



Digital fabrication as an approach for innovative architecture education

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Abstract

This paper tackles the argument of how digital fabrication is a game changing approach in architecture education. Digital fabrication is ubiquitously paced in all learning processes. It is rapidly becoming an important part of architecture education worldwide, and it can tackle architecture and urban design at all stages. This paper is essential for architecture track educators as it shows how to patronize a profound perception of digital fabrication processes among students, particularly architecture track students. The paper builds on the methodology, the application, the findings, and outcomes of a designated digital fabrication workshop for architecture track students with a non-grounded knowledge base of digital fabrication paradigm. The workshop grew out of the Smart and Future Cities Laboratory for Sustainable Urban Solutions (SFCL), which was established in the Faculty of Engineering, Ain Shams university in 2020 and is funded by STIFA. The workshop followed the design thinking approach the workshop aimed to discuss recent digital technical advances in design and fabrication, as well as the remarkable potential they have brought for architectural design and production practices. It investigates the implications of new digital design and fabrication processes enabled using rapid prototyping (RP) and computer-aided manufacturing (CAM) technologies through new pedagogy concepts and Scaffolding neophyte Students' Learning methods. The entire workshop with its applied methodology builds a justified architectural mentality among students. It brings up students that are product oriented. Digital fabrication encouraged students' creativity and customization.

Keywords: Digital fabrication, design thinking process, digital fabricated products, computer aided manufacturing, scaffolding neophyte students' learning

1. Introduction

Twenty years of technological innovation have shaped our world. New modalities have been adapted to the various fields of our lives and one of those areas is architectural fabrication. However, digital fabrication has improved architectural design approaches and construction techniques [1] and captured the attention of designers, particularly architects, engineers, and industrial designers. Consequently, professionals have assessed the results of digital fabrication and its performance based on various attributes including efficiency, product quality, and genuine design possibilities [2]. Since its creation, digital fabrication has amended the future of many industries, and the concept of design [1].

The term "digital fabrication" refers to the process of machine fabrication that is governed by technological devices such as computers [3]. The manufacturing process consists of computer-aided design (CAD), and computer modelling software [4]. The computer processes are divided into two categories: computer numerical control (CNC), and rapid prototyping (RP). In other words, these computer processes for digital fabrication can be classified as additive or subtractive manufacturing [2]. Additive manufacturing focuses on layer addition to generate the final product [5]. While digital subtractive manufacturing is entirely reliant on a tool capable of cutting and engraving through the original material.

Each fabrication technique can be accomplished using different machines that are controlled by custom software codes and programmes. Machines include 3-D printing, laser cutting, and CNC router machining [6]. 3-D printers produce the final object through digital iterations of the layering process [7]. Horizontal layers are created by these machines using a plastic filament [5]. The laser cutter expands upon the rapid prototyping additive fabrication technique. It is compatible with a variety of CAD programmes, including thunder laser [1]. Laser-cutting is capable of working with a wide variety of materials, including acrylic sheets, wood board, etc... [3]. The type of material informs the cutting intensity, power, and speed, which in turn affects the amount of time required for the machine to complete the job [8]. The CNC machining is a process that converts G-Codes into CNC components [9]. Additionally, the method works with a variety of materials, including foam board, plastics, and various types of wood [7].

To summarize, digital fabrication is a design-forward, technology-driven paradigm that has been widely adopted in recent years. It represents a leap in the field of technological innovation in the design industry, allowing designers to develop their own signature design approach [2].

2. Digital Fabrication as a Means for Architecture Education

Mass production is where fabrication technology began, which Henry Ford, founder of Ford Motor Company, introduced and refined in the early nineteenth century [10]. Proceeding with digital fabrication in architecture, as shown in Lisa Iwamoto's Digital Fabrications Architectural and Material Techniques, CAD technology takes the role of sketching [2]. Digital manufacturing has triggered new insights and pushed the boundaries of

architectural form and structure [11]. Notably, digital fabrication has a considerable influence on the architectural design process due to its role in the construction of architectural models. This has implications for both students and professors of architecture. Exhibiting excellence in the teaching of technical subjects such as optimising 3D models for fabrication processes, material and method selection, and installation [8].

