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Integrating Digital and Manual Modes of Design

A Computational Design Framework

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Abstract

This study describes a teaching experience that aims to combine application-oriented approaches to computational design pedagogy. In the scope of this study, a hybrid framework is presented, which allows students to transition from manual to digital modes of design. In this transition, parametric thinking and design are selected as a mediator. This hybrid framework is being tested in an elective course of an international master's program in interior design. Columns are selected as the architectural elements for parametric design and experimental production. An "exhibition" is chosen to complete the design, production and assembly tasks. Preliminary exercises and three main assignments guide the process. The three assignments are organized as follows: parametric design and modeling of a single column (Assignment 1-Digital), parametric design and modeling of a family of columns (Assignment 2-Digital), the materialization of an individual column and a family of columns using 3D printers (Assignment 1 and 2-Digital+Manual), and designing the exhibition for displaying columns (Assignment 3-Digital+Manual), producing and setting up the exhibition (Assignment 3-Manual). The experiment with a hybrid framework shows that parametric design (digital) modes that students were unfamiliar with were integrated into the process of developing parametric columns, while exhibiting designed products using their existing skill sets (manual modes). The participants' inability to fully illustrate their technical knowledge of parametric design and digital fabrication in a single course, and the lack of tools and materials to facilitate 1:1 scale digital fabrication have emerged as the major limitations of the teaching experience.

Keywords

design education, computational design pedagogy, parametric design, computational design, parametric column

1 Introduction

Architectural education is a process that involves the materialization of ideas. The use of technology evolves the act of design, which is an implicit and internal process. This evolution emphasizes the significance of situating current architectural education and curricula at the intersections of design and technology. While traditional architecture education is mostly application-oriented, technology education in architecture focuses on theoretically teaching computational tools/software and methods employed during the design process (Yazıcıoğlu, 2013). In this context, this study focused on integrating application-oriented approaches into computational design pedagogy. This study proposes a framework that covers both manual and digital modes of design in order to achieve this integration. In the context of this study, manual modes refer to hands-on activities such as sketching, scaled model making and detail production. In contrast, digital modes refer to digital design and fabrication activities supported by computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies. This study attempts to answer the questions of how and in what ways hybrid pedagogical approaches can be used to avoid sharp transitions between digital and manual modes of design. This approach also investigates the fusion produced by combining digital and manual modes.

The proposed framework aims to create a methodological synthesis between students' existing and lacking skills. This synthesis aims to get students to step outside of their comfort zone, learn new ways of thinking and skills, and apply what they have learned to solve given design problems. In this context, the synthesis includes a conceptual framework based on convergence and divergence between

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what students know and do not know throughout the design process. The conceptual framework adheres to Schön and Wiggins's (1992) design process of "seeing-moving-seeing". According to Schön and Wiggins (1992), each new explanation created during the design process foreshadows a new meaning, and each new meaning generates a new explanation. In other words, every design problem precedes a design decision, and every new design decision generates a new design problem. The first design solution proposed in this never-ending loop is within the student's comfort zone, and interventions that extend beyond the comfort zone exemplify the proposed framework. When students leave their comfort zone and face an unfamiliar design problem, they experience "divergence". In contrast, "convergence" refers to a situation where they return to their comfort zone and feel confident (Fig. 1). The dynamic and hybrid structure illustrated in Fig. 1 was tested in a series of assignments covering either manual, digital, or both design modes.

Architectural design products such as buildings and built environments seem to be the ideal entities for parametric definitions, including relationships, rules, and procedures (Aish and Woodbury, 2005; Eltaweel and Su, 2017; Gerber, 2007; Iordanova, 2007). Considering this, as a paradigm, "parametric thinking and design" was selected as a mediator between manual and digital modes of the proposed framework. The column was also chosen as an object for parametric design and fabrication experiments since it is a well-known archetype with which students are already familiar.

This paper is structured into five sections. After the introduction, Section 2 presents related pedagogical approaches in architecture, including manual modes, digital modes and a combination of both, and previous parametric column works. The structure of the proposed framework is given in Section 3. Section 4 presents the application of the proposed framework by detailing all exercises and assignments with their processes and outcomes. Section 5 discusses the pedagogical framework's achievements, limitations, repeatability, and future works.

2 Background

Architectural education is a discipline that follows traditional methods while rapidly changing in response to technological advancement. Architectural education is still attempting to find a middle ground between the traditional and the digital. In this context, Section 2.1 presents previous pedagogical approaches associated with the proposed framework's components which can be listed as sketching, scaled model making, detail production, parametric design, and rapid prototyping. Section 2.2 presents studies on the parametric column, which was chosen as the object for parametric design and digital fabrication experiments.

2.1 Pedagogical approaches

As previously emphasized by various researchers, sketching is an essential technique to begin the traditional design process (Belardi, 2014; Do, 2005; Goel, 1995; Goldschmidt, 1991; Pranovich, 2004). According to Wilson (1998), this position corresponds to the notion that the manual dialectic established between the brain and body is one of the most effective techniques for developing intelligence. Hand sketches used in design studios are known to provide a connection between the brain, hand, and paper. It is also a cognitive tool that assists in problem-solving activities during the design process (Cross, 1999; Konkel, 2014; Tversky, 2001).

Besides hand sketches, design processes involving scaled models can also be considered traditional methods. Scaled models are used to solve problems that arise during the materialization of design ideas. Problems not revealed in 2-dimensional design and similar representation mediums become evident in 3-dimensional scaled models. In this context, scaled models are believed to assist the design process (Dunn, 2007). The findings of a study by Michels et al. (2019) show that traditional techniques promote creativity and encourage students to think critically. Michels et al. (2019) employed physical models and conceptual representations to produce particular architectural elements observed in interiors.

