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Learning in a digital fabrication course on building tangible artefacts

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Abstract

This paper examines how students' ideas evolve into physical prototypes within a digital fabrication design course. Examining the materials used, customization approaches, iterations, and team dynamics of 26 student projects reveals interplays between ideas, available tools, materials and constraints. Findings show the predominance of techniques, design preferences, concept refinement, and teamwork challenges. The implications highlight the value of hands-on iteration for alignment with reality and the need to support collaboration skills alongside technical prototype development.

Keywords: design education, prototyping, 3D printing, fablab, digital fabrication

1. Introduction

In the rapidly evolving landscape of education and technology, the intersection of digital fabrication and hands-on creation has emerged as a dynamic and transformative field of education. Digital fabrication laboratories, commonly referred to as FabLabs, stand as dynamic educational spaces explicitly designed to immerse learners in the captivating journey of translating conceptual ideas into tangible, physical products (Pitkänen et al., 2019). At their core, these labs symbolize a paradigm shift in education, anchoring their approach in project-based activities within the realm of digital fabrication (Blikstein, 2013). This educational philosophy is marked by an immersive learning environment that places absolute importance on hands-on experiences, interweaving theoretical knowledge with practical application using a wide variety of materials and processes (Milara et al., 2019).

This paper explores the immersive journey of first-year students in a digital fabrication course that focuses on constructing tangible objects. The course is at the forefront of innovation as FabLabs redefine the traditional boundaries of learning. It provides students with a unique opportunity to merge theoretical knowledge with practical application in preparing them with the skills and insights necessary to navigate the complex world of digital fabrication, with an emphasis on creating physical objects. From laser cutting to 3D printing, students engage with state-of-the-art FabLab tools and technologies, moving beyond the traditional limits of theoretical education. Thus, this paper aims to reveal the diverse experiences of students as they navigate this course, highlighting the challenges, breakthroughs, and transformative moments that shape their learning process. As digital fabrication becomes an integral part of various industries, it is important to understand how students engage with this course. This will offer valuable insights into the effectiveness of hands-on learning methodologies.

The main goal of this study is to provide educators, researchers, and practitioners with a comprehensive understanding of how digital fabrication courses impact the development of tangible artefacts.

Additionally, this paper aims to promote a deeper appreciation for the blending of technology and creativity in modern education. Furthermore, the study examines how ideas are turned into physical objects and how digital fabrication labs and their available tools facilitate the transformation of abstract concepts into concrete, tangible prototypes.

2. Background

2.1. Digital fabrication education

The integration of constructionist approaches can enhance digital fabrication education by emphasizing active knowledge construction through personal engagement and creation (Blikstein, 2013; Iwata et al., 2020). Song (2020) notes that introducing new technologies in educational settings can promote problem-solving abilities and effective communication and deepen students' understanding of technology's integration within art and design education. Katterfeldt et al. (2015) stress that deep and sustainable learning within digital fabrication environments is crucial to skill acquisition and comprehensive subject understanding. However, the potential for open-ended idea generation and realization in educational contexts through digital fabrication is yet to be fully explored. Georgiev and Milara (2018) discuss the challenge of aligning the difficulty level of students' ideas with their current skill sets, while Suero Montero et al. (2020) advocate for a student-centred approach that prioritizes the pursuit of students' own ideas. In navigating these challenges, teachers play a crucial role, as emphasized by Pitkänen and Andersen (2018). Empowering educators with the tools and resources necessary to support students' creative endeavours is essential for fostering a conducive learning environment.

2.2. Materiality of prototypes

The use of physical prototypes in digital fabrication design education is crucial in shaping the design process and the final product (Giunta et al., 2022). Physical forms allow students to assess real-world limitations and constraints such as size, strength, and functionality. Integrating digital fabrication with engineering design (Chiu et al., 2013), provides a motivating context for students to imagine, invent, collaborate, and construct solutions to complex problems.

Further, materiality can be explored as a sustainable prototyping framework for digital fabrication tools, which can be applied in educational settings (Soomro et al., 2021). Documenting and reflecting on the prototyping process is essential, and documentation systems are utilized to record prototype progress in the digital publications domain (Barhoush et al., 2019; Erichsen et al., 2021).

