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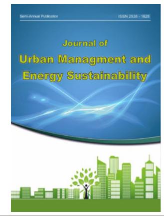

CASE STUDY RESEARCH PAPER

Computer-aided architectural construction using parametric design methods (Case study: Constructing scale models)[1]

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ABSTRACT

Technological advancements in the field of architecture, particularly in the areas of parametric design and computational optimization processes, have continued to evolve utilizing digital fabrication methods to create new scalable models. Digital fabrication, defined as a process utilizing CNC machines, 3D printers, and laser cutting, has been recognized as a digital manufacturing process. The use of digital fabrication techniques not only opens up new avenues for innovation in architectural design but also enhances performance and efficiency in construction. These processes enable architects to rapidly respond to design challenges and offer innovative solutions to improve quality and flexibility in construction by leveraging technological advancements. These transformations have not only impacted the architectural industry but also brought about significant effects on social and economic levels, fostering remarkable developments in the interaction between architects and technology. With a belief in creating more accurate scalable models and faster construction speeds, this technology offers conveniences in architectural construction. The objectives of this study include architectural construction using computer-aided design and parametric design methods, generating parametric scalable models, and developing appropriate methods for teaching digital fabrication. The research methodology is both goal-oriented and involves data collection from a case study branch. Data collection is done through a closed-ended questionnaire, conducted on 111 undergraduate architecture students, utilizing a convenience sampling method. The results indicate that while digital fabrication offers advantages, it also poses challenges in the architectural education domain. Overall, this research emphasizes the importance of empowering students and educators in this field as a case study in teaching and enhancing digital fabrication skills and architectural model construction.

Running Title: Digital fabrication using parametric design method

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
19	10	08

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INTRODUCTION

Digital technology in the field of architecture is also progressing. Parametric design methods combined with computational optimization processes and digital fabrication for creating architectural models are among these advancements. Digital fabrication is defined as the process of manipulating objects using CNC machines, 3D printers, and laser cutting through reduction or addition methods. It is believed that this technology provides many advantages and conveniences in model making, as it offers more accurate results with a faster production process. Furthermore, this understanding has implications for architecture students and professors. For example, teaching technical issues such as optimizing 3D models for construction processes, selecting techniques and materials, as well as their installation presents challenges. Therefore, studying digital fabrication is a necessity in architectural education. Students and professors need to improve their understanding and skills in processing digital designs and showcasing scale models through digital fabrication methods (Nemorin, 2016). The aim of this research is to identify methods for teaching digital fabrication in the production of architectural models. The methodology involves surveying architecture students participating in a workshop. In this workshop, the process of digital fabrication is introduced alongside computational optimization using Grasshopper. Architecture students fill out a questionnaire before and after the workshop. Study results indicate that digital fabrication, in addition to its convenience, also poses challenges for the academic community in architecture.

This article examines the application of digital fabrication and parametric design in creating architectural models, demonstrating how these technologies can provide advantages such as higher accuracy and speed in the design and construction process. It also explores the challenges that students and professors encounter in learning and applying these technologies. Digital fabrication techniques are transforming architectural design and education. This article investigates how digital fabrication techniques can be used to create architectural models at a practical scale, presenting a case study from a workshop for architecture students. In this workshop, computational design tools and processes and 3D model optimization for construction through laser cutting, CNC, and 3D printing techniques were introduced. Students were assessed before and after the workshop with questionnaires regarding their familiarity with digital fabrication. Digital fabrication offers convenience and accuracy in creating computer models but requires specific specialized knowledge (Golpasha, 2020). The results showed that most students were familiar with digital fabrication, particularly laser cutting, but faced challenges in file preparation and component assembly. This workshop enhanced the understanding of the relationship between digital design and physical construction. Over half of the students expressed a strong interest in participating in additional courses focused on digital fabrication. This article presents an educational case study that illustrates the benefits and complexities of integrating digital fabrication into architectural education. The workshop's teaching method and questionnaire results provide insights into developing curricula and teaching these rapidly evolving technologies.

