they had faced and the solutions they had adopted.

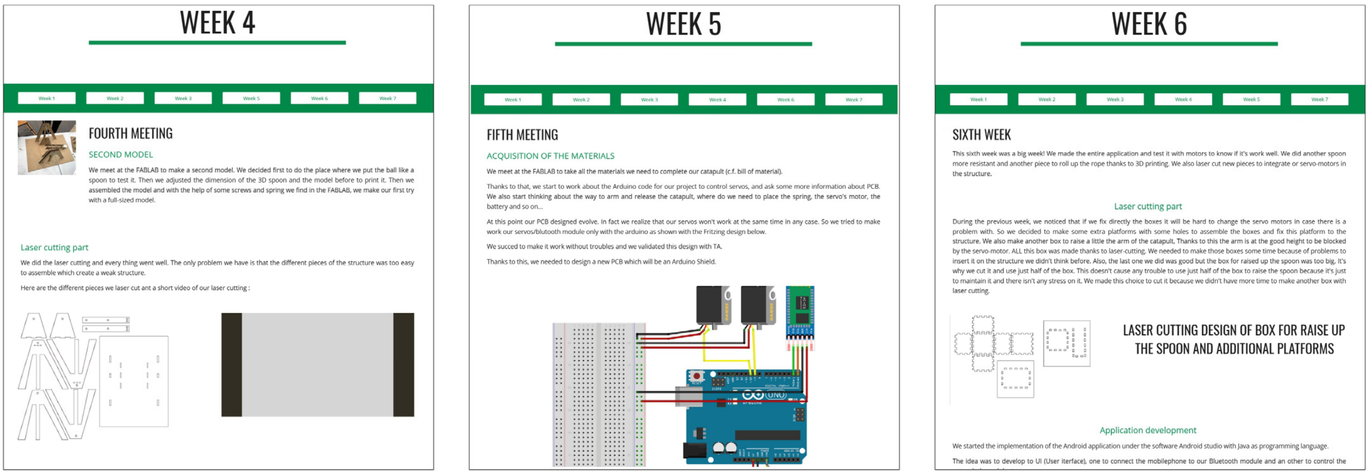

Figure 2. Example documentation of a team during three consecutive weeks of the course.

4.3. Prototypes Developed and Produced in the Course

Various design activities and digital fabrication processes were used to design and fabricate the prototypes in the course. Figure 3 presents six example prototypes developed in the digital fabrication course, including 3D models, early designs, and final prototypes over three years. An early prototype of an obstacle-avoiding car is seen in Figure 3a, while a 3D model of an automatic table cleaner is presented in Figure 3b. A realistic 3D software rendering of a prototype of a sun-following solar panel is shown in Figure 3c. The final prototype of a 3D-printed breath-controlled lockable case and trebuchet can be seen in Figure 3d,e. Figure 3f shows the base and top components of a bird-shaped piggy bank.