Consequently, digital manufacturing has become a need in architectural academics [8]. Both students and teachers must have a better grasp of and capability for converting digital designs to scale model representations via the use of manufacturing technology. In that regard, using computer-aided technology for digital fabrication have historically been more accessible and well-known. As a result, numerous design academics, scholars, and students have had the opportunity to understand the benefits and drawbacks of incorporating digital fabrication into their concepts [10]. In fact, the use of digital fabrication in architecture education has become widespread in many schools, and there is an increasing demand for learning computer-aided manufacturing (CAM) logic and fabrication expertise [7].

Clearly, architecture students instil a variety of learning paradigms, including but not limited to model-based thinking, production techniques and procedures, and a variety of software abilities. However, this paper stems from the stance that even those architecture students who use digital fabrication use it in the final stage of their design or in their finishing work. While the Smart and Future Cities Laboratory for Sustainable Urban Solutions (SFCL) methodology of learning aims to pave the way for computer-aided manufacturing (CAM) technologies to be used instead as a sketching tool.

This paper contends that planning and enabling digital fabrication activities wherein students create digital models using digital fabrication requires both technical and pedagogical skills. The next portion of the study renders theoretically grounded practical recommendations for how to enhance digital fabrication learning activities via the use of diverse pedagogical strategies. It demonstrates how facilitators and researchers at the (SFCL) may build digital fabrication activities that aid in student learning. The method of learning elaborates on two perspectives: examining the learning of novice pupils and cooperatively scaffolding problem-solving via the use of design thinking approaches. It seeks to metamorphose the typical thinking approach, which starts with sketches and ends with product manufacture.

3. A generic overview of Scaffolding neophyte Learning as a pedagogical method for digital fabrication learning

I. Scaffolding pedagogical strategy and its effect on cognitive and emotional learning

Traditional educational practices and pedagogy may have an impact on current and future educational practices and pedagogy. However, when the possibility of cognitive and emotional learning is examined in these learning situations, it is stated unequivocally that just installing digital tools and surroundings is inadequate [12].

It is vital to comprehend how novice learners generate information and the difficulties they may encounter along the way to develop a new mentality for learning, transforming students' cognitive minds from their typical prototype to a new one. According to human cognitive architecture and prior empirical research, minimally guided instructions are less effective and efficient for a novice learner than instructional strategies that place a premium on direct control over learning processes [13].

Direct instruction can help students develop their capacity for learning as well as their ability to recall and apply information to new situations, and enhance cognitive processes (e.g., choosing, organising, and integrating information), and expands to also encompass their problem-solving abilities. In that sense, Wood, Bruner, and Ross defined scaffolding as a process "that enables a novice to solve a problem, carry out a task, or accomplish a goal that would be impossible for him to accomplish on his own" and which, through the human facilitator's questioning, stimulates visual scaffolds that provide useful strategies and approaches to a task and demonstrate or model solutions [14].

Academies may utilise scaffolding to aid students in understanding not only how to perform a task effectively, but also why it is important to perform it correctly. Moreover, they may monitor and detect pupils' learning processes, progressively diminishing their visible support. [15]

Scaffolding approaches aid in the shift from conventional lecture-based instruction to inquiry and project-based instruction [16]. Students acquired skills in issue solving via innovation, creativity, critical thinking, effective communication, collaboration, and, of course, new knowledge. This teaching paradigm is adopted via a planned workshop on digital fabrication conducted by SFCL experts. It introduces the concept of a technology-enabled and project-based learning environment with the goal of reprogramming students' thinking patterns from product-driven to need-driven pattern.