MATERIALS AND METHODS

The history of construction technology begins with mass production, initiated in the early 19th century by Henry Ford, the founder of the Ford Motor Company. (Moradi nasab et al., 2016). This method worked with replicated model production, which cheaper the relationship between quantity, time, and precise predictions of quality and operational costs. In architecture, for example, Lisa Iwamoto's book "Digital Productions: Architectural Techniques and Materials" refers to the shift in attitude towards code technology, which replaced drafting with coding technology, introducing and expanding digital production as a novel process in architecture (Iwamoto, 2013). Seely also emphasizes that digital production impacts the architectural design process, as it plays a fundamental role in supporting the construction of architectural models (Seely, 2004). Furthermore, Dan has explained why architecture students and professionals create models; he clearly elaborates in the book, demonstrating that presenting creative ideas in design-based fields is crucial. This concept is particularly relevant in architecture, where we cannot often see the outcome, that is, the finished building, until the end of the design process. The initial concept progresses through a process that allows the designer to examine, revise, and refine ideas with greater detail until the project design is ready for construction. Models in this process can be highly diverse objects, allowing designers to express their thoughts creatively (Noori, 2017). Digital production has bridged the gap between idea and production. Establishing direct digital connections through "file-to-factory" processes means modeling with computers and producing with machines that require a computer model file, as well as numerically controlled production devices that fill this gap (Kolarevic, 2004). The use of digital design and production is becoming increasingly common among architecture students (Hemsath, 2010). This paradigm of digital design and production technology has been described by Stoutjesdijk as the fourth industry, aimed at making digital production techniques accessible to all. It represents a shift from a world of consumers to producers, where anyone can produce energy, information, food, and goods based on shared knowledge networks and digital production devices (Stoutjesdijk, 2013). Milena Stavric and her colleagues, in research conducted at Graz University of Technology in Austria, have examined the rapid development of parametric tools for architectural design and its challenges. This research investigates the parametric approach using existing modeling tools, Python coding, and software computation. The examples presented in this article demonstrate that diversity in solving parametric design can only be achieved by understanding the breadth of various disciplines explored in this course. Meanwhile, fostering innovation in digital fabrication is only possible through the interaction between geometry, programming, and a deep understanding of material properties and construction tools (Stavric, 2016).

In a similar study on the manufacturing of industrial parts, Nemorin examined the challenges and problems that students had with modeling and 3D printing a product, the findings of which are presented in the table below (Nemorin, 2016):

Parametric design and digital manufacturing:

In his book Parametric Design for Architecture, Wasim Jabi explains that parametric design is a design process based on algorithmic thinking that brings the details of a parameter to the surface. This process enhances and clarifies the possibility of enhancement and the relationship between design goals and how the design responds to problems (Jabi, 2013).

Table 1- Digital fabrication strategies in design education (Stavric, et al. 2016)

Course Name	Construction Type	Material Type	Additional Skills
Digital Fabrication	Laser Cutting, CNC Milling	Flat Sheet (Paper), Thick Panels	Geometry, Programming (Grasshopper3D)
Generative Design	Laser Cutting	Flat Sheet (Paper)	Programming (Processing), Hardware and Control, Sensor Integration (Kinect)
Interactive Systems	Robotic Assembly, Hot Wire Cutting	Volume Brick, Block	Grasshopper3D Programming, Mathematics
Digital Design	Optional	Optional	Programming (Grasshopper3D), Geometry, Optimization

Table 2 - Key findings of 3D printing (Nemorin, 2016)

Description
It is a difficult and exhausting task and can be frustrating and filled with failures.
Requires scientific and mathematical understanding and precision, as well as trial and error and perseverance.
Significant time is required for 3D printing projects.
Most of the time in 3D printing is spent on planning and computer-aided design rather than the printing itself.
3D printing is not appealing to students and is exhausting like traditional school activities.
Failure in 3D printing projects can be distressing for students.
It creates a separation between the student and the product they are creating.

Table 3 - Parametric design for architecture (Jabi, 2013)

Advantages	Descriptions
Creating space for experimentation and analysis	This process allows for testing different methods and ideas, helping improve designs.
Enhancing the connection between overall goals and design details	This approach enables designers to incorporate various objectives into their designs and implement necessary improvements.
Promoting design methods and solving complex problems	Parametric design facilitates the optimization of the design process and the resolution of complex issues.

Table 4- Digital Production (Bukstein, 2013)

Advantages	Descriptions
Possibility of Utilizing Multidisciplinary Knowledge in Design and Production	This process involves the use of various knowledge areas, including 2D and 3D design.
Creating a Direct Process from Design to Production	By using code and CAM, the design process is directly transferred to production with specific devices.
Enhancing Accuracy and Quality in Production	The use of digital manufacturing devices such as 3D printers leads to higher accuracy and quality.