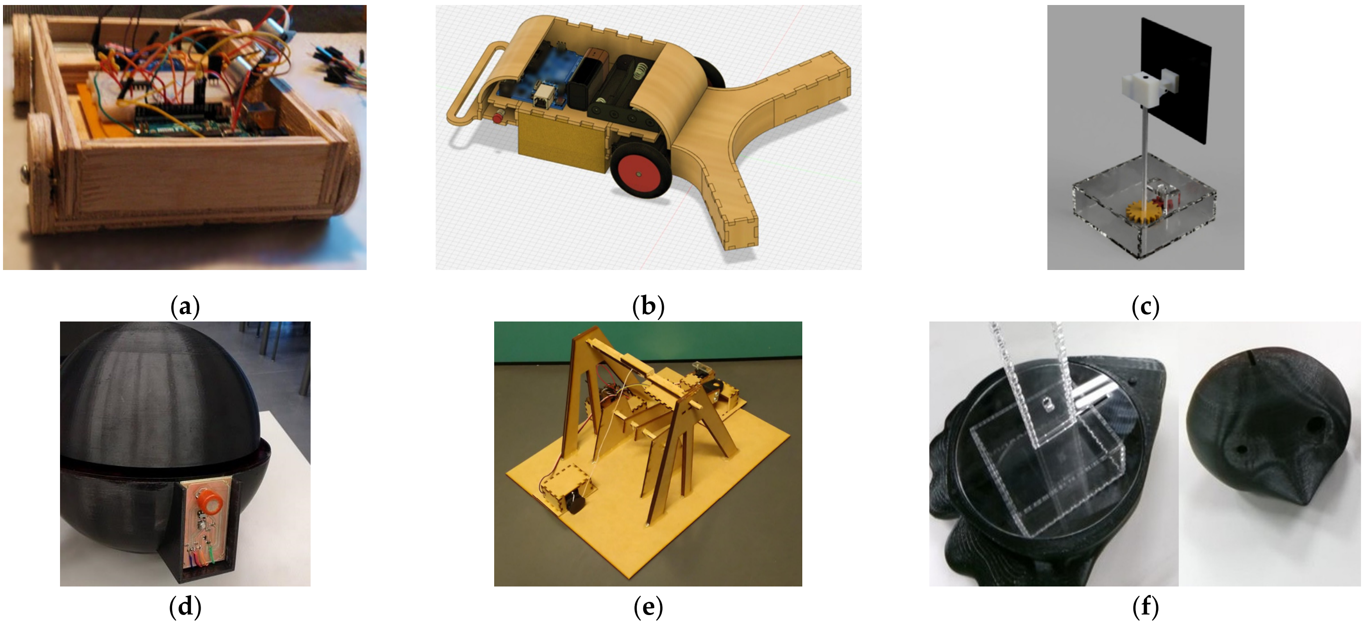

Figure 3. Six example prototypes at different stages of their development: (**a**) an obstacle-avoiding car, (**b**) a table cleaner, (**c**) a solar panel, (**d**) a lockable case, (**e**) a trebuchet, and (**f**) components of a piggy bank.

The prototype output in digital fabrication design education might differ from typical digital fabrication activity outcomes. The general purpose of these prototypes is to satisfy course requirements, and there is no immediate need to keep them beyond the course duration and grading.

5. Results

The outcomes or prototypes, documentation, and self-reports are used to examine sustainability considerations. This examination resulted in refined sustainability indicators and requirements.

5.1. Refined Sustainability Indicators and Requirements

Figure 4 depicts a further developed conceptual framework for sustainable digital fabrication prototyping based on the course. Several sustainability sub-indicators are identified concerning recycling, reusability, transportation, energy consumption, waste reduction, and emissions. Some of the sustainability sub-indicators serve as inputs, and others are outputs or consequences of the digital fabrication prototyping process. In the following subsections, we elaborate on the connection between sustainability sub-indicators in Figure 4 and the examples provided in Figure 3.