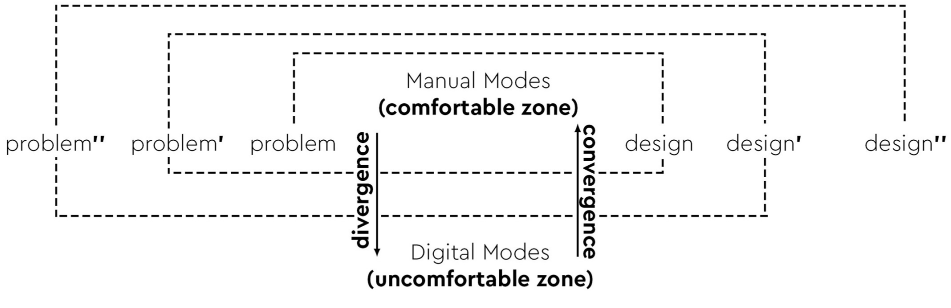

Fig. 1 Defined dynamic structure between modes and zones

In addition to sketching and scaled model making, another manual work mode is detail production and prototyping. Some studies also focused on detail design and production using traditional techniques (İmamoğlu et al., 2009; Konkel, 2014; Schneiderman and Freihoefer, 2013). These studies commonly conclude that there is a feedback process between the designed details and the prototyping of the details. This procedure can be described as revisiting the design phase after evaluating the prototypes of the designed details and can be defined as "the success of failure". It can contribute to self-improvement and finalizing their designs by a method of trial and error. The framework suggested by the authors includes the detail design and rapid prototyping phases. When students make mistakes within their comfort zone, the proposed framework aims to have positive outcomes for both the students and the process.

One of the negative aspects is that these approaches, described through detail design, prototyping and production processes, require significantly more resources and workforce from both students and the school (Gutai and Palaiologou, 2021). Moreover, traditional design approaches have adverse effects, such as a lack of design practicality, difficulty in solving complex problems, and a shortage of variety in design alternatives. Since this study focuses on the minimization of these negative aspects, parametric thinking and design are selected as themes.

Parametric design allows for the creation of many design alternatives; it is a practical tool for providing flexibility in alternative selection (Alalouch, 2018; Barrios Hernandez, 2006; Lee et al., 2014). Parametric design also accelerates the solution of complex ideas that traditional approaches have difficulty solving and creates optimum conditions (Anderson and Tang, 2011; Harding and Shepherd, 2017; Oxman, 2017). Another definition of parametric design is the ability to identify, configure, model, and modulate form using a matrix with a potentially infinite design population (Oxman and Oxman, 2014). In this context, Oxman and Oxman (2014) defined parametric design as a new epistemology and a method that supplements the shortcomings of traditional design education approaches. Rather than a historical and formal pursuit, this new epistemology has a research-oriented structure aided by emerging technologies. This research-oriented structure does not describe a structure that will be added to traditional design education methods; rather, a new way of thinking must be developed from the start. For instance, Alalouch's (2018) approach does not intend to replace or compete with the fully computerized process of parametric design; instead, from the beginning, it provides a systematic and structured way to "seed" parametric thinking in design education. According to Romaniak and Filipowski (2018), using interfaces that allow parametric modeling, such as Rhinoceros and Grasshopper, increases students' programming skills, which are crucial for their development. The structure of the parametric design approach promotes the development of new pedagogical models in design education.

2.2 Parametric column

One of the pioneers in using well-known architectural elements as models to foster parametric thinking and exploit its potential was Mark Burry. Burry (1996) used the columns of La Sagrada Familia to demonstrate that parametric design is an effective solution in this particular case. Another study by Barrios Hernandez (2006) produces many alternatives of Antoni Gaudi's columns. In another context, Perugini and Andreani (2013) examine the parameters of the complex forms designed by Pier Luigi Nervi. Furthermore, it was demonstrated that the careful interpretation of the geometric elements that comprise an architectural aid in discovering a common matrix and that the columns of these architectural elements can be parameterized (Paris and Wahbeh, 2016).

In another study on the pedagogical use of columns as a parametric design object, students designed and built three 4 m tall prototype brick columns by incorporating functional load-bearing criteria into the column design in a parametric system (Gramazio Kohler Research, 2010). In this context, Sousa and Xavier (2015) used parametric design tools to conduct shape explorations (columns, walls, shells, etc.). Later, a selected column alternative was created using an industrial robot and identical EPS blocks (Sousa and Xavier, 2015). Furthermore, parametric column variations were created by incorporating L-systems into the process to test concepts like branching (Nikitaras, 2019).

The studies confirm that well-known architectural elements, particularly columns, are recognized in parametric design and digital fabrication. Accordingly, these basic architectural elements consist of a parametric modeling scheme that specifies which attributes of a geometric model are parameterized; and how the designer can change the values of the parameters. This parametric modeling scheme reveals the geometrical features of architectural elements. In this study, the geometrical forms of the columns are investigated instead of their structural features.

The reasons for choosing columns as design objects of the proposed framework are as follows:

- The columns, by nature, have a repetitive structure. They appear distinct, but if they can be connected to a common matrix, they can be generated from a single parametric model.
- Columns have a variety of forms and types but could be traced back to their rules and proportions to reconstruct their parametric models.
- Despite the well-known structure of the columns as form and feature, it is implicit that this structure is suitable for parametric modeling. They are thus well suited for a pedagogical approach used by students learning parametric modeling for the first time.
- The authors preferred that the chosen design object contributes to the proposed framework's hybridity. Column types and forms students are familiar with and are within their comfort zone converge with the unfamiliar parametric design process. Therefore, columns can be considered as suitable choice as the "design object" in the study.
- The creation of an "individual column" as a result of each change in a defined parameter for the columns and a "column family" as a result of the changes made in the parametric model form the basis of assignments,
- Columns designed in accordance with the determined parameters can be materialized/fabricated in different scales.
- Compared to other well-known architectural forms, the structure of the columns running in the Z axis will require less or no support in the 3D printing process. This can make the prototyping process much faster. Thus, students can instantly see the parametric design outputs and decide accordingly.