2.3. Materialization of designs

The prompt execution of ideas and the constant improvement of prototypes are crucial to refine concepts (Georgiev and Taura, 2015). However, the combination of open-ended ideation and the use of digital tools to realize complex designs has not been thoroughly explored. Various approaches have been suggested, such as balancing technical difficulty and capabilities (Georgiev and Milara, 2018), or incorporating student-led ideas (Suero Montero et al., 2020). Research has also investigated the teaching requirements for design based on tools and project types, which can affect the number of iterations (Iwata et al., 2020).

The use of digital tools to create and customize electronic prototypes has been a topic of discussion. This discussion has mainly focused on the open-source hardware field (Mellis and Buechley, 2012) and the sustainability field (Soomro et al., 2021). To explore this topic further, Georgiev and Nanjappan, (2023) examined a digital fabrication course emphasising the importance of sustainability in design education.

While technical skills are important, the collaborative and iterative process of developing prototypes requires a greater focus on overcoming barriers, finding workarounds, and evolving ideas from conception to finished products. Analysing project journeys can reveal key principles underlying skill-building, problem-finding, and depth of learning enabled in makerspaces (Tomko et al., 2020).

However, research into how initial ideas shift in response to hands-on constraints, modifications required to align vision with suitable materials, and prototyping choices that emerge has been limited.

Thus, examining the evolution of concepts and physical forms can provide insights into the real-world complexities of digital fabrication education.

3. Method

3.1. Design education case

The education case is a 5-ECTS course that is specifically designed for first-year BSc digital fabrication students. The course is delivered in person at a European university and involves a combination of lectures and FabLab project work. The course is taught in English, and a total of 88 students participated in the course for the year 2022, all of whom gave informed consent for their data to be analysed.

Throughout the course, students worked for a total of 135 hours over seven weeks to learn design skills. The course is unique in that it teaches digital fabrication skills to students from various disciplines using project-based learning. In the first two weeks of the course, six direct-instruction lectures introduced students to various concepts such as FabLab, physical and electronic design, 3D modelling and printing, and 2D design.

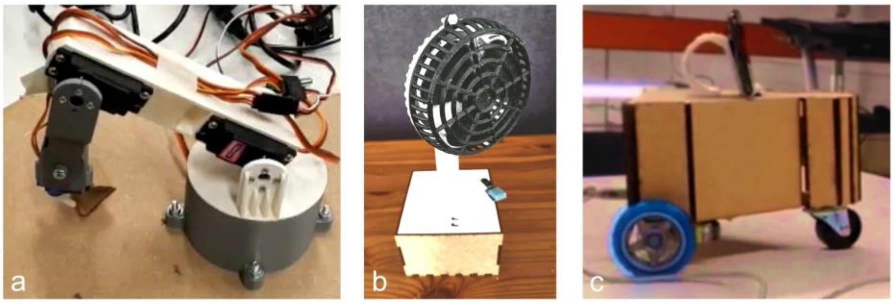

Figure 1. Example prototyping outcomes: (a) programable robot arm; (b) automatic fan triggered by temperature changes; and (c) face tracking and person following robot car that uses the smartphone for some of the functionality

From the second week to the seventh week, students worked in teams of two to four to design and build an interactive device with custom mechanical and electronic parts, sensors, actuators, and software. The students were assigned into teams based on their prior programming and prototyping experience and skills. For instance, students with no prior experience in programming and prototyping were assigned to the same groups. Further, they were provided with professional fabrication tools in the FabLab to apply their lecture knowledge, and the instructors provided weekly feedback to help teams overcome technical challenges and implement their ideas within the course timeline.

Each team had to create a physical device interacting with its environment to realize its ideas. The device had to include software-controllable movable components, at least one sensor, and one actuator, with the software responding to sensor readings. All teams presented mid-term progress updates to instructors and classmates, and after seven weeks, teams presented their interactive prototype and project documentation, highlighting the fabrication process lessons. Figure 1 presents three prototypes which vary in their complexity and in terms of material prototyping challenges.

