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Interactions between analogue and digital explorations in Computational Design: lessons learned from Architectural Workshops

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Abstract: This study investigates the use of analogue tools throughout the process of parametric architectural design and explores the impact of modelling technologies on such design activities. This research focuses on the interaction between students, sketches and scale models, the roles and methods of materializing such prototypes, and the difficulties they face. The originality of this paper lies in considering both the traditional physical models and the computer-aided manufacturing technologies available, examining the various applications of materialization tools, and analysing the roles fulfilled more specifically by physical models throughout a parametric design process. The research methodology is based on observations in the context of architectural training, through two workshop case studies: (i) "Digital Materiality" organized at the University of Mons, in collaboration with the University of Liège; (ii) and "Digital Design Fabrication" at the National School of Architecture in Nancy. Additionally, a survey is conducted amongst the students to gain insight from their perspectives. The results reveal different levels of integration of digital technologies in modelling processes, and highlight certain limitations regarding the adoption of digital fabrication tools. Analogue practices are shown to still constitute a key component of the students' thinking, designing and communicating processes. Findings emphasize the roles of physical models and their significance in the current digital context.

Keywords: *architectural models; architectural design process; parametric design; prototyping*

1. Introduction

The use of 3D physical artifacts in architectural education is advocated as central to experiential learning (Kolb, 1984). Materializing ideas enables designers to go through phases of active experimentation and passive observation. According to Gibson et al. (2002), assembling three-dimensional elements helps the designer to understand the spatial consequences of 2D drawings. Similarly, computer-aided design tools and 3D digital modelling are currently an essential part of architectural practices (Picon, 2010; Carpo, 2012). Among the available software, computational architectural design tools have emerged and created a significant paradigm shift in the field of architecture, offering new possibilities for creative exploration, efficiency, and sustainability (Stals *et al.*, 2021; de Boissieu, 2022).

Computational design practices have gained significant traction in recent years due to advancements in technology and design software. Architects and designers are now able to leverage sophisticated codes and libraries through visual programming tools (such as Grasshopper for Rhino or Dynamo for Revit) to create complex architectural geometries and intricate spatial relationships.

One of the key advantages of computational design lies in its ability to facilitate the translation of digital design data into physical artefact through the use of digital fabrication tools (see section 2.2). This integration allows for greater accuracy, precision, and efficiency in the implementation of architectural projects. It also opens new fields of exploration for architectural design and construction, especially through robotic technologies (Carpo 2017).

This paper aims to explore the design-fabrication continuum within the context of computational architectural design in pedagogic settings. By examining two case studies of architectural workshops and asking the participating students to reflect upon their experiences, we seek to analyse the impact, means and role of prototyping throughout architectural processes. Furthermore, we investigate the challenges of parametric design and model-making in the training of future architects.

2. Literature Background

2.1 Representation in architecture

The architectural physical model and drawing are two fundamental tools for spatial and architectural design (Silvestri, 2009). Arielli (cited in Silvestri, 2009) explains that a representation is the description of a concept or situation that highlights its distinctive features. In order to create such a description, an artifact is used, which plays a decisive role in the process (Safin *et al.*, 2007).

This artifact can take various forms. In the early stages of the design process, hand sketching remains widely used in architectural design (Safin *et al.*, 2007), as well as scale prototypes, or "physical models". Certain geometries are more easily readable in physical models than with other means (Gibson *et al.*, 2002). They also facilitate communication within the design team during the early stages of design alongside and in complementarity with other representation media.

The limitation of 2D representation is also pointed out by Silvestri (2009, p.42), explaining that plasticity of a physical model, i.e. its effective material three-dimensionality, allows for unifying the different two-dimensional images into a single representation. In this paper, we refer to sketches and hand-made physical scale models as analogue artifacts.

Furthermore, Yang (2005) shows that the process of constructing a physical prototype allows for the design of solutions that other means of representation cannot achieve: manipulating and physically testing the material allows the designer to make choices that they would not have considered without this material (Yang, 2005).

That being said, Loyer (1974) attributes certain limitations to the architectural physical model. He explains that at their typical scales, models allow for verifying the coherence of volumes but do not provide a good understanding of interior or exterior spaces. As it is impossible to enter them and perceive the space, Loyer advises relying on experience. Another drawback of the physical architectural model is its tendency to distort our vision at a human scale because we look at it from above, from an aerial perspective. Furthermore, the physical model remains time-consuming to achieve, which often hinders its use. Architects often do not have the time to work with models, except when they are very simple and fast to make (Gibson *et al*., 2002).