3 Pedagogical framework

3.1 Definitions: manual, digital and hybrid modes

The proposed framework aims to create a methodological synthesis between students' existing and the skills they lack. In this study, the manual design mode refers to the tasks students complete within their comfort zone using familiar tools, methods, or approaches. On the other hand, digital modes can be defined as experiments that students do not know how to do, are unfamiliar with, and are outside of their comfort zone. In addition, the hybrid mode represents processes resulting from the combination of manual and digital modes.

At this point, the authors' manual, digital, and hybrid definitions are not constant but somewhat configurable. What is comfortable for students and what is not may differ in each case, and generalization is impractical. However, the definitions used in this study were customized to the semester and students involved in the teaching experiment. Since the tutors had prior experience with exchange students from the same institution, they could organize the course in this manner. The preliminary studies and the difficulty of the given tasks are designed to understand the students' skill levels. Since there were no significant differences between the students' outputs in these studies, the concepts of digital, manual, and hybrid could be defined in the proposed framework through comfort zones. However, researchers using this framework should correctly construct these definitions for their specific cases before using it.

3.2 Course: Digital representation techniques for interior design (DRTID)

The International Master of Interior Architectural Design (IMIAD) is an international knowledge and experience-sharing platform organized as a master's degree in interior architecture. The program aims to bring master-level interior architecture education to an international level, share interdisciplinary education and professional experiences in international settings, and work with students from various countries. According to a contract signed by four universities, the IMIAD Program partnership is made up by the interior architecture departments of the party countries. The Digital Representation Techniques for Interior Design (DRTID) course is an elective course offered by Istanbul Technical University (ITU) as part of the IMIAD program.

Students enrolled in the IMIAD program spend their second semester at partner institutions other than their home institution, taking courses from the host institutions' curricula. When the curricula of the partner universities were examined, no courses related to parametric design were found. This situation demonstrates that the parametric design knowledge of IMIAD exchange students is mostly limited. Furthermore, while students generally have 3-dimensional solid modeling skills, they are unfamiliar with parametric modeling tools and environments such as Rhinoceros computer-aided design (CAD) software and Grasshopper virtual scripting environment (VSE). The primary goal of the course is to introduce students to how to express their interior architectural design solutions through solid modeling and digital representation techniques. Considering the participating students' lack of knowledge of parametric thinking and parametric design skills, the course content has been updated to include an overview of parametric design. The teaching methodology consists of:

- online tutorials to introduce the use of solid and parametric modeling environments,
- online meetings to develop individual and group works and to get feedback from the tutors on the given assignments,
- in-person meetings to produce design solutions that are developed as a group.

All online modules of DRTID were conducted through the Zoom platform. Students received information about the assignments and submission details from the Miro Board and the official platform of the institution.

3.3 Tutorials, assignments and evaluation

In the 14-week long DRTID course, five online tutorials were planned to provide students with the necessary knowledge to accomplish the given assignments. Instead of giving all tutorials before the assignments, the tutorials were distributed to the weeks where students need taught skills. The tutors gave the following tutorials:

- Tutorial on 3D solid modeling through using Rhinoceros (Week 2)
- Tutorial on parametric modeling through using Grasshopper (Week 3)
- Tutorial on parametric modeling of a single building component (Week 6)
- Tutorial on parametric modeling of a family of building components (Week 8)
- Tutorial on exporting parametric models for 3D printing (Week 10).

Following the tutorials in Weeks 2 and 3, the preliminary exercises were created to be executed as individual work to become familiar with the Rhinoceros-Grasshopper interface through basic solid and parametric modeling tasks. Further to the tutorial in Week 6, the first assignment brief asked for the sketching and modeling of the initial ideas for a single building component, and producing parametric variations of the designed component. The second assignment consisted of designing and modelling a building component family, which also included the parametric modification of these components. The final assignment covered the exhibition design process to display all prototyped building components (Fig. 2).

The students were expected to complete the preliminary exercises (15% of the grade), two individual assignments (50% of the grade), and a group assignment (35% of the grade). Students submitted digital and physical scaled models during the semester, and at the end of the semester, they prepared presentation boards and an exhibition. In Section 4, the student works as an outcome of the given assignments are presented in detail.

4 Application of the framework

This section presents the given assignments with their outcomes. These works were produced by 13 master-level exchange students from the IMIAD program who were enrolled in the 2021-2022 Fall Term's DRTID course.

4.1 Preliminary exercises

The preliminary exercises were designed to have two parts. The first exercise aimed to familiarise students with the interface and basic commands of Rhinoceros CAD software. The brief of the first exercise was as follows: "Please design and model a single cube with basic commands/operations of Rhinoceros (at least 3). Please take

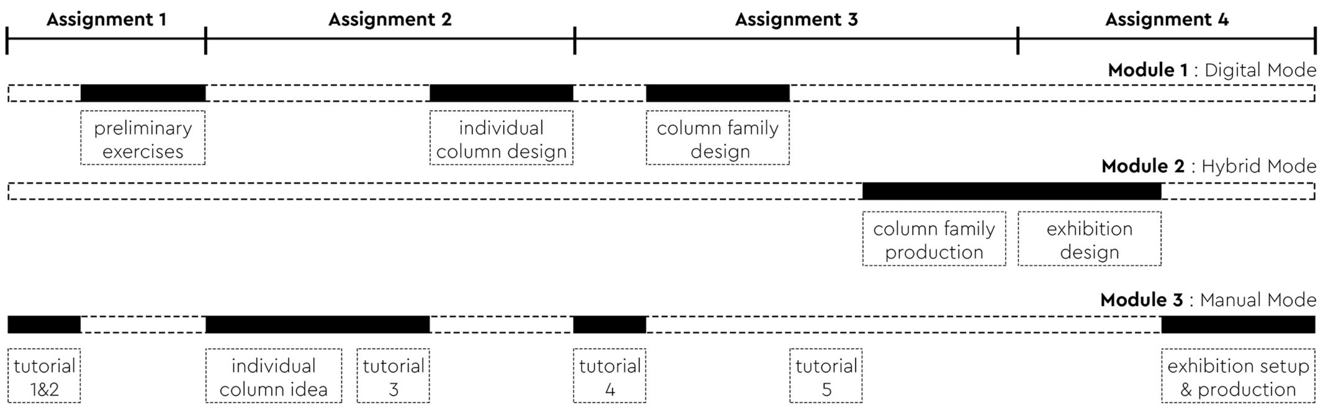

Fig. 2 The DRTID course structure for the 2021-2022 Fall Term

3 screenshots of your cube and place it on Miro Board. The cubes have to be presented in the shaded view and one of the screenshots has to be the NE axonometric view.".