Parametric design allows the designer to define the relationships between elements or groups of elements and to relate values or expressions to these definitions, organizing and controlling them (Noori, 2017). Dan also adds that this process continues until desirable outcomes are selected based on the criteria of “efficiency” and “aesthetics.” He also notes that for newcomers to this field, the parametric design process can initially be very time-consuming; however, it depends on the willingness to learn (Woodbury, 2010). In the first decade of the 2000s, the prices of prototyping equipment such as laser cutters and 3D printers significantly decreased, and open-source hardware made these technologies more popular. Digital manufacturing technology became better and more accessible, and the intellectual activities enabled by this new technology gained more importance (Blikstein, 2013). There is a significant definition of digital manufacturing: it is a process that starts with digital design and concludes with output from a manufacturing machine. Digital manufacturing is a pedagogical model and activity that encompasses multidisciplinary knowledge, including 2D design, 3D design, and the use of tools and machines. This process begins with code (computer-aided design) and then transfers to CAM (computer-aided manufacturing) software. The output from CAM is ready for production with a specific device, such as a 3D printer, laser cutter, or CNC machine (Blikstein, 2013).

Teaching Digital Design and Production

The first digital manufacturing laboratories appeared in architecture schools in the late 1990s and were the result of collaboration with mechanical engineering laboratories (Celani, 2012). Rapid prototyping and CNC machines became the first model production devices in architecture. In the following years, techniques and strategies expanded rapidly. Essentially, there are three phases for digital manufacturing (Asgari and Fathi, 2022): Digital Design Phase: In this phase, a virtual model is created using coding software. The 3D model is exported as a triangular mesh or surface.

Preparation Phase: This stage involves setting production-specific parameters. As a result, a CAM file is generated and then sent to the device.

Production Phase: Manufacturing tools produce parts based on CAM data, either with or without human assistance or interaction. The assembly of the produced parts may need to achieve their features and final appearance until they are ready for use.

Focus of the Construction Phase (Smit and Charlotte, 2016):

Externalize ideas and concepts into forms, samples, and products.

Select both analog and digital materials to transform ideas into samples and products.

Experiment creatively with various manufacturing technologies.

Visualize and display objects in different forms and continuously adjust settings.

Litrature Review

In recent decades, with advancements in science and technology, various fields of design and architecture have also experienced significant transformations. One of the important aspects

Table 5- Digital Production Stages (Celia, 2012)

Digital production stages	Descriptions
Digital Design Phase	In this phase, a virtual model is created using CAD software. The 3D model is exported as a triangular mesh or surface.
Preparation Phase	This involves setting production-specific parameters. As a result, a CAM file is generated and then sent to the device.
Production Phase	Manufacturing tools produce parts based on CAM data, either with or without human assistance or interaction.

Table 6 - Construction Phase Activities (Smit and Charlotte, 2016)

Construction phase activities	Descriptions
Externalize ideas and concepts into forms, samples, and products.	Transition ideas and concepts into forms and samples that are accessible for analysis and evaluation.
Select analog and digital materials to transform ideas into samples and products.	Choosing and using diverse and appropriate materials for producing products and samples according to needs and objectives.
Experiment creatively with various manufacturing technologies.	Utilizing different technologies and exploring innovative ways to create high-quality and efficient products.
Visualize and display objects in different forms and continuously adjust settings.	Presenting and showcasing produced products and samples in various forms for evaluation and improvement.

of these changes, especially in architecture, pertains to a new perspective on the design and construction processes of architectural models related to the use of digital technologies. In this context, two essential elements, known as "digital manufacturing process" and "parametric design," have particularly attracted the attention of researchers (Hamed Mirjafari et al., 2022). The digital manufacturing process refers to the effort to achieve architectural goals through the use of CNC machines, 3D printing, and laser cutting by following incremental or decremental paths. This process enables architects to construct architectural models with high precision and greater ease. Parametric design is recognized as an algorithmic and computational process that relies on parameters and the relationships between them. This method allows architects greater flexibility in designing complex shapes, with software code compared to traditional methods, minimizing repetitive tasks (Noori, 2017). Digital skills such as parametric design and the digital manufacturing process are rapidly being recognized as essential tools for architects. Practical training focused on optimization processes seems to be the best way to teach students these skills. However, there are gaps between digital design knowledge and physical skills in the manufacturing process that need to be addressed. Digital manufacturing process workshops can effectively teach parametric design skills and digital optimization techniques to architecture students. Hands-on learning through construction will increase students' understanding and interest in pursuing studies in the use of these emerging technologies. Ultimately, the aim of this paper is to evaluate these concepts and main hypotheses through a case study for architecture students. This research was conducted on 111 undergraduate architecture students at the Islamic Azad University, Tehran South Branch, who participated in the digital manufacturing technology workshop, with a sampling method utilizing convenience sampling. We will evaluate surveys, existing critiques, and the impact of practical education on equipping students with essential capabilities in the digital manufacturing process.