II. Digital fabrication education in the perspective of SFCL researchers

Finally, from the perspective of SFCL researchers, digital fabrication in educational premises is not limited to learning-oriented design and construction activities using technology such as 3D printers and laser cutters. Rather than that, it emphasizes a deliberate approach to digital fabrication as a hybrid learning environment that combines digital fabrication, design thinking, and collaborative ideation and innovation to tackle challenges. This workshop outlines the idea of a technology-enabled and project-based learning environment, reformulating students' thinking patterns from its product-driven pattern into a need-driven one. Ultimately, in terms of SFCL researchers' point of view, digital fabrication in education premises is not merely learning-oriented design and building activities using technology such as 3D printers and laser cutters. We instead highlight a designed approach to digital fabrication as a hybrid learning environment that integrates digital manufacturing, design thinking, and collaborative ideation and innovation to tackle problems. To synopsis, the following diagram (Figure 1) illustrates how digital fabrication learning should elaborate

tacitly in architecture learning and how scaffolding learning techniques and architecture learning should work collaboratively to obtain superior learning outcomes.

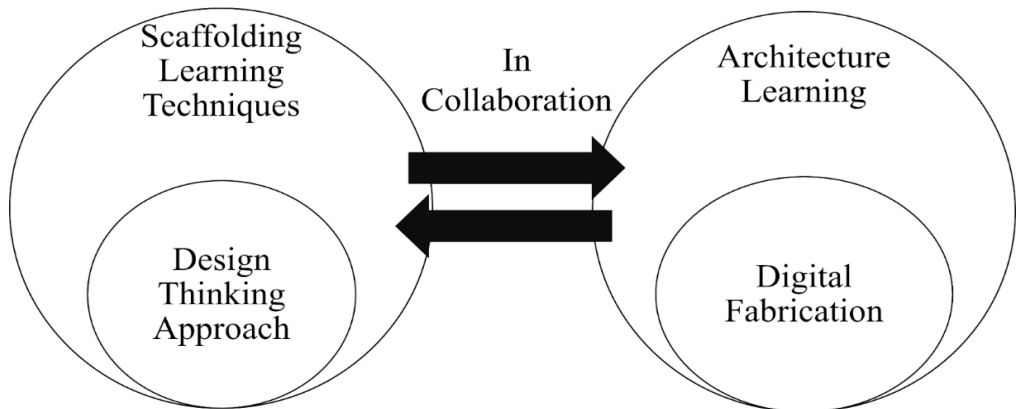


Figure 1. Scaffolding learning techniques into architecture learning approach (Author)

4. Reflection of Scaffolding neophyte Learning pedagogical method on the digital fabrication workshop

As a pedagogical shift result, scaffolding in both cognitive and affective learning processes is necessary to make the learning experience with emerging digital technologies relevant and engaging [17]. Different pedagogical models and design methodologies were implemented in the integrated digital fabrication learning workshop to foster productive interactions and thereby improve the quality of collaborative learning. The technique of design thinking is a direct application of the scaffolding concept in education [18].

I. Design thinking as pedagogical approach of Scaffolding neophyte Learning techniques

Design thinking is a creative, dynamic, and imaginative method to problem solving that is human-centred and collaborative [19]. It combines an end-user-centric approach with multidisciplinary collaboration and iterative testing to create desired, user-friendly, and economically feasible solutions or improvements [18]. It enables the transition from making people want things to creating the things they desire [20].

Design thinking is a five-step approach for developing meaningful ideas for resolving real-world problems or achieving a specific objective for a specific set of people. The five steps are as follows [21].

1. Emphasize; Empathy is essential for Design Thinking attaining human-centered design [20]. Human-centered innovation and design is concerned with people as talking to people, understanding their points of view, and emphasizing with their circumstances allows for gaining a much better understanding of their needs [21].

2. Define; The next step is to ensure addressing the correct problem. In the Empathize stage, users' information and observations should be evaluated. However, many approaches to problem solving begin with defining the problem but it must be ensured to define the correct problem [22], while considering the individual experience and knowledge gleaned and what can this experience add to solve the problem from distinct perspective [18]. A problem statement is essential for a successful Design Thinking approach because it will focus on the specific needs that have been identified. Usually problems are not what people, it is beyond what they describe thereby defining the real problem is the most critical step [21].
3. Ideate; Now is the time to brainstorm as many viable solutions as possible. It is time to comprehend the problem from the perspective of users and having a clear problem statement [22]. Furthermore, Encouraging the team to think creatively to produce innovative solutions to meet the needs of the users.
4. Prototype: it the step in which narrowing the domain of proposed solutions to have different prototypes for the best solutions solving the problem [23].
5. Test: Once prototypes have been created, the team and users can put them to the test. This stage is more concerned with the experience that surrounds it [18]. It is not only focused on the item or solution, but the user is also providing feedback in order to make adjustments and changes [23]. The feedback provided during this step allows the team to iterate and make changes and adjustments to the prototype as needed [20].