Following this exercise, the students were given a second exercise that aimed to show the relationship between Rhinoceros and Grasshopper. In other words, the exercise was on how a cube designed and modeled in Rhinoceros can be redefined with visual scripting in a Grasshopper environment. The brief of the second exercise was as follows: "Please design and model a single cube with basic commands/operations of Grasshopper. Please take 3 screenshots of your "baked" cube and place it on Miro Board. The cubes have to be presented in the shaded view and one of the screenshots has to be the NE axonometric view. Please rely on the boundaries of the cube.". Fig. 3 shows the cubes produced by the students for the initial assignment.

4.2 Assignment 1 - Individual parametric columns

As is already emphasized in the Pedagogical Framework section, one of the subjects of this course was to design and produce the parametric variations of a single building component. Each student was therefore asked to create a parametric column by defining its parameters. Before creating parametric models in a computer environment, students could use the manual tools and methods they knew. The brief of the first part of Assignment 1 which covered both manual and digital modes, was as follows: "Please express your initial design ideas on a parametric column with sketches. Please present your sketches on A3 paper (landscape orientation) and place it on the Miro Board. Be aware that your designs are definable with parameters, rules, or mathematical relations to be modeled in Grasshopper.".

The sketches and diagrams shown in Fig. 4 were significant in emphasizing that the parametric design paradigm is a process that students can complete using the methods they are familiar with. In this context, sketches served as a starting point for the conceptualization phase before digital/parametric modeling. For the second part of this assignment, students were asked to digitally generate their parametric column ideas prepared during the first part of Assignment 1 (Fig. 5). The brief of the second part of the assignment is as follows: "Please place your Grasshopper definition for the initial modeling phase of your columns. You can revise this column when you develop your definitions. And also, please place 3 variations (screenshots) created with your parametric model.".

4.3 Assignment 2 - Parametric column family

Following the parametric modeling of individual columns, students were asked to design a family of columns in which all columns rely on a parametric logic for the next assignment. The concept of "attractor" was also introduced to the students, which can be defined as a virtual magnet. Attractors can modify many parameters of the parametric model such as scale, rotation, color, and position. The brief of Assignment 2 was as follows: "First, please build the definition given and create a column family affected by an attractor. Second, put your initial shape to the definition and link the attractor to your definition to change one or more parameters. Third, create a 5 to 5 grid of columns. And finally, bake your model and fit it to a 15 × 15 cm base.". The column families were guided by attractors that could be moved in different directions. According to the defined position of the attractor point, the parameters of each column were affected differently, and