2.2 Prototype fabrication and rapid prototyping

The term "digital fabrication" encompasses the various ways of transforming a digital model into a physical artefact. It can be defined more specifically as a manufacturing process undertaken using a computer-controlled machine. As underlined by Picon, "the computer appears as the centre from which a whole series of computer-controlled machines is distributed, such as 3D printers, laser cutters, milling machines, and engravers, allowing for the development of prototypes and rapid fabrication" (2010, p.166, translated from French).

Digital fabrication undermines the historical separation between architectural design and the process of construction. Mitchell and McCullough already stated in 1995 that the integration of Computer-Aided Manufacturing (CAM) technologies with Computer-Aided Design (CAD) tools was redefining the relationship between design and production. Sundar, Selwyn, and Elanchezhian (2005) define Computer-Aided Manufacturing (CAM) as the use of computers to plan, manage, and control manufacturing operations in a factory. They add that unlike computer-aided design, CAM is actively used in the process of manufacturing. The industrial tool enabling computer-controlled manufacturing is often associated with the acronym CNC (Computer Numerically Controlled), referred to as CNC Robots. These technologies continue to evolve, and although still underdeveloped in the building industry (Stehling *et al.*, 2014), CNC machines enable the efficient realization of complex forms generated by digital tools.

"Rapid prototyping" sometimes has slightly different meanings in the literature. Kolarevic (2001, p.272) explains that this notion is often associated with additive manufacturing technologies, commonly known as 3D printing. However, he later specifies (2003) that rapid prototyping is part of the field of digital fabrication, but its application is reserved for the design phase, while CAM is employed to define computer-assisted production and construction (Kolarevic, 2003). Dubois, Aoussat, and Duchamp (2014, p.5) define rapid prototyping as "a set of tools that, when combined, lead to intermediate representation objects of product design: digital models (in terms of model geometry), mock-ups, prototypes, and pre-series." The purpose of these models is to verify and validate the functions that the product must fulfil (Dubois *et al.*, 2014).

Through the Digital Design Fabrication (DDF) method, Sass and Oxman (2006) propose a digital design method that integrates rapid prototyping technologies. They observe that contemporary digital design and construction fall into two categories. The first category is visualization, involving the production of images or videos. The second category is information, where digital models contain all the necessary information for construction (thus referring to Building Information Models). The DDF method merges two sequences of the process (modelling and fabrication) into one. This method suggests generating a multitude of prototypes that can be constructed at a high level of detail. It allows for both digital and physical exploration of sometimes highly complex forms. Furthermore, it provides a multitude of possible solutions, considering the structure and construction, even at early stages of the design process. This method leverages the benefits of prototyping and explores numerous material-based solutions.

Today, rapid prototyping encompasses three main technologies according to Sass and Oxman (2006): (i) 2D cutting, (ii) abstractive technologies and (iii) additive technologies. Kolarevic (2001) adds another category to the previous three, which is (iv) formative technology. Among the digital fabrication tools, for example, are robotic manufacturing, 3D printing, and CNC milling.

2.3 Parametric design

Parametric design is a specific subset of Computational design (de Boissieu 2022, Caetano *et al.*, 2020). The term "parametric design" refers to a design methodology that emphasizes the use of parameters and relationships to drive the generation and modification of architectural designs. It is rooted in the idea that architectural form and function can be defined by a set of interconnected parameters that can be adjusted and optimized to achieve specific design goals (Bottazzi, 2018; Caetano *et al.*, 2020). These parameters can range from geometric dimensions and proportions to environmental factors and performance criteria.

This approach necessitates an intermediate stage between the initial idea and the final design, where designers invest time and effort to produce an algorithmic description of the intended design (Leitão, 2013). This description includes the logic and dependencies between input parameters and dependent geometric operations. The execution of the algorithm then generates the 3D model. Consequently, the production of the algorithm precedes the actual generation of the shape. This significant shift in the iterative design process of a virtual artifact coincides with a fundamental cognitive transformation, transitioning from modelling a designed "object" to modelling the "logic" behind its design (Leach, 2009; Stals, Jancart & Elsen, 2021).

By adopting this approach, architects are no longer solely focused on designing the building itself but also the underlying design process. This shift empowers architects to explore beyond their initial design ideas in ways that would be impractical using traditional design and modelling methods, delving deeper into the exploration of alternative design possibilities (Aish & Bredella, 2017). That being said, according to Pallasmaa (2005, p.13): "working on a computer inhibits creation because it engages fewer sensations. The computer creates a distance between the creator and the object". In that regard, digital fabrication tools and the associated prototypes can recreate engagement towards materiality.