Methodology

The aim of this research is to identify the process of teaching digital fabrication to architecture students. The research method is through the analysis of a questionnaire that was extracted from architecture students. This research focuses specifically on a workshop that was held for undergraduate architecture students at Islamic Azad University, South Tehran Branch. In this workshop, a digital fabrication process is

Figure 1: Digital Design and Digital Manufacturing Workshop (Authors' Source)

presented that begins with learning parametric design and then a computational optimization process is performed using the Grasshopper tool. Architecture students will have the opportunity to complete a questionnaire at the beginning and end of the process during the workshop.

Through this workshop, students gain an understanding of the basic Grasshopper process as tools for digital design and file optimization for manufacturing. This workshop includes the digital design process, which involves applying parametric design, the optimization stage, and then preparing the manufacturing file. In the workshop (Fig. 1), students learn how to create a 3D model using Grasshopper and prepare the manufacturing file. The researcher presents the final scale of the constructed model as an explanation of the process outcome. Questionnaires were sent to the targeted individuals before and after the workshop was completed. Each participant indicated their opinion about the workshop by answering the questionnaire. The results of the questionnaires completed by participants were analyzed by converting the response options. Positive response options (very good, strongly agree, and very satisfied) are converted to the number 5, while the results of very negative response options (very bad, very dissatisfied, very disagree) are converted to the number 1. The questionnaire consists of three pages. In Figure 2, the first page of the questionnaire includes six questions. This page asks about personal data and familiarity with digital manufacturing and whether they have ever used digital manufacturing before. At the end of the first page of the questionnaire, there is a yes or no question regarding whether they had any experience with digital manufacturing prior to the workshop; those who had experience can proceed to the second page, while those without such experience can skip to the third page of the questionnaire. The second page of the questionnaire in Figure 3 is for those who have experience with digital manufacturing. This page asks for details about their digital manufacturing project and the challenges they faced, as well as an evaluation of the digital manufacturing product. In Figure 4, the third page of the questionnaire inquires about their reactions to the workshop and their interest in the elective course on digital manufacturing.

DISCUSSION AND FINDINGS

The workshop was held in the Computer Aided Architectural Design and Construction class of the Faculty of Art and Architecture, Islamic Azad University, South Tehran Branch. The workshop was held in three sessions, the last session of which was held two weeks before the students' final exam. One of their final exams was the construction of a scale model for presentation in the architectural studio. The total number of participants was 111 students, spread over different academic years. The researchers are to teach the students digital design using Rhino and Grasshopper software. These tools allow for changing geometric parameters and making immediate changes to the model during design. The students are not familiar with Rhino and Grasshopper. They will be trained through the Computer Aided Architectural Design and Computer Aided Architectural Design and Construction class. Also, the researchers are prepared with the final digital fabrication product to better explain these lessons. The questionnaire is given as the beginning of the workshop and will be collected at the end of the workshop.

Laser Cutting and Contour Technique

Contouring means creating distinct and defined lines on the surface of a three-dimensional model. To use the contour technique in Rhino, we first had to create our 3D model and then use the Curve Tools or similar tools in Rhino. Using these tools, we created specific lines (contours) on the surface of our model. These lines may be based on a specific height or position in the model. Contour lines can be edited and their position or slope can be changed. In this workshop, we considered distances of 2 mm, 2.1 mm, and 2.1 mm, depending on the MDF material. We checked the representation of our model with the contours to ensure that the changes were applied correctly. Then, we numbered the resulting surfaces in Rhino with a written command and closed our cutting sheet with dimensions of 90 x 120 cm, based on the thickness of 2 mm MDF.

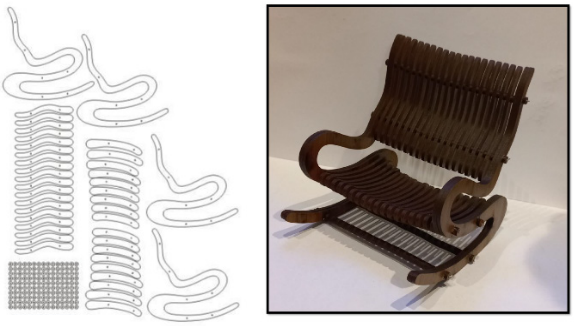

Figure 2: Making a chair using the contour technique (authors' source)

Laser cutting and waffle structure in the xy axis
The waffle structure is created using an algorithm in Grasshopper. Before starting to build the 3D model, it is essential to ensure that the scale is set in Rhino. The main step in Figure 6 is creating a section as the shape of the 3D model, and then we performed cuts of the model as surfaces along the X and Y axis. Then, in Grasshopper, we used the tongue and groove technique to combine the panels. Surface numbering for construction was also done in Grasshopper.