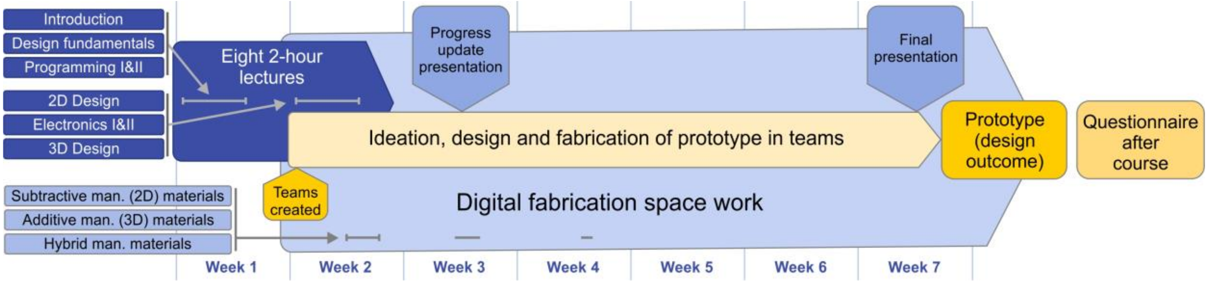

Figure 2. The digital fabrication course process

The documentation includes details about idea generation and the chosen concept, a weekly diary, a summary of the project's main outcomes, and a reflective analysis of the individual's progress and knowledge. Further, the students, as a team, completed an online questionnaire at the end of the study, detailing the design models, materials, and electronic components used in their prototype together with their teamwork experience. The course process is illustrated in Figure 2.

3.2. Materials, tools, and components

3.2.1. Material access

A wide range of readily available materials formed an integral part of the course, providing students with a spectrum of options for both additive and subtractive manufacturing processes. In the realm of additive manufacturing, students had access to materials such as Polylactic acid or polylactide (PLA) plastic, Acrylonitrile Butadiene Styrene (ABS) plastic, resin, and nylon, each possessing distinct properties that catered to specific project requirements. PLA and ABS plastics, for instance, offered versatility and durability, while resin provided a high level of precision and fine detailing, and nylon contributed strength and flexibility to the manufacturing process. On the subtractive manufacturing front, the materials at students' disposal were geared towards cutting and engraving. This included versatile materials like acrylic, Medium-density fibreboard (MDF), plywood, wood, cardboard, and vinyl. In addition to physical materials, the course also delved into the realm of electronics, enabling students to integrate electronic components into their projects.

3.2.2. Digital fabrication tools

The digital fabrication space used in the course is a flagship node within the FabLab network. It offers a variety of standard digital fabrication equipment along with conventional (traditional hand tools) and specialized tools that are readily available for student use. The hardware fabrication tools are diverse and include additive manufacturing processes facilitated by top-tier 3D printers such as the high-quality Stratasys Fortus 380mc, precise Formlabs Form 3, and versatile desktop models like the Raise3D Pro2. Subtractive manufacturing processes are supported by advanced laser cutters that feature both large-scale capabilities with the Epilog Fusion 75W CO2 Laser and precision small-scale operations with the Epilog Fusion M2 40 Laser. In addition, the space is equipped with electronic workbenches and supplementary tools such as 3D scanners, a vinyl cutter, and a computer numerical control (CNC) precision milling machine, enabling a comprehensive range of fabrication techniques and projects.

Students also have access to a suite of software tools tailored to different aspects of digital design and fabrication, including Inkscape for 2D design, Autodesk Fusion 360 for intricate 3D modelling, and specialized software such as Tinkercad and Eagle 8 for electronic circuit design. Importantly, although these software tools are typically used within the course, students are encouraged to explore and utilize other software that aligns with their project needs and personal preferences, fostering a culture of flexibility and creativity in digital design and fabrication endeavours.