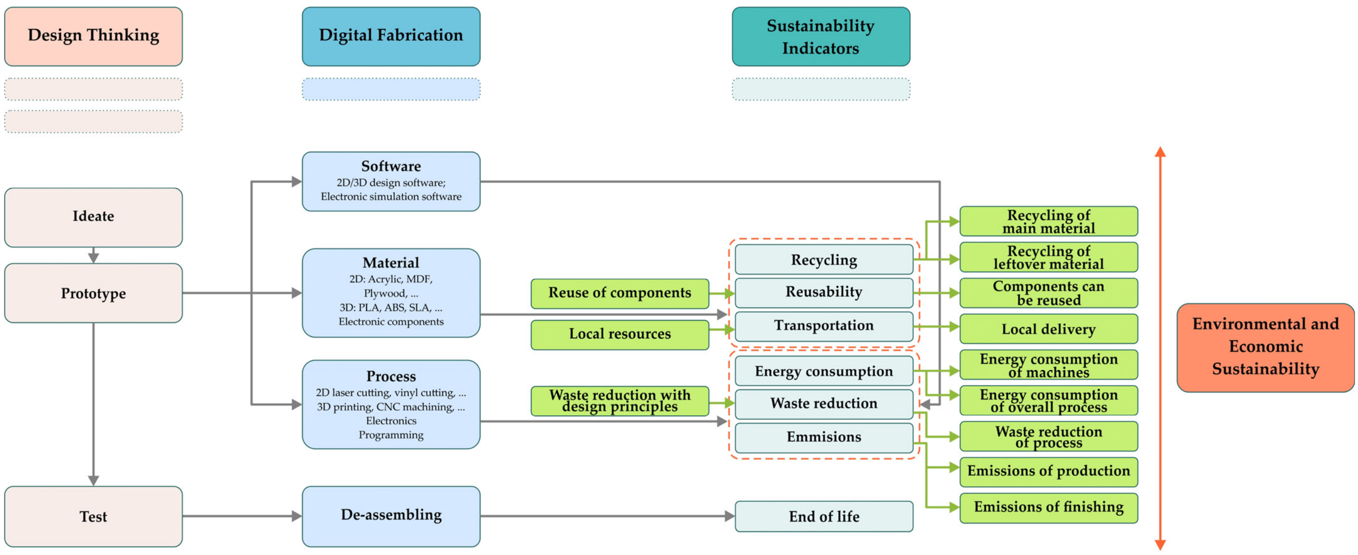

Figure 4. The extended conceptual framework for sustainable prototyping based on the prototyping and testing stages in the design thinking model.

5.2. Recycling

With regard to recycling, two main instances can be identified. The first is recycling the primary material. For example, particular 3D printed materials allow for recycling, contrary to certain wood-based or plastic-based laser-cut materials (see Figure 3b,e). A 3D-printed example can be seen in Figure 3d. The second instance is the recycling of leftover material. For example, certain excess materials from laser cutting can be reused for smaller objects and prototypes.

5.3. Reusability

Reusability involves the consequent use of components from previous projects that have been de-assembled or the future re-use of elements of the currently designed prototypes (see Figure 3a for an example of the possibility of disassembling electronic components). Reusability cases often involve electronic components and their connections.

5.4. Transportation

Transportation can be an advantage of distributed manufacturing, such as digital fabrication. This includes using local resources as much as possible, thus reducing environmental effects from the transportation of materials and components and using the outcome or prototype in the local context. This can also include prototypes designed to solve local problems.

5.5. Energy Consumption

Consumption of energy primarily concerns the machines directly used for digitally fabricating prototypes; however, this also affects the overall process, including the various energy sources that help produce the prototype. For example, different 3D printing technologies and different 3D printing solutions may have substantially different energy consumption. Furthermore, the material for 3D printed model support and how it is removed after printing, mechanically, or by dissolving it have different energy consumption and environmental impacts. The example in Figure 2d shows a prototype that uses a 3D-printed shell that can have substantially different environmental effects depending on how it is designed and printed. Digital fabrication spaces on a larger scale and with higher utilisation might have less energy consumption in the overall process.

5.6. Waste Reduction

Waste generated during the utilisation of 3D design processes and 2D design processes has different natures and implications. The abovementioned observations regarding energy consumption are also valid for waste reduction. For example, dissolvable 3D-printed model support might generate significantly more waste and have negative environmental impact than mechanically removable support. In the example in Figure 3c, the main housing at the bottom is made of plastic-based laser-cut material, which has an advantage over the 3D-printed solution.

In general, waste can be reduced at the design stage by applying certain design principles targeting waste reduction. For example, the way large 3D printed objects are created and potentially divided into smaller parts might significantly reduce 3D printing time and 3D model support, thereby reducing energy consumption and waste.

5.7. Emissions

Emissions generated during the utilisation of 3D design processes and 2D design processes have different effects and implications. In addition to the different emission effects of main 3D printing technologies and various 3D printing post-processing solutions, different 2D laser-cut materials can generate unwanted gas emissions.