Laser cutting and circular waffle structure
In the circular waffle technique, we first drew the 3D model in the Rhino environment and then used an algorithm in Grasshopper to obtain the waffle cuts around the Z axis. As in Lesson 2, we used the tongue and groove technique to combine the panels. Surface numbering for construction was also done in Grasshopper, as shown in Figure 7.

3D printing of Voronoi surfaces

This lesson describes the 3D printing process. It begins with design using an algorithm in Grasshopper, followed by the optimization process using Cura for construction. The student learns from a video of the construction process. In this video, a successful example and an unsuccessful example are presented. In Figure 8, a simple additive layer of the Voronoi structure is created using an algorithm in Grasshopper and then sent to Cura. The Cura software will provide an estimated construction time. The 3D printing duration is approximately 6 hours.

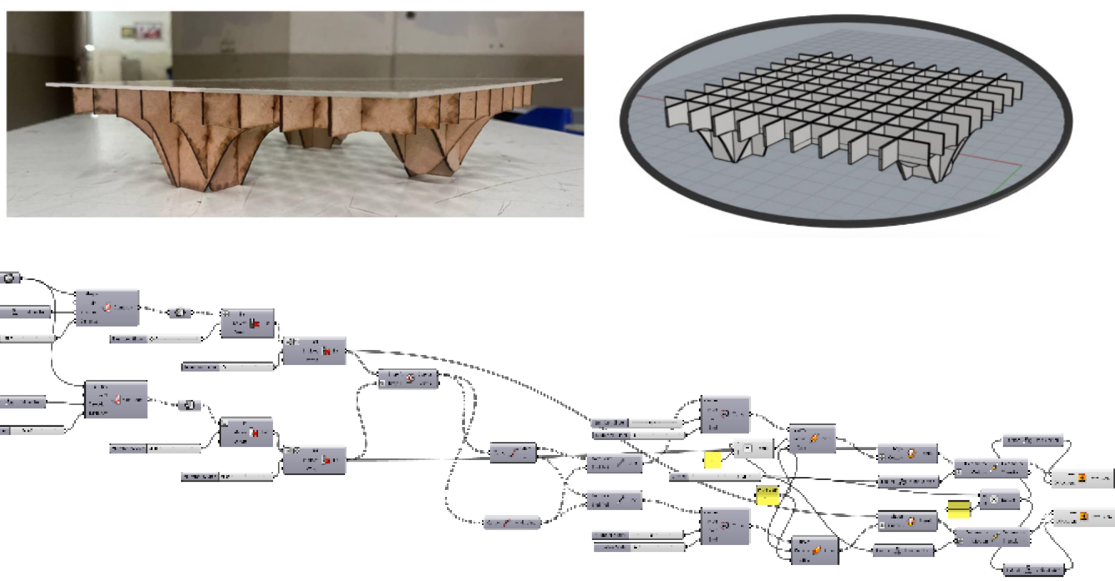

Figure 3: Making a table using the ruffle technique (authors' source)