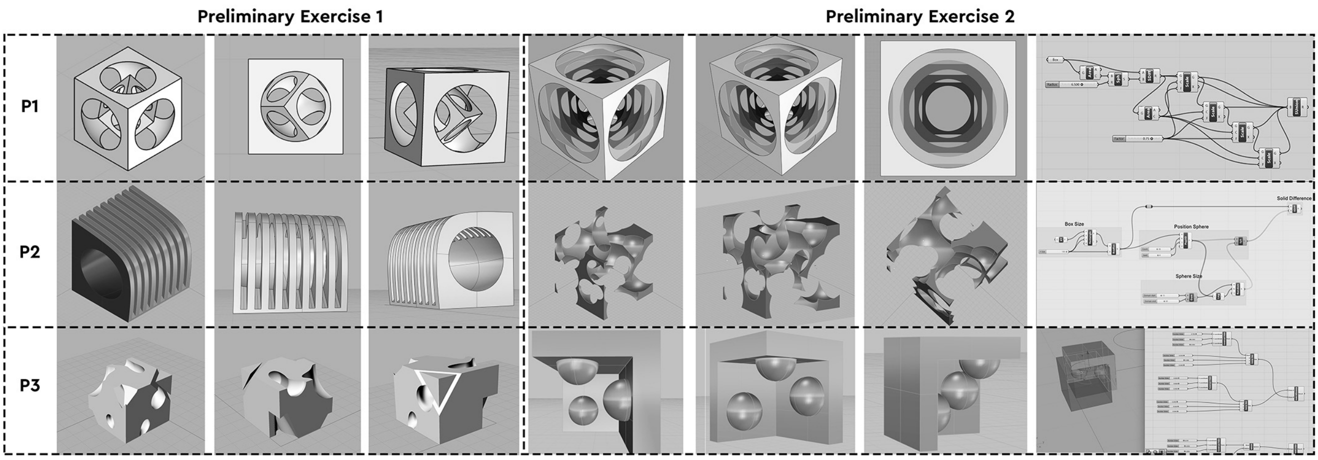

Fig. 3 Outcomes of the preliminary exercises

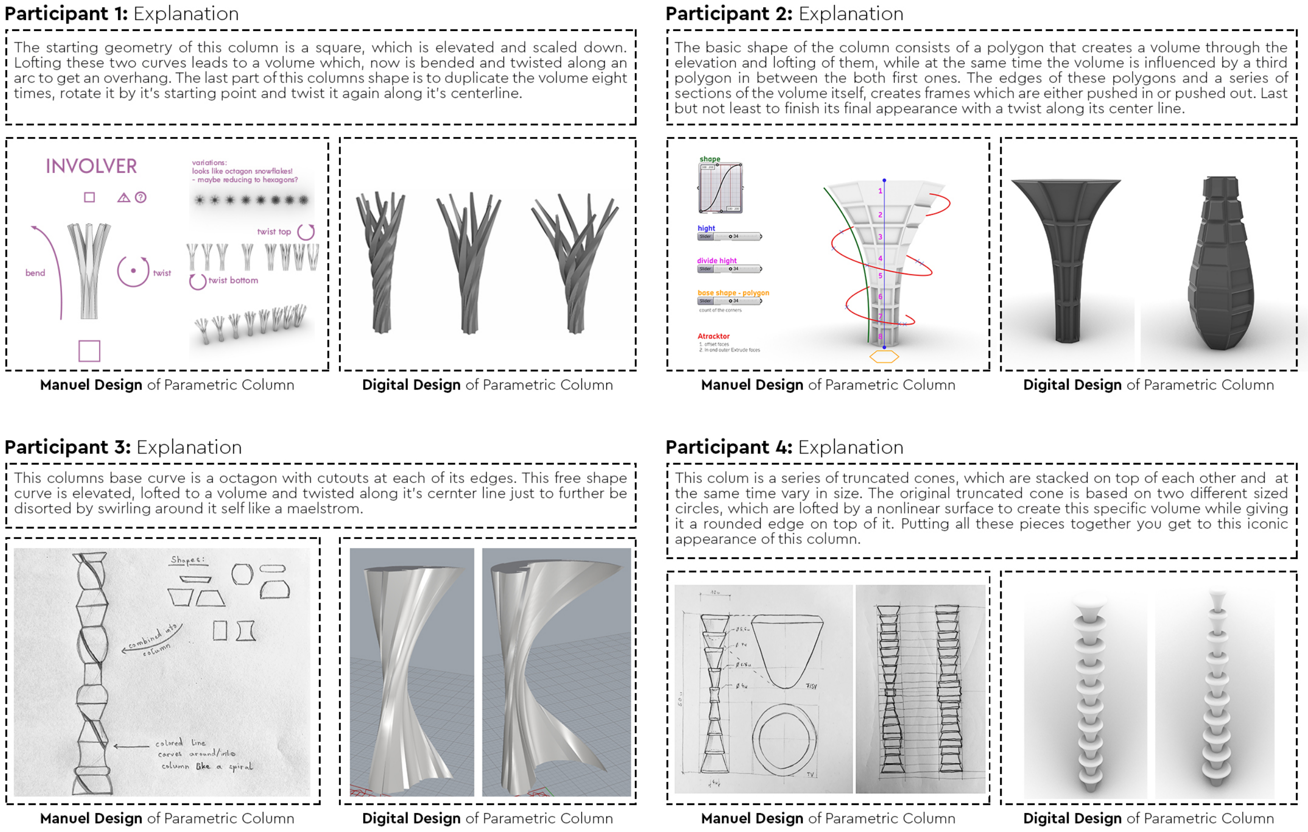

Fig. 4 Sketches and digital models of individual parametric columns

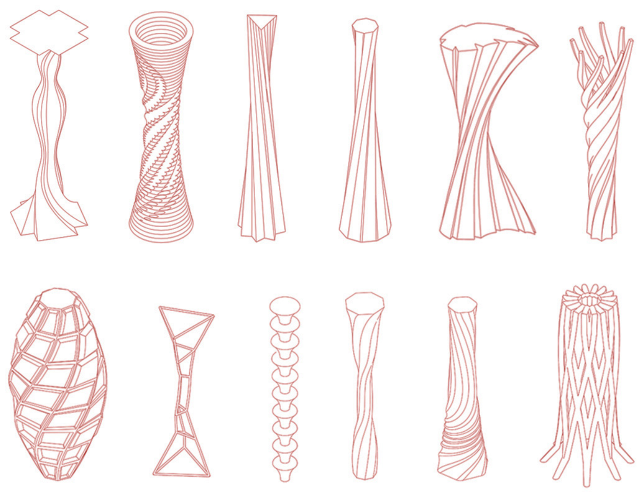

Fig. 5 Individual parametric columns

25 members of the column family differed from each other while keeping their internal order (Fig. 6).

Following the submission of the digital models created as a result of Assignments 1 and 2, the prototyping of 1:20 scale models is expected. Considering the scales of the parametric models and available fabrication equipment of the host institution, two types of 3D printers were selected for production. Before starting the 3D printing, a tutorial was given to teach the students how to prepare their digital model files for 3D printing. The types of the 3D printers were FDM (Fused Deposition Modeling) and SLA (Stereolithography) 3D printers. First, all columns and column families were prototyped by FDM printers that use thermoplastic materials. However, resin-based SLA printers that provide higher precision were used due to particular columns' details and form complexity (Fig. 7). At this phase, some students were asked to modify their models to be producible by the 3D printers. As a result of this process which included shifts between digital and manual, 26 (2 models for each student) models were all printable.

4.4 Assignment 3 - Exhibition design and setup

Until Assignment 3, previous assignments were completed and submitted individually. However, Assignment 3 was structured as a collaborative endeavor. The goal of Assignment 3 was to design and produce an exhibition to display the scaled prototypes based on the individual columns and columns families produced during the semester. The last assignment started with defining the works packages for the design and fabrication of the exhibition and the formation of student groups. Considering the work packages, four groups were formed by the students.