Specifically, there are various trade-offs between these 3D printing technologies and solutions. For example, the case in Figure 2D might be printed with higher quality in a thermally controlled environment with large 3D fused deposition modelling (FDM) printers, but this would have a substantially greater environmental impact, both in terms of energy and emissions, than printing on small desktop 3D printers.

6. Discussion

6.1. Recycling and Reusability of Materials and Components

Recycling 3D printed material is a significant opportunity [60]. In the case of digital fabrication, it is dependent on the local (fabrication space, institution, or city) possibilities and practices. Recycling 2D printed material is addressable on the ideate stage through optimising the design and leftover material. The latter is an easy to implement intervention in digital fabrication design education.

The reusability of components is a vital sustainability implication. Reusing electronic components is typically challenging due to custom-made electronic circuits and the integration of materials [61]. However, digital fabrication design education relies on standard components and uses predominantly commonly used sensor solutions [4,62], which can facilitate reuse as long as it is targeted during the ideate and prototype stages. Additionally, reusing 3D-printed components can save significant time [63].

6.2. Transportation and Energy Consumption

Transportation has often been pointed out as an advantage of distributed manufacturing; in particular, the environmental impact due to long-distance transportation can be reduced by making products locally [4,64]. Preparing a set of locally available materials to be used in design education might positively affect transportation sustainability indicators.

Energy consumption, in addition to utilisation patterns, has been found to be a significant factor in the environmental impact of digital fabrication [65]. Design education interventions can leverage different scale 3D printers for purposes appropriate for the particular design scale and quality. Further optimisations of scheduling can reduce its energy consumption [4].

6.3. Waste Reduction and Emission Reduction

Waste and emission reduction are somewhat intertwined with recycling and energy consumption. Waste relates to excessive material use [13], and the ideate stage offers essential opportunities to minimise waste. Interventions in design education can tackle optimisation of the prototyping process (mostly in the ideation stage) and avoid unnecessary iterations (mainly in the prototyping stage). Emissions can be reduced by matching the scale of the 3D printers or 2D fabrication machines to the particular design or task at hand. Such a match would reflect in energy consumption and utilisation patterns [65].

6.4. Identified Potential Sustainability Impacts and Interventions

Based on the original conceptual framework for sustainable prototyping [4] (Figure 1) and its extended version (see Figure 4), it is possible to elaborate on the potential for sustainability impacts in digital fabrication design education.

The three stages of the design thinking process, namely ideate, prototype, and test, represent the potential for substantial positive sustainability impacts and interventions (Figure 5). These results show potential sustainability impacts regarding software for design, simulation, and testing for digital fabrication. To a greater extent, initial iterations of the ideate stage and, to a lesser extent, prototypes and tests stages can realise such impacts by being partially or fully executed using the software.

Example interventions include:

- Ideating and exploring alternatives with delayed proceeding to prototyping;
- Using 3D simulations for prototyping and testing;
- Using simple non-digital prototyping for initial iterations;
- Using electronic simulation software to find alternative sensing or actuating solutions.

The examples provided in Figure 3b,c show 3D simulations of prototypes. Such simulation can be used for iterative improvement of the design solution prior to progressing to the physical prototype. Furthermore, early prototypes can be made from materials that are not necessarily digitally fabricated (e.g., DIY materials). Depending on the purpose and stage of the prototypes [39], they can be made with cheaper, more sustainable materials, such as cardboard.

6.5. The Role of the Ideate Stage in Digital Fabrication Prototyping

The role of the ideate stage of the design thinking model can be highlighted. In the ideate stage, a wide range of sustainability considerations can be implemented regarding materials, processes and de-assembly (Figure 6). In particular, careful sustainability-considerate selections can be made concerning the material. These selections can match the actual purposes of the iterations. For example, the degree of sustainability and environmental impact of the materials of the prototype can match the fidelity [52]; for instance, low-fidelity early prototypes can be made from recycled or repurposed materials. Furthermore, such materials can match the purpose of the prototype [39,53] and its lifespan [14]; for instance, prototypes for a quick demonstration of an idea can be made from repurposed materials.