3.2.3. Access to electronic components

The students participating in this course were initially provided with a predetermined set of components, predominantly Arduino-based. This predefined kit encompassed essential elements such as Arduino Uno or Nano, cables and jumper cables, breadboards, battery holders, switches, LEDs, DC motors, Micro Servo motors, H-bridges, resistors, and various other minor components. While this standardized set served as a foundational toolkit, it was not an exhaustive collection, potentially limiting the scope of creative exploration. To overcome these constraints and encourage a more expansive range of experimentation, the FabLab maintained an extensive inventory of diverse components beyond the default set. This inventory, readily accessible to the students, opened a spectrum of possibilities, allowing them to explore and integrate a wide array of additional elements into their projects. The FabLab and the course further facilitated an adaptive approach by accommodating requests from students for specific components, tailoring the available resources to individual project requirements. Notably, the default set of components was introduced to the students during the second week of the course, allowing them to familiarize themselves with the foundational elements before expanding their creative possibilities with the broader array of resources available in the FabLab. This strategic sequencing aimed to strike a balance between providing a structured introduction to essential tools and materials and empowering students to venture beyond the limits of the default set as they progressed in their projects.

4. Results

4.1. Prototype ideas and versions

Throughout the course, students work on team-based projects to build prototypes by applying their theoretical knowledge and practical skills. The class comprises 26 teams with 2 to 4 members in each team, emphasizing the collaborative effort of designing and developing physical prototypes with digital fabrication techniques. Of these teams, 13 successfully implemented their original ideas, showcasing innovation and independent thinking. Additionally, 10 teams partially executed their initial concepts through adaptive means. Interestingly, three teams changed their ideas during development, demonstrating the dynamic nature of the creative process. The project submissions indicate a progression in ideas, with 15 teams submitting Version 1, nine teams iterating to Version 2, and one team each presenting Versions 3 and 4. This diverse structure of submissions encourages varied creative approaches and reflects the flexibility and evolution inherent in the project development lifecycle.

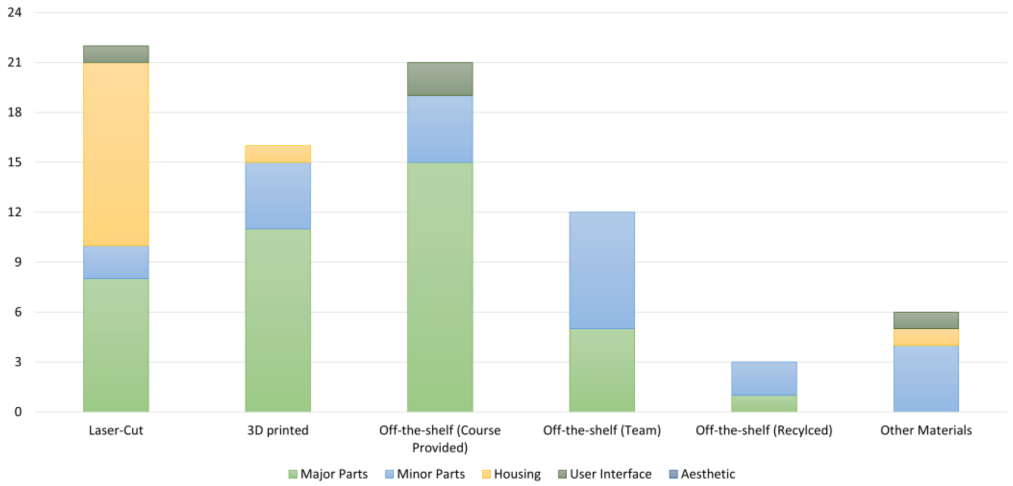

Figure 3. Preferences of groups of materials for prototype parts

4.2. Primary materials and manufacturing process used in the prototypes

The teams primarily used carboards, acrylic sheets, plywood, medium-density fibreboards (MDF), high-density fibreboards (HDF), thermoplastics, such as Polylactic acid or polylactide (PLA) and Acrylonitrile Butadiene Styrene (ABS). They also combined MDF/HDF or Acrylic with 3D printed parts to build the prototypes. Of 26 prototypes, nearly 23 consisted of primary parts produced from a subtractive manufacturing process, and 14 included parts from an additive manufacturing process. Only three prototypes included parts from the hybrid manufacturing process (combining 3D printed material with MDF/HDF or Acrylic sheets). Four prototypes used off-the-shelf or readily available components (such as toy outer shell) that were not produced at the FabLab using any one of the manufacturing processes.