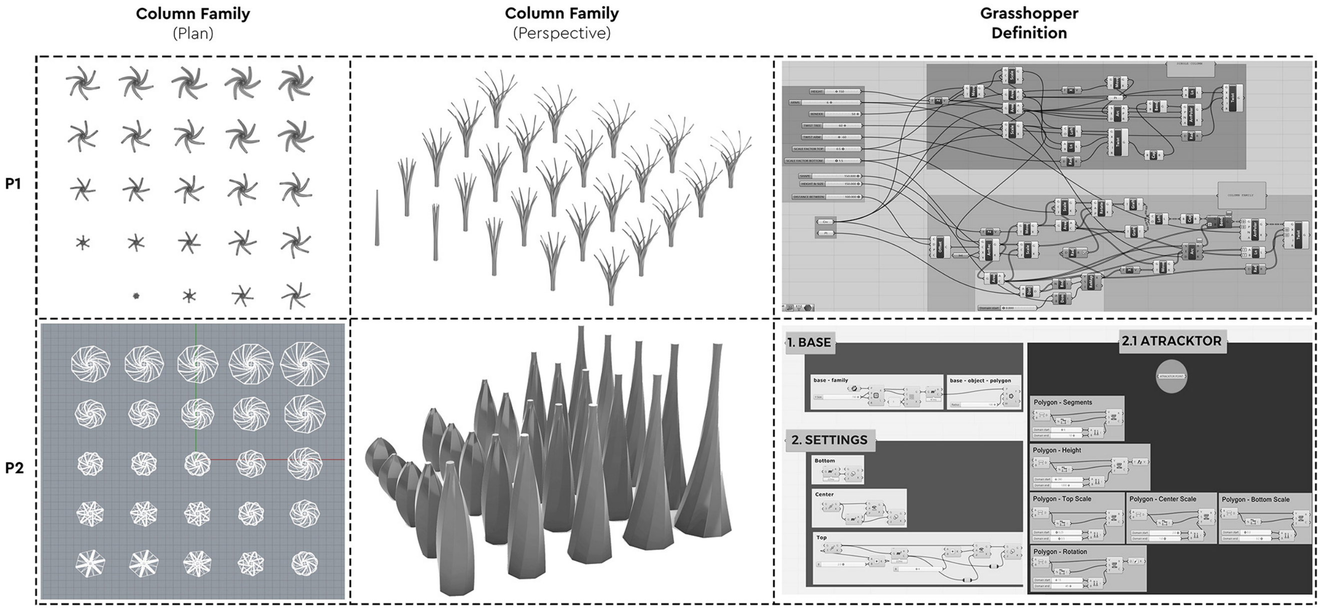

Fig. 6 Parametric column families and associated Grasshopper definitions

(a) (b)

Fig. 7 Collection of (a) SLA and (b) FDM 3D printed columns

The groups and their responsibilities were as follows:

- Group 1: Detail Design (4 people): The group in charge of resolving the design's connection details. Joint detail on the floor and exhibition plane between plywood and stick; joint detail between plexiglass and plywood; stick material and connection details, etc. The visuals of the detail design group's work can be seen in Fig. 8.
- Group 2: Graphic Design (3 people): The group in charge of designing and printing all visual materials for the exhibition, such as posters, informative texts, diagrams, graphics, and illustrations. Fig. 9 shows visuals related to the work of the graphic design group.
- Group 3: Construction (4 people): The group in charge of producing designs whose connection details have been resolved and approved. This group is primarily responsible for installing the exhibition components in the exhibition space after the components have been manufactured.
- Group 4: Documentation (2 people): The group in charge of creating the exhibition archive by documenting the entire process visually and in writing during the exhibition's design. Videos showing the process from the beginning to the end of the exhibition can be created in collaboration with the graphics group.