Consequently, Design thinking techniques in learning support demolishing students' old mindset and building a new one, reformulating their thinking patterns from its product-driven pattern into a need-driven one.as a result the digital fabrication workshop was initiated with a design thinking approach.

5. Overview of the workshop

It was a one-week workshop held by SFCL at Ain Shams University's Faculty of Engineering. It was organised and moderated by a team of interdisciplinary researchers from SFCL. This workshop was intended to be more project-based than lecture-based.

The workshop was designated to include three phases,

1. At first, it was essential to restructure the students' way of thinking, therefore all activities were pedagogical ideology-driven activities and brainstorming ones. this would give them a chance to apply the new intellectual skills of thinking. This facilitates the measurement of students instilling skills transformation as well as to support the students throughout the upcoming activities.
2. Herein comes the second phase aka the technical phase, it represents the application phase using various software programs and different machines. Students were to build digital fabrication knowledge through learning diverse skills cumulatively.

3. They were to elaborate on the final product, integrating all acquainted knowledge through the workshop intellectually to get their final fabricate product.

The First stage of the workshop includes,

- An introduction for the workshop's theme by introducing digital fabrication and its primary applications in architecture.
- Participants explored the context of their work throughout the process.
- An adoption of scaffolding learning methods starting with a lecture about the design thinking approach of problem solving to open a constructive criticising way of thinking among students (Figure 2).



Figure 2. Design thinking process introductory session, source: Author

In the second stage of the workshop,

- Students were asked to apply the design thinking method through a product-based project.
- It was triggered by a need to be catered or a problem to be solved regarding handling their tools at college.
- Students then were divided into various thematic groups of 3 to 4 members.
- Each group was to apply the design thinking approach considering its entire process.
- Students had time to brainstorm together to define the problem they would tackle through a 3d model product with various themes.

6. Reflecting on design thinking process

On each day it was prepared to investigate one stage of design thinking of various stages. For explanation, on day one, the workshop facilitators and researchers have

demonstrated how design thinking approaches adoption as a novel intellectual way of thinking will facilitate their problem identification. Then students were asked to make their selected modelling ideas for a defined problem solution or a catered need using traditional modelling tools such as cutters and foam sheets as well as leveraging any recycled material. This was to patronise their mindsets for problem solving approaches even when their potentials are not adequate. They had to address the problems they may face using those traditional tools. This should aim at cultivation of an iterative problem-solving mindsets.

The second day (Figure 3) was set to feature defined introduction exercises designed to familiarise students with the machines, such as semi-structured small projects demonstrating, manufacturing a keychain, a nametag, and logos. Technically, these projects required students to learn how to cut and engrave geometric objects using a laser cutter, how to generate and combine geometric shapes using vector drawing software, and how to import bitmapped pictures from the web.