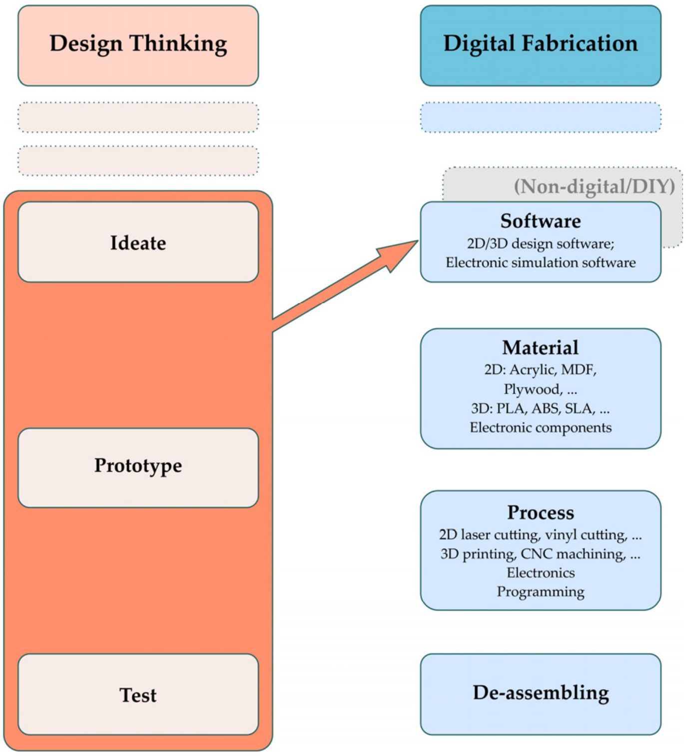

Figure 5. Identified potential high sustainability impacts concerning the use of software for design, simulation, and testing for digital fabrication.

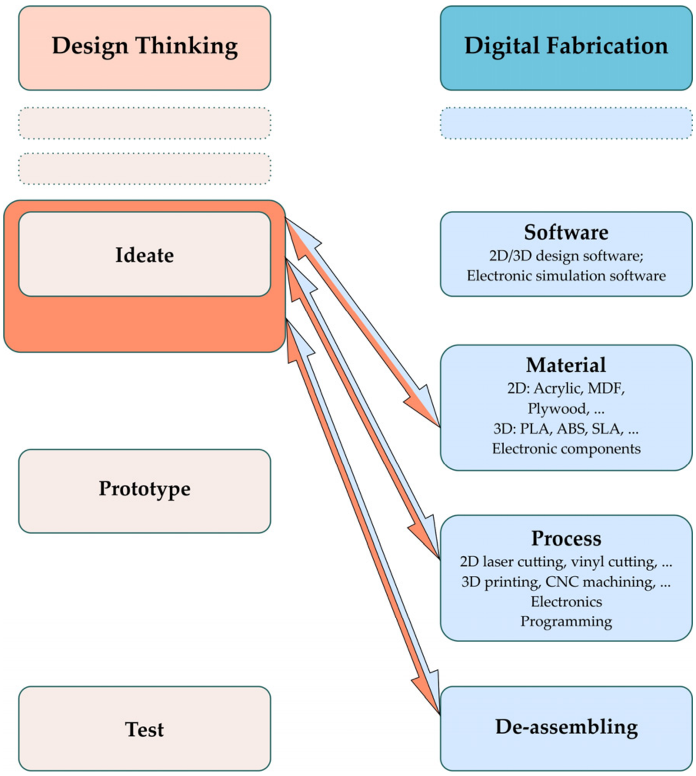

Figure 6. Identified potential high sustainability impacts concerning materials, processes, and de-assembly during ideation in digital fabrication.