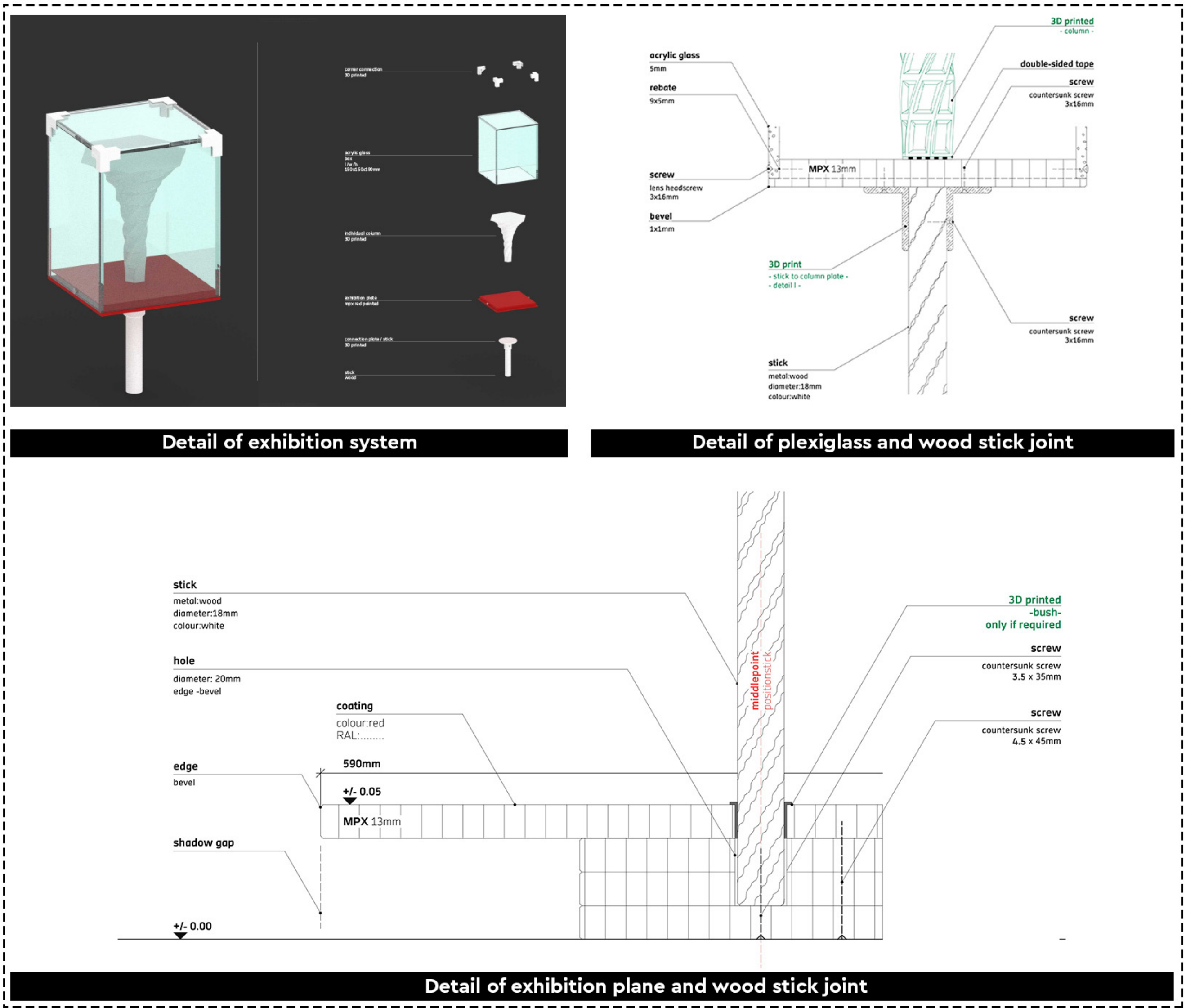

Fig. 8 Details produced for the exhibition

During the exhibition design and fabrication, students used the modeling workshop of the host institution and met with tutors weekly for critiques. In this case, exhibition production took place at the end of the process (Fig. 10). In addition to the tasks of Assignment 3, each student was required to submit a poster containing their work done through the process. These posters included the individual parametric column design, individual parametric column family, and Grasshopper definitions for parametric productions.

4.5 Evaluation of the hybridity of assignments

This section presents the evaluation of assignments in the context of the intended hybrid framework. Since these cubes were the preliminary productions of students by using Rhinoceros and Grasshopper for the first time, it is critical to observe the development of tool use throughout the semester. In this context, the students' cube exercise became a document to understand how students work with the interface and commands of the Rhinoceros and Grasshopper for a well-defined task. At this point, it was observed that there were no major differences in parametric design and modeling knowledge among students. Thus, the tutors were able to clarify the definition of skill sets that are in the students' comfort zone and those that are not.

For Assignment 1, students explored the relationship between hand sketching and digital modeling, keeping the parametric thinking logic in mind. Compared to preliminary exercises, individual parametric column assignments required originality. To achieve an original design solution, students defined their initial shapes, parameters and their relations by sketching and then translated the

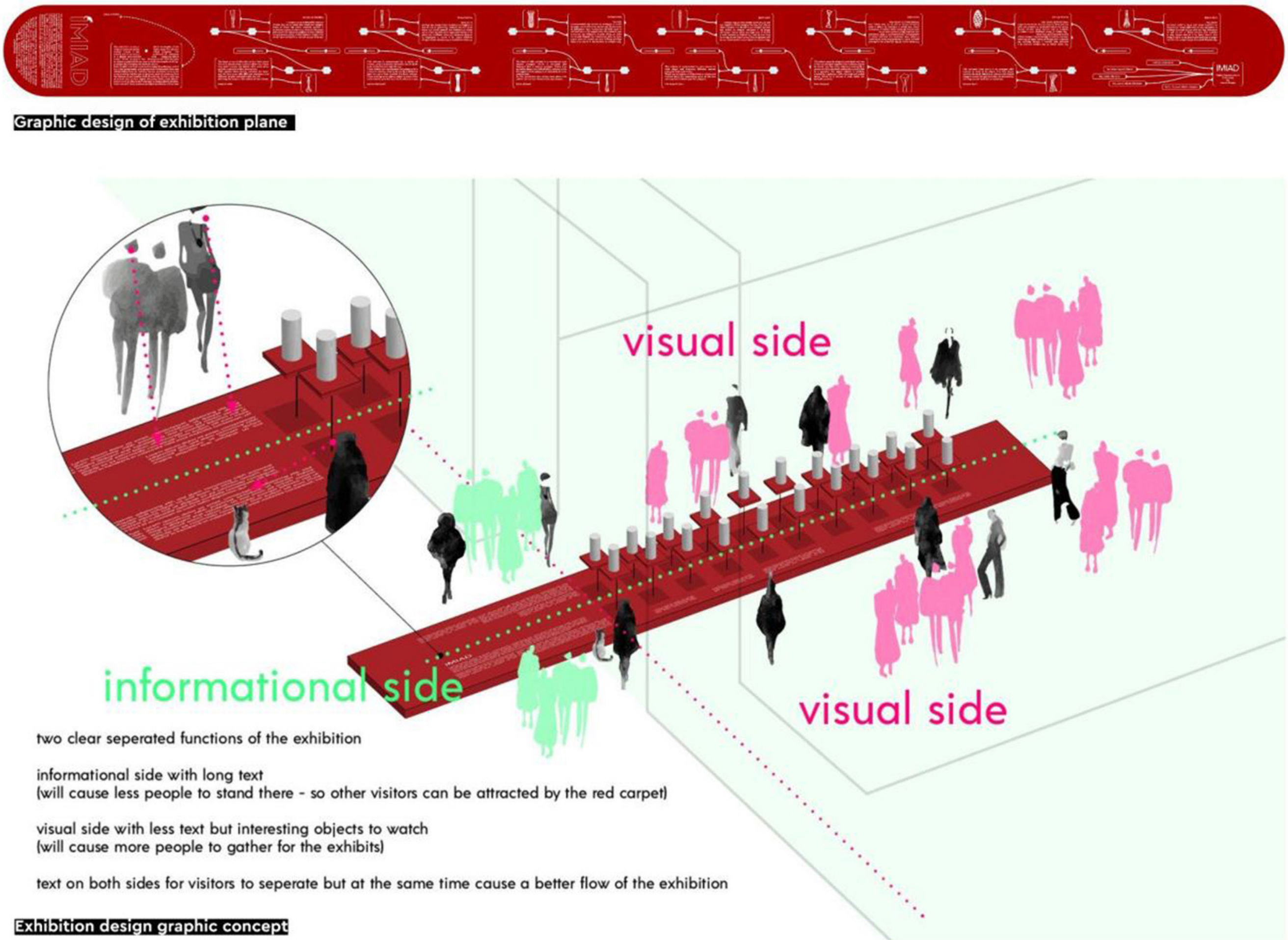

Fig. 9 Graphics produced for the exhibition

(a)