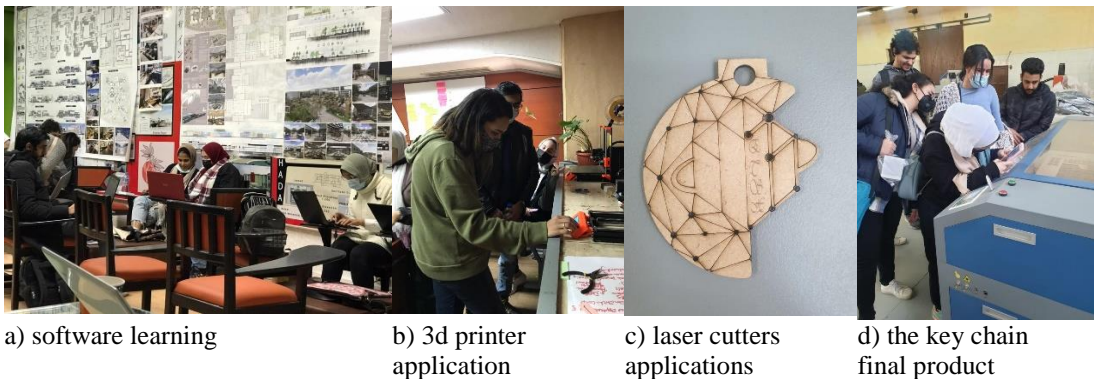


Figure 3. Day two, source: Author

Additionally, they will be taught how to use 3D printing and laser cutting software and operations procedures. Facilitators reasoned that by assigning students to build very personal goods like keychains and nametags, they would develop a greater interest in the technologies, since they would be developing items for daily usage, thus attracting the attention of their colleagues. They would be pleased of their achievements and relate their newly acquired engineering ability with the manufacture of socially significant artefacts. Students were ecstatic as they worked on their keychains. The plan was successful, and they returned much more pleased with their acquisitions. Students' knowledge regarding Digital fabrication was thriving, and they were ecstatic at the prospect of making stuff.'

On day three, the students participated in an online brainstorming session. Initially, the students were claimed to present their non-digitally created 3D models, interrogating the challenges they faced in creating the model and how they tackled them using the available materials they have, accentuating the ability of digital fabrication machines to facilitate their modelling problems. They were to articulate the operational digitised tools they aspired to have in order to create their model optimally. In addition to pre-structured and facilitated

learning activities, more spontaneous collaborative activities were recommended. They were shown images of digitally fabricated models. Each group claimed to analyse the manufacturing process of a selected model using a laser cutter and a 3D printer demonstrating its technique of joining and combining. This means that students were provided with opportunities to engage in learning activities which places students' needs, interests, and experiences as the starting point for their explorations. This activity patronises the adoption of all the five steps of design thinking technique. They started to read the problem that triggered each model and emphasised with it then they defined the problem in a clear statement. They were asked to ideate the solutions for the problem in various ideas, one of them is the proposed one that they have its picture. Furthermore, they were to explain why the proposed prototype is the optimum solution and if there is an addition to make it better.

This type of learner-centred approach fosters a creative learning environment and allows for personal affective as well as cognitive experiences [24]. A sound learning environment also guides and supports students' interests and encourages active participation in learning [25]–[27]. To support learning activities in the ways described above, pedagogically sound practices must be established. After the brainstorming activity, it was the optimum time to provide them with an introductory session about fusion 360 software to qualify them for their application via their own model.

On day four, through a one day working session, they were educated how to create their 3d models using fusion 360, however 3d modelling is not the sole prerogative of fusion 360 (Figure 4). Fusion 360's main privilege is Connecting and Assembly [1]. Fusion 360 supports connection-based assembly technology, which is a simple method for components joinery [28]. The incorporation of assembly into a modelling integration process promotes design efficiency. Assembly strategies are critical for precision-manufactured products. Joining is a sub-function of an assembly that brings together many components to perform a specific function; it depends on embedding the logic of component assembly within the geometry of each component, for that modeler is in no need to use any external welding or sticking assembly material [11].

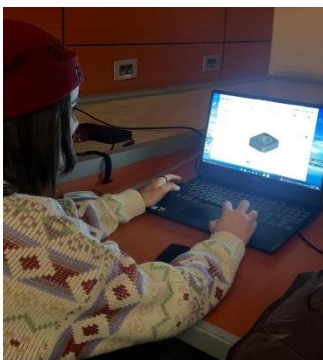


Figure 4. Fusion 360 learning session (Author)

Figure 5. Joining techniques (Author)

On day five they started to apply the acquainted design thinking, technological and digital fabrication skills on their own project- the same projects they were selected from day1-. This fosters their analytical cognition and comparative- based critical memory, instilling the knowledge of digital fabrication versatile technologies, obtaining the main goal of the workshop. They were given no restrictions and limitations for their ideas while supported with guidance to create them. Therefore, for many groups, the balance between directness and openness created the foundation for iterative cycles of reflection and action in which the students used and revisited experiences and actions from previous activities to support their ideas.