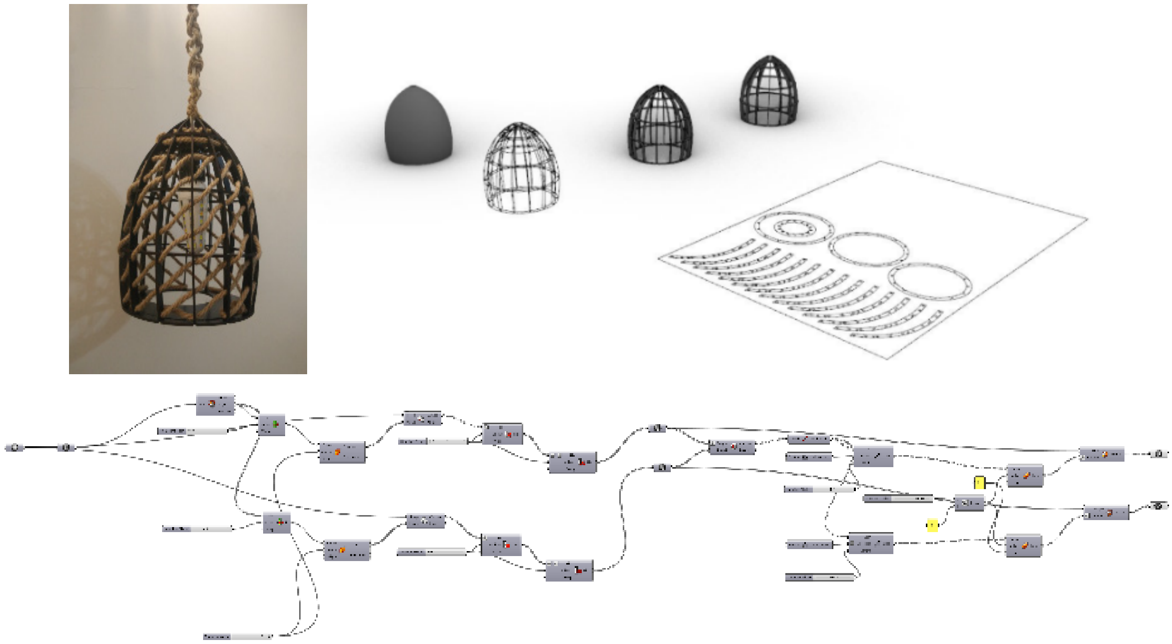

Figure 4: Making a chandelier using the circular ruffle technique (authors' source)

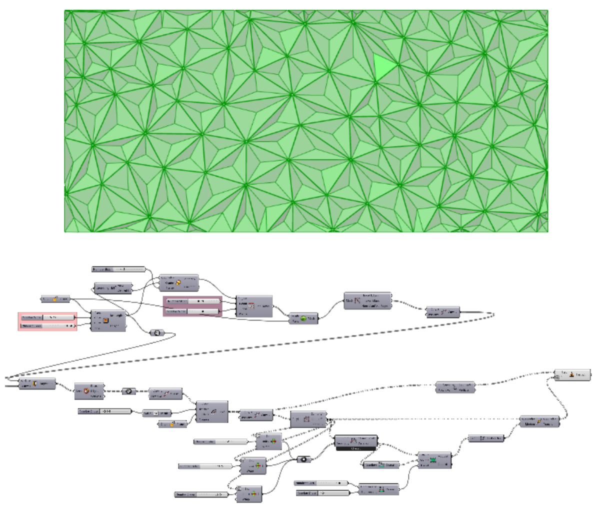

Figure 5: Construction of a 3D Voronoi surface using 3D printing technique

In the Q&A section that takes place before filling out the final questionnaire, students' interest increases as many students ask more questions about the issues they encountered when preparing the 3D model for construction. The digital design process workshop using parametric design tools like Rhino and Grasshopper is recognized as an appropriate method for preparing the 3D model for construction. Similarities have been found in research conducted by other researchers, which show that students gain experiences in creating non-standard shapes and modifying parameters. They also have the opportunity to learn about the digital construction process. Additionally, this aligns well with digital construction training based on Blikstein (2013). He stated that a fabrication lab is needed for engineering and invention so that students can safely share their digital constructions and ideas. This accelerates the invention and design cycle with long-term projects and deep collaboration. As Marshall McLuhan quoted, "We become what we behold. We shape our tools, and thereafter our tools shape us" (McLuhan, 2014). Furthermore, Nemorin added that the deep development of digital construction materials in a workshop can be more effective if students have hands-on experience with trial and error (Nemorin, 2016).

Questionnaire analysis:

One hundred and eleven architecture students participated in the workshop, spread across different levels of the academic year. As shown in Figure 6, 41% or 46 students were male, and 59% or 65 students were female. The workshop participants were mainly from the second to the fourth year of architecture studies. For more details, 68% of the respondents were in their third year of architectural studies, while 3% were in their second and fifth years, and 27% of the respondents were in their fourth year of study.

Figure 7 shows that 38% of students have no familiarity with digital fabrication, and the rest of the students have moderate or little experience. Of those who used the techniques most often, 68% used laser cutting, 14% used 3D printing, 11% used CNC, and 8% used other digital fabrication methods.