3. Methodology

3.1 Context and Focus

Parametric design in architecture is gradually spreading and being taught in universities. However, it is still rarely implemented in Belgian architectural firms, most of them being SME (Stals et al., 2018). According to Stals et al. (2017), 51.5% of the surveyed architectural firms have never heard of the term “parametric model”. These practices thus remain very limited and uncommon, in France as well (de Boissieu, 2020).

In this paper, we rely on pedagogical settings to identify the roles that physical models might play for architecture students who discover parametric design for the first time. We examine the making of these models, as students have increasing access to various machines and tools for digital fabrication. We also address the students' perception of these models as well as the difficulties they encounter during their fabrication.

The purpose of this study is to highlight how physical models may or may not influence architectural students and give a better understanding of the renewed role of physical models in the digital era of architectural design. By identifying such roles, this research intends to provide insights on how architects might still integrate physical prototyping into their design workflow, and thus bridge the gap between digital and physical representations.

3.2 Methods of Data Collection

This work follows a qualitative and exploratory research approach. We conduct observations (Martineau, 2005; Baker, 2006) of students engaged in digital design activities and utilizing rapid prototyping tools. In this study, the observations focus on the produced artifacts, particularly physical and digital models. However, sketches remain an interesting tool for analysis and are not neglected. The observations are conducted using a grid to support the researcher when taking notes. The grid is divided into action "sequences". This support is improved and inductively enriched by the successive observation sessions.

We acknowledge that the presence of the teachers and the researcher has an influence on data collection, even though students were observed to be highly concentrated and invested in providing explicit descriptions of their designs and progresses. Additionally, the teachers contributed to the advancement of the design by providing advice and guidance, thus being somehow part of the design team. Consequently, the teachers’ activity is mentioned when they’re involved.

To confront the researcher's perspective with the students’ own experiences, the participants are asked to fill in four questionnaires throughout the process (Pourtois & Desmet, 2007). The aim of these questionnaires is to assess the influence of parametric modelling, of (rapid) prototyping tools on the students and their design processes, and to evaluate their experience at different moments throughout their design processes. The participants are 2nd-year Master's students: they already have some experience in architectural design or construction engineering. Fifteen out of the thirty-one participants had never user parametric modelling. Eighteen had never used digital fabrication tools.

3.3 Cases studied

In Belgium, the University of Mons, in partnership with the Faculty of Architecture of Liège, organizes a workshop with 2nd-year Master's students in architecture, namely "Digital Materialities". This case will be referred to as Case A. This workshop announces its aims as follows: to raise students’ awareness of digital architectural culture; to implement a *Digital Continuum* principle; to explore the relationship between Materiality and the Digital; to integrate digital fabrication techniques and digital architectural culture in a design context.

In France, the School of Architecture of Nancy hosts a digital design and fabrication workshop. This workshop focuses on architectural design, representation and realization. It aims to experiment with a creative morphological approach guided by geometric modelling, coupled with computer numerical control (CNC) machines. The workshop takes place at the École Nationale Supérieure d'Architecture de Nancy (ENSAN) for a full week. This case will be referred to as Case B.

3.3.1 Case A

The Belgian workshop involves a total of 18 students, including 5 students from the Faculty of Architecture in Liège and 13 students from the Faculty of Architecture in Mons. The supervisory team consists of the courses' professors: Mr. Gallas (UMons), Mr. Delvaux (ULiege), and an IT specialist from the Digital Culture Laboratory, Mr. Bianchi (ULiege). The exercise is carried out by 2 teams of 4 students and 2 teams of 5 students. These four teams will be referred to as A1, A2, A3, and A4 throughout this work.

The initial phase (February 15th to 16th, 2017) consists of briefing the students about parametric architecture and modelling, about the assignment and teaming them up. The second phase, namely the design phase, takes place at the university Fablab from February 20th to 24th, 2017. The final presentation takes place on March 20th, 2017, in the presence of an external jury.

The assignment is to design a "dynamic" structure to improve the acoustic comfort of the Bélian Chapel (chapel of the Faculty of Architecture in Mons) for various uses. To achieve this, the students are required to use the potential of parametric modelling and rapid prototyping tools to materialize their proposals.

The students have access to the following machines: a laser cutter (Cyborg LS-1080-K); a vinyl cutter (ROLAND CAMM-1 Servo GX-24); a CNC milling machine (HEIZ High-Z S-720); and four 3D printers (Makerbot and Ultimaker).

3.3.2 Case B

The Digital Design and Fabrication Workshop is intended for 2nd-year Master's students in architecture, engineering, and design who have completed the A.M.E. (Architecture, Modelling, Environment) curriculum at the National School of Architecture in Nancy. Its purpose is to train students in the iterative design-fabrication process, using parametric tools like Rhinoceros-Grasshopper, and rapid prototyping tools such as laser cutting and 3D printing. The supervisory team consists of Mr. Hanser, Ms. Hochscheid, Mr. Besancon, Mr. Duchanois, and Mr. Gless.