They started with modelling on fusion 360 hence exporting their work rather than RD-works software for laser cutters or Prusa-slicer software for 3d printing. Afterwards, they proceeded with the synthesis process, finalising the fabrication process of their models by joining and assembling their cut and printed components (Figure 5).

It was noticed that they began leveraging design thinking methodology to solve all problems they face while finalising their project. In this context, they commenced to criticise their products generating more ideas for product improvement. Suffice to say that students have built a novel creating and designing mentality based on a structured iterative process of ideation. Ultimately, on day six, they presented their final products, commencing the process from scratch, proceeding with problem definition until the final digitally fabricated product, accentuating the solution for the problem they tackled from the beginning. The following figures show some examples of the students' final products (Figure 6) & (Figure 7).



Figure 6. Examples of students' final products groups: 1 & 2, source: Author.

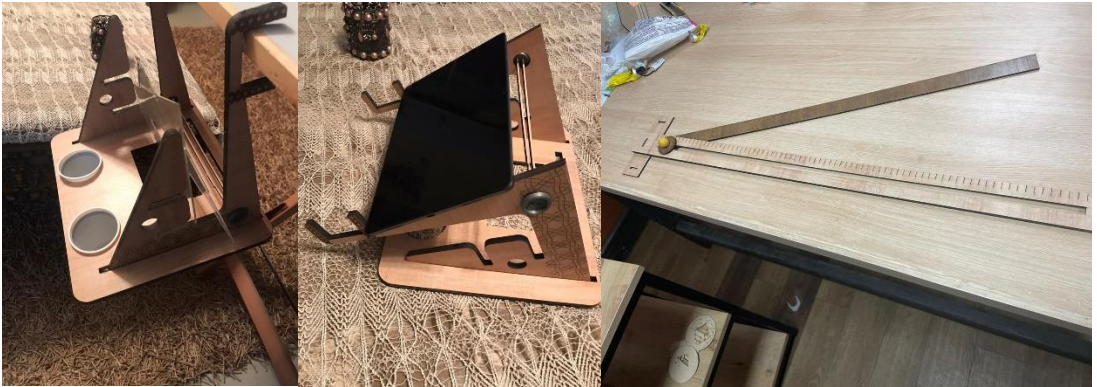


Figure 7. Examples of student's final products, groups 3 & 4, source: Author.

Discussion

Following the training, a pool of sixteen students was questioned to determine their level of satisfaction with the workshop. As illustrated in the following figure (Figure 8), students initially described their level of competence in relation to the skills or knowledge associated with the course content as being low (on average less than 1.5/4), but by the end of the training they perceived their knowledge to have increased by nearly twofold to almost 3.5/4 (Figure 9); Additionally, students evaluated their level of satisfaction with the following areas of the training module

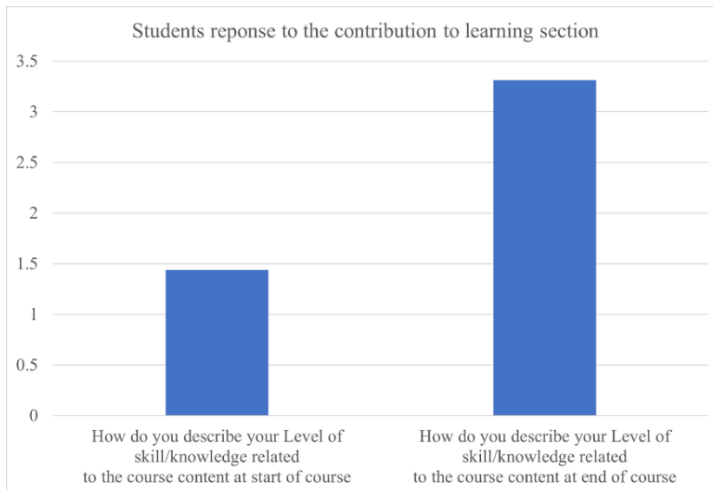


Figure 8. Level of students' satisfaction at the beginning of the workshop, source: Author.