Table 7: Relationship between digital manufacturing and parametric design

Option	Response Frequency	Frequency Percentage
Strongly Disagree	0	0%
Disagree	0	0%
Neutral	15	13.5%
Agree	84	75.6%
Strongly Agree	12	10.8%
Total	111	100%

From Table 1, we can see that none of the stu-

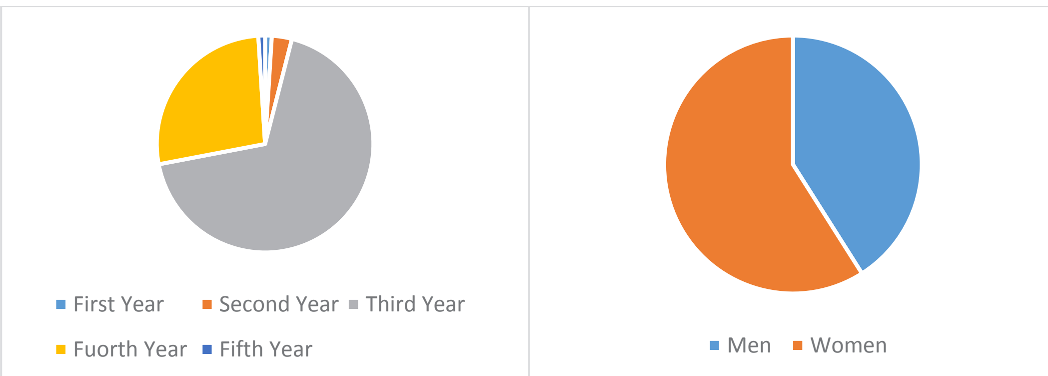

Figure 6: Background of participants (authors' source)

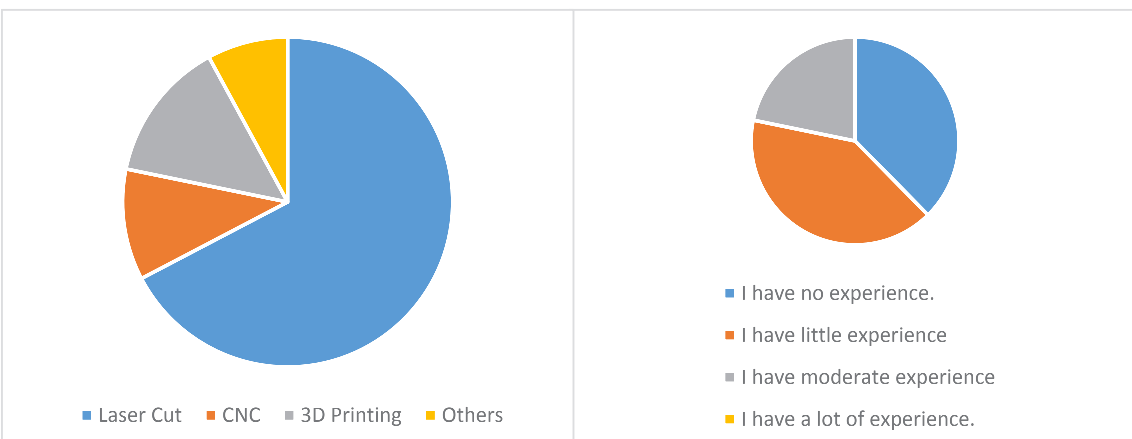

Figure 7: Top image: Students' experience with digital fabrication techniques and bottom image: Using these techniques in academic assignments

dents opposed the connection between digital fabrication and parametric design, and 13.5% of them, or 15 people, were neutral about this issue, 75.6%, or 84 people, agreed, and 10.8%, or 12 people, strongly agreed.

In the graph in Figure 8, we see that 29.7%, or 33 people, strongly agree with participating in elective courses in the field of digital design and manufacturing, 48.6%, or 54 people, agree, 19%, or 21 people, are neutral, and only 2%, or 3 people, are against participating in these courses.

Option	Response Frequency	Frequency Percentage
Strongly Disagree	0	0%
Disagree	0	0%
Neutral	12	10.8%
Agree	48	43.2%
Strongly Agree	51	45.9%
Total	111	100%