4.3. Material preferences for prototype parts

Our students' prototypes typically consist of five major components: major parts, minor parts, housing, user interface, and aesthetics, each playing a crucial role in the design and development process. While major parts are the essential components that define the core functionality of the prototype, serving as the backbone of the design, minor parts complement the major components, contributing to the overall functionality and structural integrity. The housing encompasses the outer shell or casing that encloses and protects the internal components, ensuring a unified and durable structure. The user interface involves the interactive elements through which users engage with the prototype, including buttons, screens, or controls that facilitate user interactions. Aesthetics refers to the visual and stylistic aspects of the prototype, focusing on its overall appearance and design appeal.

Figure 3 presents the material preferences for different parts of the prototypes. A major part of the 15 prototypes primarily consisted of off-the-shelf materials provided by the course. Whereas 11 prototypes consisted of 3D-printed components for major parts, and only 8 included laser-cut components. On the other hand, seven teams procured additional components, and 4 used other readily available parts as minor components for their prototypes. Off-the-shelf recycled parts were preferred for minor parts of the prototypes. Laser-cut components were highly preferred for enclosing the designs as outer shells for 11 prototypes. The prototypes used different components to use as user interfaces.

4.4. 2D and 3D designs for prototype parts

Our students' prototypes included existing and own 2D designs, including different types of laser-cut materials such as living hinges and laser-cut boxes. Figure 4 presents the details of 2D designs utilised in the final prototypes. Laser-cut boxes were highly used in the prototypes as major parts or as the outer shell. Living hinges were used either as a minor part or to house the design in two prototypes. Students preferred to design their own models rather than use existing models to build prototypes.

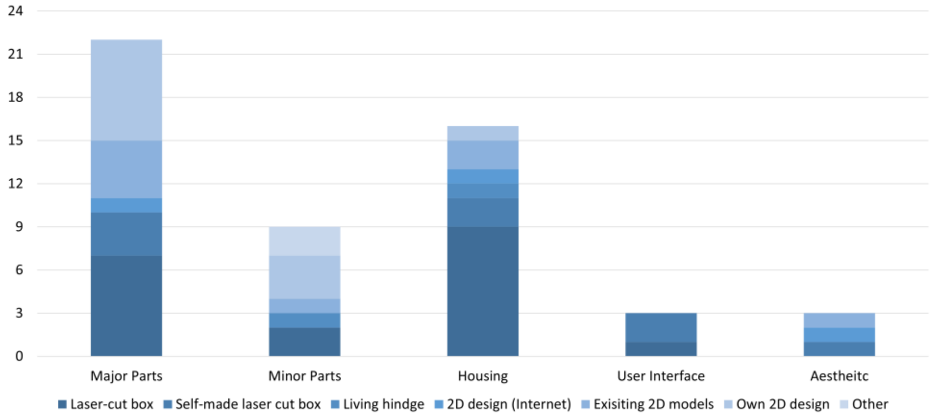

Figure 4. Utilization of 2D designs in prototypes

Regarding 3D models, our students preferred to make custom-designed 3D models rather than using existing ones, primarily to create major components of their prototypes, followed by minor or outer shell components. Figure 5 details how 3D models were utilised in the students' prototypes.

4.5. Electronics design, programming and testing methods

The students used various approaches to design the electronic circuits to implement the functionalities of their prototypes. While 17 prototypes consisted of circuit designs inspired by the internet, 12 included circuit designs built from scratch during the course. Only one prototype was reported using a circuit design from the internet. Eighteen teams preferred to simulate their circuit designs using the Tinkercad before building them on a breadboard. To test their circuit design, all teams followed the recommended divide and conquer approach; they tested different electronic components separately before bringing all the functionality together. The functionality of 4 prototypes was biased based on the initial components pack given to the students at the beginning of the course.