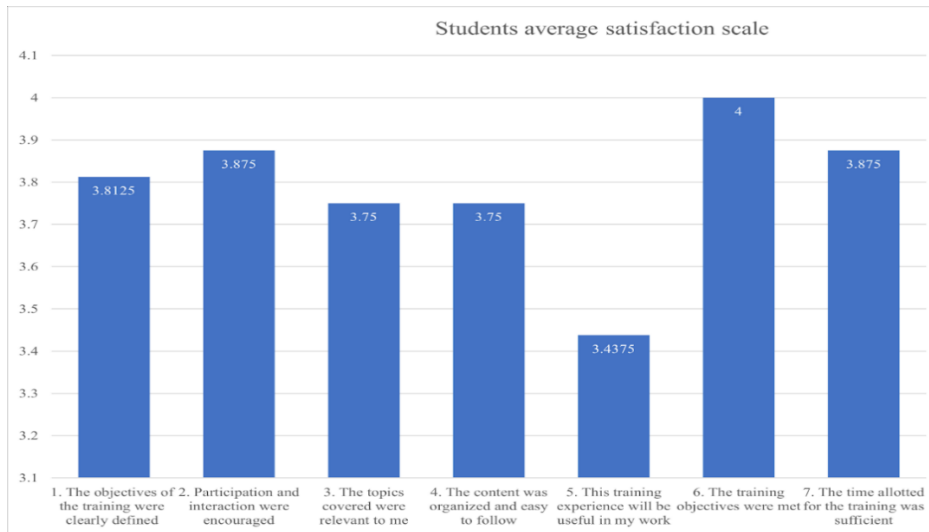


Figure 9. Level of students' satisfaction at the end of the workshop, source: Author.

To proceed, this is a synopsis of the students' perceived satisfaction with the course, assessing the clarity of the objectives, the encouragement of participation, the coverage of pertinent topics, the organisation of the content and its ease of use, the usefulness of the training experience, the achievement of the objectives, and finally, the training's time management.

The objectives were rated highest, 4/4, due to the clarity with which they were presented and the students' follow-through with the assistance of the trainers; the usefulness of the training for future work was rated lowest, 3.4/4 on average; this can be attributed to the small scale projects produced by students majoring in architecture and urban design, who may not fully comprehend the capacity of such programs; this indicates that additional consideration should be given to visualise the capacity of such programs in their implementation on an architectural scale.

The poll was then subclassified to have a better understanding of the many topics on which students could have a viewpoint.

According to the survey, the training objectives were perceived to be clear, receiving a rating of nearly 3.82/4. This can be credited to the introductory session, during which the objectives were explained with the students in an open dialogue about their preconceptions of the course and the course's actual content, namely their anticipated outputs. The training content was well organised and prepared, earning a comparable rating of roughly 3.82/4; this may also be ascribed to the teachers' description of the intended timetable, as well as their online and offline assistance (Figure 10).

The training workload was also rated relatively high, nearly 3.82/4, which can be attributed to its organisation and conduct in a condensed time frame; rather than being crammed, it was concentrated to ensure that the training content was shared in a fashion that would permit for student absorption without becoming heavy handed. The arrangement of the training was scored highest, averaging 3.94/4, since students felt catered to by the many resources made available to them, such as having online learning days to allow students to balance doing their training and having time to unwind following the academic term.

There is no doubt that trainers played a significant role in the management of the training session for students, as evidenced by their reported levels of satisfaction (Figure 11), which particularly metered the students' satisfaction with trainers, their perception of trainers as knowledgeable about the training topics and respectfulness in handling and moderating the training session; both were rated higher than 3.81/4. Trainer preparedness was also rated higher than 3.75/4.