(b)

Fig. 10 Photos from (a) exhibition production phase; (b) fully set exhibition sketches into a Grasshopper definition. With this technique, students discovered that various original and complex forms could be created by combining basic paper-based definitions and Grasshopper VSE. As a result of the first assignment, all students completed the parametric design process, which began with sketches and ended with parametric column models.

The second assignment was more challenging than the previous ones as it needed the consideration of the relation of multiple parametric members. In other words, this study was designed to take the first assignment's beginner parametric modeling to the next level. The students were pushed by adding new parameters to existing ones in their models and working on multiple parameters simultaneously. The tutors encouraged the variations that students produced, which was where they moved outside of their comfort zone the most. To avoid losing the students' motivation, the tutors decided to switch from this assignment, which was outside their comfort zone, to assignments within their comfort zone.

The first two assignments finished with the 3D printing of the digitally produced models. Until this phase, the gradual increase in difficulty and step-by-step structure of the exercises prevented the students from experiencing information overload. Additionally, the transition between modes helped students keep their minds clear and become motivated. Finally, this motivation was enhanced by the synergy of group work, using familiar manual design modes, and a collective output to exhibit. As a result of the final assignment, all students completed their tasks within their comfort zone. The exhibition was set exactly as planned.

5 Conclusion

This study examined whether the relationship between digital and manual design modes could translate into a hybrid pedagogical framework through a teaching experiment. The proposed framework aims to improve the lacking skills (digital mode) of the exchange students of the IMIAD program by using their existing skill sets (manual mode).

Since, IMIAD students are familiar with and skilled in the design and production process (manual modes), a module that includes exhibition design, production of its components (horizontal elements, vertical elements, display units, graphic design, detail design, etc.), and its set up took place at the end of the teaching experiment. Parametric design (digital modes), which IMIAD students are unfamiliar with, was incorporated into the process of developing the objects to be displayed in the final exhibition.

In this direction, the study's main limitation was that the parametric columns designed by the students could not be produced in 1:1 scale. Instead of 1:1 scale, parametric columns were produced at 1:20 scale. The reasons for this limitation are:

- Although learning the tools (Rhinoceros and Grasshopper) was quick, developing the parametric design idea took a long time because the students had no prior experience with parametric thinking. At the points where design idea development was stagnant, there was a tendency to shift to more familiar manual modes.
- Students would have had to digitally divide the design object into sub-parts, produce it with digital fabrication tools, and then manually assemble these components in 1:1 scale production. Despite prior experience with manual assembly and detail design, the students were unfamiliar with subdivision, detail modeling, and strategies for preparing digital models for fabrication.
- Tutors gave five tutorials for the digital production of the designed parametric columns. If tutors taught lacking digital design and fabrication skills, the majority of the course (at least 8 weeks) would consist of tutorials. Therefore, tutors decided to produce scaled prototypes rather than 1:1 scale columns.
- The scale of the prototype was 1:20, allowing it to be printed in one piece using a 3D printer, making it possible for students with little prior knowledge of 3D printing to feel at ease and complete the production. The production of parametric columns at 1:20 scale rather than 1:1 scale made the process quick and almost seamless. However, this prevented tutors from discussing students' effective use of digital fabrication skills. If 1:1 production was used, the quality disparity between students would be more visible during the production stage, as digital modes would be strategically used to include a few extra phases.
- Lack of resources was another reason parametric columns could not be produced as 1:1. All the materials used in the exhibition had previously been used in other exhibitions. In this study, the students designed the exhibition's assembly details, production details and graphics and reused the materials. Furthermore, the carpentry equipment required to create the exhibition and the 3D printers used to create the 1:20 scale column prototypes were available at the faculty. However, the equipment needed to produce a 1:1 scale column was unavailable.

As a result, it is thought that researchers in various disciplines can use the proposed framework. The vision for future studies is as follows:

- The skill sets of the student groups may differ. This reality is not a blanket statement for all students, but a framework developed after reviewing incoming student profiles. For the review, preliminary studies were used, and it was determined that the students lacked proficiency in parametric design. Thus, the proposed framework can be applied to diverse student profiles. This method, for example, can be used to improve manual production skills in a group of students who prefer digital production. The proposed framework can be experimented with again with new digital and manual modes by changing the objects and expected design outcomes.
- The design object in this paper was a self-standing column with no context. Designing and modeling the column in a context or built environment may cause both the design process and the outcome products to change in future studies based on the presented teaching experiment.
- The design object does not exclusively need to be an architectural element such as a column. Using the proposed framework, it is also possible to work on a semi-open or closed space scale instead of an architectural element, such as a funicular structure, vaulted or dome compositions.
- Parametric design, considered a digital mode, can also be expanded by considering it a generative design. Self-standing objects or spaces can benefit from performance analyses such as structural analysis or shading analysis. As a result, rather than producing design alternatives for a form with parametric modeling, generative modeling can switch to form exploration that measures various performances. At this point, 1:1 scale design production can be incorporated into the process. Physical testing and validation of digital performance analysis can benefit from 1:1 scale production.
- If future studies include form-finding and performance analyses in addition to parametric modeling, the approach proposed in this study may be of interest to disciplines such as architecture, interior design, product design, and areas such as structural engineering.

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