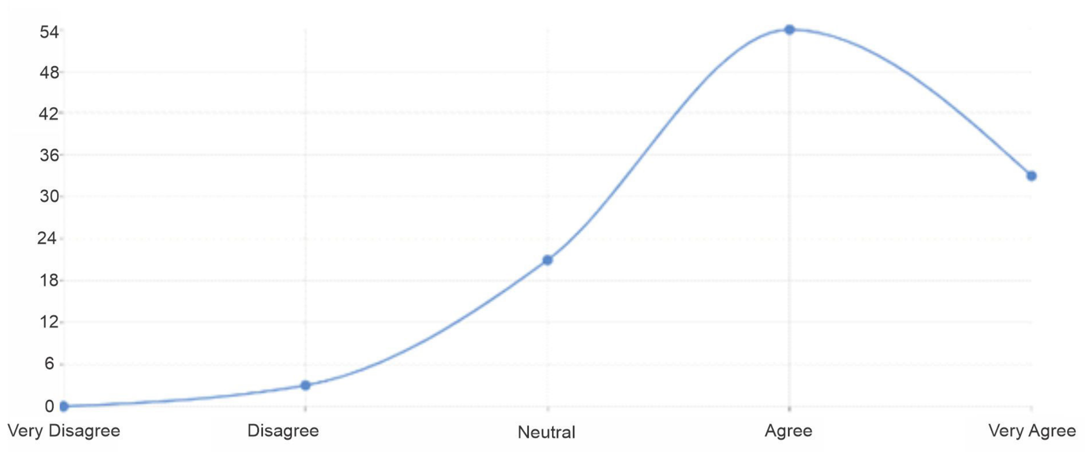

Figure 8: The level of willingness to participate in elective courses in the field of digital design and manufacturing (authors' source)

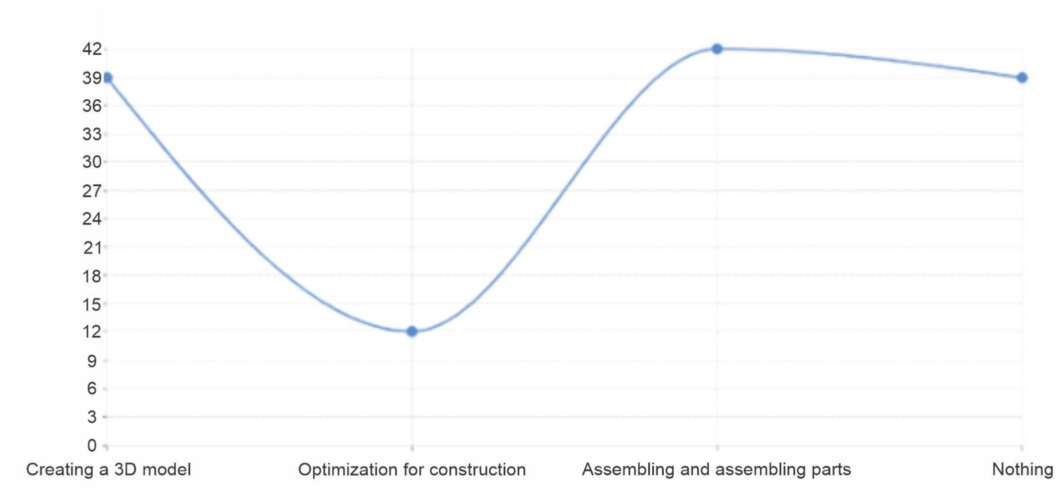

Figure 9: Problems during the manufacturing process (Authors' source)

Regarding students' sense of need for digital fabrication and parametric design courses, according to Table 2, it is observed that none of the students disagree, 10.8% (12 people) are neutral, 43.2% (48 people) agree, and 45.9% (51 people) strongly agree.

In the digital manufacturing process, we may encounter problems, one of which is the problem of creating a 3D model, which is related to the students' software capabilities, and another is the problem of optimizing and preventing material waste, and the next problem is assembling and assembling the parts. In the graph in Figure 9, we see that assembling the parts with 37.8%, building a 3D model with 35%, and optimizing with 10.8%, respectively, caused the most problems for the students, although some faced more than one problem, and 35% of the students completed their project without any problems.

Figure 10 explains the second page of the questionnaire. This graph is about the students' responses to their digital fabrication work, which shows that most of them are satisfied with their digital fabrication product, such as accuracy or scale, appearance, time spent on fabrication, efficiency, and durability. However, it is observed that they are not satisfied with the price of the fabrication product. We observe the students' satisfaction in the speed and time spent on fabrication, which is different from the opinion of Nemorin.

CONCLUSION AND RESULTS

The questionnaire report shows that students have a high familiarity with digital fabrication, particularly the use of laser cutting, which is prepared using Rhino for creating a 3D model, AutoCAD, and CorelDRAW, and helps students complete their architectural design studio tasks. Overall, they are satisfied with their digital fabrication product but dissatisfied with the cost of producing it. Additionally, the optimization file and the social aspect were the biggest challenges for students dealing with digital fabrication. There is also a problem in creating the 3D model, but it is not significant. The workshop has successfully introduced the digital fabrication process and its connection to digital design in preparing a scaled model, using Grasshopper as a parametric design tool. The workshop confirmed that digital design and digital fabrication are interconnected. Digital design is a crucial part of the process that brings ease in the next stage. Students find that digital design using Grasshopper, such as experimenting with waffle, contour, and Voronoi structures, is engaging and creates an understanding reflected in their interest in participating in the optional digital fabrication course.

Figure 10: Second page of the questionnaire students' responses

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