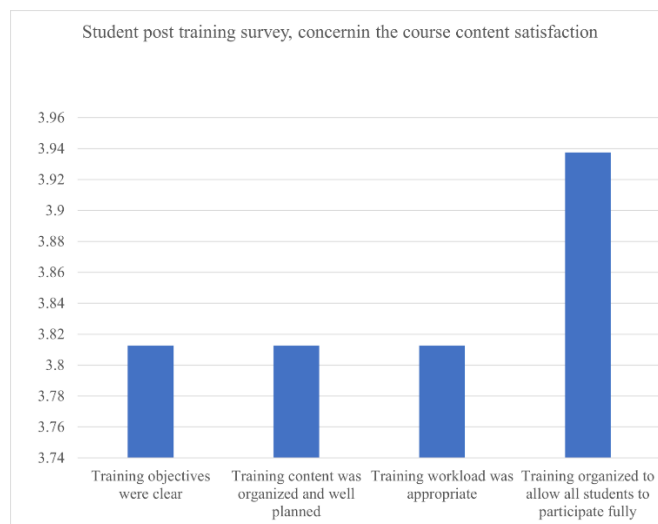


Figure 10. Level of students' satisfaction with the workshop's content, source: Author.

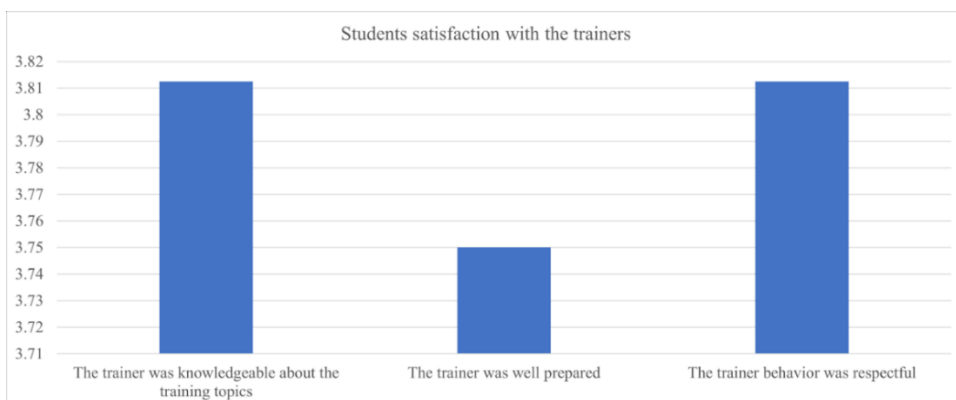


Figure 11. Students' satisfaction with the training, source: Author.

7. Conclusions

This study pointed out that adequate scaffolding is needed to improve opportunities for cognitively effortful and effectively meaningful learning. This is especially important in the situations where maker activities and digital fabrication procedures are introduced to novice trainees, since they need to be familiarised with the making culture as well as possibilities and tools.

The workshop succeeds in introducing the digital fabrication process and its correlation with digital design in making a product based on a need, which uses fusion 360 as an assembling tool. The workshop confirmed that learning architecture and digital fabrication are interrelated. Digital fabrication and technological manufacturing are a vital part of the learning process in architecture schools which brings students of interdisciplinary collaboration architecture with fabrication learning. Different ways of organising digital education illustrated in particular how different types of pedagogical design and digital tools have been used to support cognitively effortful and affectively meaningful learning in groups. design digital fabrication activities to support students' learning based on different pedagogical learning proposition: novice students' scaffolding learning through problem-solving and design thinking activities.

According to "The Effectiveness of a Design Thinking Course in Promoting Critical Thinking Skills." [29]; design thinking promotes critical thinking, making it a vital quality for 21st-century students. [30]. Production involves the interaction of the embodied mind and its physical surrounds to articulate meaning, designers can engage with and discuss ideas regarding an object's physical presence use their physical surroundings to articulate their thought and communicate it with the instructors. Object prototyping helps generate a common language through shared analogies [23] which enhances the empathy of students to their contexts and environment [31]. Design thinking additionally reduces cognitive biases and can also boost innovation by correcting cognitive flaws as shown in studies [32], [33]; It also fosters fluidity and exuberance, which enhances motivation and project concentration. [33]; In design thinking, limitations are perceived as opportunities, and constructive failures strengthen resilience. As a result, design thinking may promote resilience in the face of failures and ambiguity. Along with dynamic learning, collaborative flow, unexpected solutions, and innovative material [29], [33].

The efforts made by the lab to create an accessible learning experience for students were new, and they laid the groundwork for a larger outreach to adapt so many more students with a variety of learning needs, by utilising a variety of tools and techniques that enable students to learn at their own pace and take ownership of their educational experiences.

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