Furthermore, this interaction between the ideate stage of design thinking and digital fabrication aspects can be aided with automatic means (for potential aids, see [51,53,54,66]). The aim of timely and extensive analysis of automated documentation systems might be instrumental there [51,52].

6.6. Sustainable Experiences with Digital Fabrication

The ensuing experience of contributing to something greater (e.g., maker movement) leads to a feeling of purpose and meaning that provides a sustainable experience and promotes the subject's well-being throughout the whole process [67]. The digital fabrication paradigm, particularly makerspaces and FabLabs, creates a sense of contribution among participant makers [68], as well as a sense of empowerment [69]. In the case of sustainability in digital fabrication design education, such a sense of contribution can be achieved in two directions:

- Sense of contribution toward the maker and FabLab community;
- Sense of contribution toward the sustainability of a fabrication activity.

In the latter case, it is essential to increase students' environmental awareness in digital fabrication prototyping and understand the importance of designers' decision-making through the cycle [13]. Hence, students' awareness of these sustainability aspects and impacts is critical.

The following items can be identified as essential to be included in educational interventions toward sustainability in digital fabrication design education:

- Educational interventions should emphasise awareness of various possibilities and alternatives for materialising prototypes in terms of technologies and approaches. Depending on the idea for the prototype, substituting the fabrication of the entire prototype structure with a different digital fabrication process [70] might positively affect sustainability (see Figure 3b, in which the entire structure is to be realised with a 2D process—laser cutting). Decomposing the prototype structure and materialising different components with different digital fabrication processes can have a similar positive effect (see Figure 3f).
- Education should focus on understanding the characteristics of multiple design iterations, their purpose, and their sustainability implications. Early design iterations intended for learning [39] can be realised in low-fidelity and leftover, recycled or repurposed available materials (see Figure 3a).
- Interventions should also leverage the connection of specific design thinking stages with digital fabrication sustainability indicators. The ideate design thinking stage can be leveraged to achieve more sustainable materials, processes, and de-assembly procedures. Ideate, prototype and test design thinking stages can be partially executed with the help of software (see Figures 5 and 6). Overall, the ideation stage can be leveraged to improve sustainability indicators.
- Educational interventions should incorporate awareness of the potential reuse of components and possibilities of elements to be re-used. A pool of parts suitable for reuse [63] can be built along with the design for the reuse of components (see Figure 3a).

Integrating requirements for awareness, understanding, and ways to leverage different sustainability indicators is essential. This can be done in course documentation (see Figure 2) or deliverables (Figure 3). To that end, using social means, such as using a common documentation platform where students can share solutions and achievements, can be helpful.

Digital fabrication spaces, such as makerspaces and FabLabs, have been seen as examples of heterogeneous engineering (an integration of the social and technical aspects of engineering practice) [71]. Moreover, the highlighted items must be integrated into the social environment during the digital fabrication activities in the courses. This creates an overall sustainable experience for individuals, teams, the whole group/class, and maker communities.

7. Conclusions

This study examined sustainability considerations in the context of digital fabrication design education. We formulated criteria for evaluating these sustainability considerations and analysed the development of the design process and the outcomes of a digital fabrication course. Based on the results, we extended the conceptual framework for sustainable prototyping. The extension focuses on sustainability sub-indicators affecting recycling, reusability, transportation, energy consumption, waste reduction and emissions. The prototyping process and the outcomes of the design education context in FabLab were used to exemplify this extended conceptual framework.

The limitations of this study stem from the fact that a single course was used to outline sustainability considerations qualitatively. Furthermore, some of these sustainability considerations might depend on the tools and machines in the digital fabrication space utilised in design education. The digital fabrication space used in this course (FabLab Oulu) is a member of the FabLab network; hence, it contains a standardised set of tools and machines.

The findings will benefit educational interventions that focus on or incorporate sustainability in the context of digital fabrication design education. The highest impact of such interventions would be in design education cases that follow design thinking practices and iterative design process principles. Future work should facilitate ideation, prototyping, and testing as the main tools to achieve a high sustainability impact.

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