4.6. Teams' feedback in building prototypes

All teams faced several challenges, such as communication and contact issues, team member participation and roles, workload distribution and time management, positive team experiences, and unique project-related challenges. 11 teams reported challenges related to communication, coordination, and adherence to schedules, which were recurring themes in their feedback. They reported keeping contact with other team members, and the deadlines were challenging throughout the project (e.g., *" keeping contact with other members of the team and the deadlines.")*, response times were long sometimes, and it did not work with their schedule. Also, they highlighted the lack of clear communication about the roles and responsibilities. Four teams reported the challenges related to team member participation, leadership (e.g., *"the team lacked a clear leader who would divide work and oversee it got done"*), role allocation (e.g., *"it [was] hard when we first divided jobs due to each member strength"*), and motivation. They primarily mentioned the lack of motivation among the members, poor leadership, and non-participation in the activities. On the other hand, four teams reflected on the workload distribution, time management, and external factors like the COVID-19 pandemic affecting the team's ability to work efficiently. Nevertheless, three teams highlighted their positive experiences within their teams, highlighting that teamwork was successful and enjoyable despite some challenges. Only two addressed challenges specific to the nature of their prototype design, including its size and technical aspects, such as broken and faulty components.

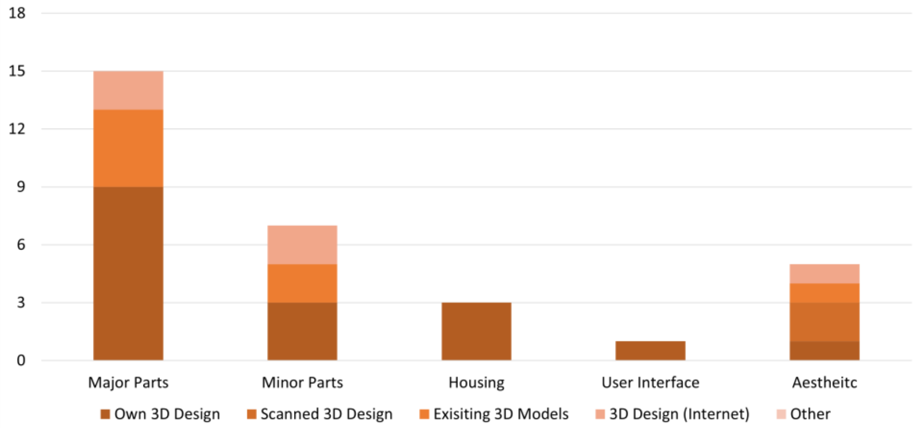

Figure 5. Utilization of 3D designs in prototypes

5. Discussion

The discussion centres around how theoretical ideas shape physical prototypes through design iterations, material constraints, element and material fit, customization needs, and real-world project challenges.

The process of idea development through prototyping iterations is illustrated by versions 1-4 of prototypes. This shows the potential progression and refinement of concepts, as supported by Georgiev and Taura (2015). The iterative refinement observed in teams producing multiple versions (up to version 4) highlights the importance of hands-on prototyping in idea development. However, due to time constraints, 15 teams remained at version one. Teams adapted their approaches based on the practical realization of concepts. Figure 1 shows prototypes showcasing various challenges encountered or their absence during prototyping. The first prototype team (Figure 1, (a)) dealt with mechanical design issues, while the second team (Figure 1, (b)) faced challenges with the production process, leading to a change from 3D printing to a combination of 2D and 3D design. In contrast, the third team (Figure 1, (c)) took a flexible approach, combining multiple solutions and approaches to overcome challenges. Overall, flexibility was crucial as ideas encountered physical constraints during development.

5.1. Material preferences and utilization of design models

Digital fabrication education involves using tangible objects and principles of constructionist learning, as stated by Tomko et al. (2020). The selection of primary materials has a significant impact on the implementation of prototypes, with subtractive manufacturing materials such as MDF, acrylic, and 3D printing materials playing a crucial role. While these materials allow for iterations, they also limit design possibilities. Larger projects often face material constraints, leading teams to adopt creative solutions such as combining processes or performing DIY repairs. Material selection depends on part function, with specific materials chosen to suit functional prototype components, considering properties such as strength and aesthetics. When using existing versus new designs, there are trade-offs between customization and efficiency, as seen in prototypes that use edited designs to varying degrees. Teams typically use 2D design/laser cutting for housing and 3D design/3D printing for major functional parts, emphasizing a balance between effort and originality in design implementation. Figure 1 highlights prototypes that leverage both existing and customized designs, illustrating the various approaches teams use in material and design choices. Overall, material selection and design customization play critical roles in shaping the functionality and aesthetics of prototypes in digital fabrication education (see Figures 5 and 6).