The workshop is attended by 13 students with diverse backgrounds and experiences. The workshop is open to various disciplines. Out of the 13 students, 4 have an engineering-construction background and therefore have limited experience in architectural design.

The exercise is carried out by 3 teams of 3 students and 1 team of 4 students. These four teams will be referred to as B1, B2, B3, and B4 throughout this work.

The assignment is to create a pergola, frame or shelter on a site chosen by the students. The design must rely on the use of parametric models, and students are specifically asked to materialize at a reduced scale using rapid prototyping tools (laser cutting and 3D printing).

3.4 Data Analysis

The data collected allows us to "map out a reality to be studied" (Anadón and Guillemette, 2006, p.39). The purpose is not to conduct an exhaustive statistical study on a large number of students, but rather to gain an exploratory understanding of 8 groups of students interacting with models, in two given pedagogic settings.

All the data collected (observation grids, videos, photographic documentation, and responses to questionnaires) have been transcribed and coded in grids per group (8 grids in total, one for each group of students). To treat this large amount of data, the researchers sequence it through "Critical incidents" (Flanagan, 1954), i.e., "Hot Spot" moments that indicate a pivotal moment in the design process, often manifesting itself through a notable emotion or attitude. Each sequence is described by a text summarizing the observation, a photograph if available, a list of actors (humans, e.g., students or teachers, as well as non-humans, e.g., sketches, software, machines, physical model, architectural references, or any other tool or actor involved) and their interactions to characterize the hot spot. These hot spots are therefore subjectively detected, as discussed in the final part of this paper.

Based on the filled-out observational grids, eight timelines are developed to trace each group's process, and a description of each model created is presented in the form of tables. They constitute a trace of each group's process and allow us to divide the design process into major design phases. The filled-out grids can be provided upon request. They allow the identification of the different prototypes created during the design process and the role they play in this process.

The questionnaires were not intended to nurture a statistical study but rather to gain a more precise understanding of the students' perspective. Given the short time-period we were given to interrogate the students, we could not conduct semi-structured interviews. The data collected through the questionnaires is presented in terms of the proportion of obtained responses rather than percentages to keep in mind the size of the samples, as this is exploratory research.

4. Findings

This section presents the observations and answers that were collected. Discussions about what we can learn or hypothesize based on these results can be found in section 5.

4.1 Hand-made prototypes and sketching supporting the digital modelling process

The digital modelling stage and the fabrication stages do not always occur in any specific order. The digital modelling stage and fabrication often overlap, intertwining in an iterative process. One of the identified roles for physical models is to act as a support for digital modelling. Sketches are also found to be used not only to ideate and communicate, but also to support digital modelling.

In Case A, intention sketches and traditional physical models are created early on in some of the groups. These artifacts serve the primary purpose of exploring initial forms and ideas, as often reported in the literature. However, particularly in the A1 and A3 groups, they are used as a starting point for parametric modelling and as a support for reflection during the modelling process. In Case B, students also use sketches as a support for parametric modelling, but no traditional physical models are created beforehand.

The interaction between the students and sketches as support for the development of parametric modelling happens in groups A1, A3, B1, B2, B3, and B4, thus in 6 out of the 8 observed groups. In the following subsections, we highlight two teams' processes to illustrate such inter-relation between sketches, physical modelling and parametric modelling.

4.1.1 Case of the A1 group:

The process of the A1 group started with the creation of conceptual sketches. Parametric modelling was initiated quickly afterwards, and such digital modelling led to an initial form ((0), see Fig. 1). However, on the second day, physical models (1) and (2) were created during a group ideating-testing sequence. These models shaped the final and definitive form of the project. The students relied on these physical models to agree on the final intentions. Parametric modelling was then carried out with the aim of reproducing the physical model. In this case, digital models replicate analogue sketches and models.

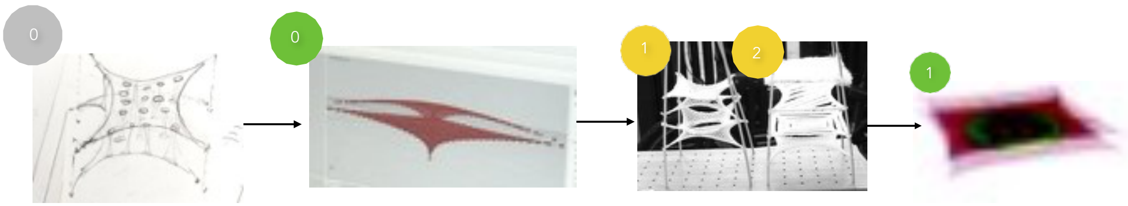


Fig. 1: Evolution of the models in group A1. Numbered in grey: the sketches. Numbered in yellow: the physical models. Numbered in green: the digital, parametric models.