5.2. Circuit design and implementation

The students used a variety of techniques when designing electronic circuits for their prototypes. Some chose to use internet designs as inspiration for their projects (17 prototypes), while others constructed their circuits completely from scratch (12 prototypes). The majority of students preferred to use Tinkercad for simulation before moving on to breadboarding. When it came to testing, teams used a divide-and-conquer approach. Very few of the prototypes were influenced by initial component packs.

5.3. Challenges faced by teams

Teams encountered various challenges throughout the project, encompassing communication, participation, workload distribution, time management, positive team dynamics, and project-specific hurdles. Communication and coordination issues were recurrent, with 11 teams struggling to maintain contact and meet deadlines, citing long response times and unclear roles and responsibilities. Four teams faced difficulties in team member participation and leadership, noting a lack of motivation, poor leadership, and role allocation problems. Additionally, four teams grappled with workload distribution, time management, and external factors like the COVID-19 pandemic, hindering efficient work. However, three teams highlighted positive team experiences, emphasizing successful teamwork despite challenges. Only two teams addressed prototype-specific challenges, such as size and technical issues like broken components. Overall, these challenges underscore the multifaceted nature of project management, requiring effective communication, leadership, and adaptation to overcome obstacles and ensure project success.

6. Recommendations and future work

This study reveals significant implications for project-based learning, research methodologies, prototyping technologies, design processes, and team collaboration. The prototyping process and evolution of ideas across multiple iterations demonstrate the value of learning-by-doing in design education, making such hands-on projects more effective in enabling a holistic understanding of the interplay between ideas and prototypes. The study also provides a template for detailing and analysing the realization process of ideas, which can be useful for future research. Technological implications are in terms of the widespread availability of certain materials, which presents challenges for FabLab management to ensure access to adequate subtractive and additive options that align with students' needs.

The design process implications include the functional interdependence with materials selection, suggesting the importance of involving experts alongside novice designers early in the conceptual development phase. Rapid prototyping can also expose unanticipated constraints to incorporate earlier, improving the design process. In terms of team dynamics, the study reveals the complex human dimensions alongside technical prototyping skills needed for collaborative innovation, highlighting the value of scaffolding to facilitate interpersonal interactions.

These implications apply across educational and design practice settings. Further research is needed to understand the barriers and enablers of ideation, utilization, and realization in digital fabrication design education.

7. Limitations

Although this case study on design education provides valuable insights into the prototyping process, materials used, and the evolution of ideas, it has some limitations. Firstly, the data is confined to a specific design course context, which includes assigned student teams, provided materials, and project timelines. Secondly, there is a reliance on self-reported student data, which can lead to subjective interpretations. While the qualitative feedback highlights discussion points, it does not allow for quantitative analysis. To overcome these limitations, it is essential to expand analyses across multiple such courses over time. Nonetheless, within its scope, the results offer valuable insights into the prototyping process, materials, and idea evolution within its scope, aiding in the improvement of design education practices.

8. Conclusions

This paper examined how students' ideas and concepts are realized into physical prototypes in a digital fabrication design course and analysed the materials, tools, iterations, and challenges involved. The majority of prototypes were created via subtractive manufacturing, and 3D printing was less common. Teams collaborated to integrate different processes and modified components. The use of original 2D laser cuts and 3D prints was preferred by teams over pre-existing designs. Multiple iterations of prototypes demonstrated how concepts could be refined when physical implementation was restricted. However, more than 50% of teams only created only one version due to time constraints. Problems with team collaboration, such as coordination and communication, arose frequently and impeded prototype development. The study emphasises the value of experiential learning and the interaction of concepts, materials, and procedures. Moreover, the prototyping process requires the harmonisation of ideas with appropriate materials and personalisation alongside efficient teamwork, which are fundamental experiences of digital fabrication education.

Acknowledgements

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