On the third day, group A1 eventually created sketches used as a visual support during a discussion with the supervisors about possible methods for developing the algorithmic plan for parametric modelling. These sketches are specific to the development of the parametric model.

4.1.2 Case of the A3 group:

The A3 group also used the physical model as a support for parametric modelling and thinking. The model, shown in Fig. 2, is made of foam board, wire and fabric. It represents a precise depiction of what the students intended to design. It served as a reference throughout the digital modelling design. Eventually, it is the sole completed model created prior to the final design's model.

Fig.2 : initial physical model of the group A3.

This physical model is heavily used as a showpiece during the Grasshopper modelling phase, to the extent that it is placed *on* the computer keyboard during one of the modelling stage sequences (Fig. 3).

Fig.3 : Photography of the group A3 working process.

Group A3 extensively worked with sketches during the modelling phase. Some of the sketches involved numbering each canvas, which allowed the designers to organize the algorithmic plan for parametric modelling. In these sketches (Fig.3), one can see drawings and the numbering of the 13 canvases, the 10 anchor points in columns below, and the three keystones (marked V1, V2, and V3).

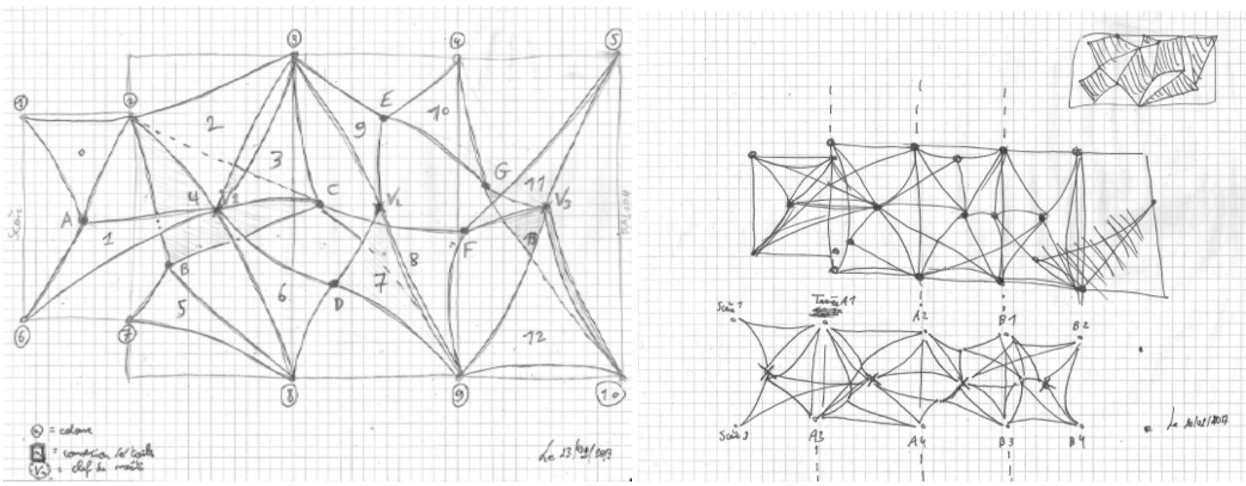


Fig. 4: Photographs of some A3 group's sketches.

These two analogue tools (physical model and sketches) have been seen to be used by students as support for parametric modelling. This observation demonstrates that, in a digital era, designers still express a need for non-digital support to support their reflection. Such use of analogue tools highlights a specific approach, quite unique to parametric modelling.

4.2 Numerical simulation, physical verification

In Case A, the parametric model is also used to simulate situations, and behaviours, or to define a way to materialize the solution. This is particularly apparent in the case of groups using tensioned fabric in their designs, namely groups A1 and A3.

The actual elastic property of tensioned fabrics is simulated in the parametric model. The participants were encouraged to pursue this approach by their teachers. This simulation was made possible through Kangaroo, a Grasshopper plugin[1].

Using such a digital model, the students were able to test out forms by incorporating material characteristics such as elasticity or self-weight and optimize the form to reduce constraints. Figure 5 below illustrates the A3 group's use of this plugin. The left image shows three modelled fabrics without activating the plugin, i.e. without considering the intrinsic material properties. The right image represents the fabric's shape, after applying the plugin.

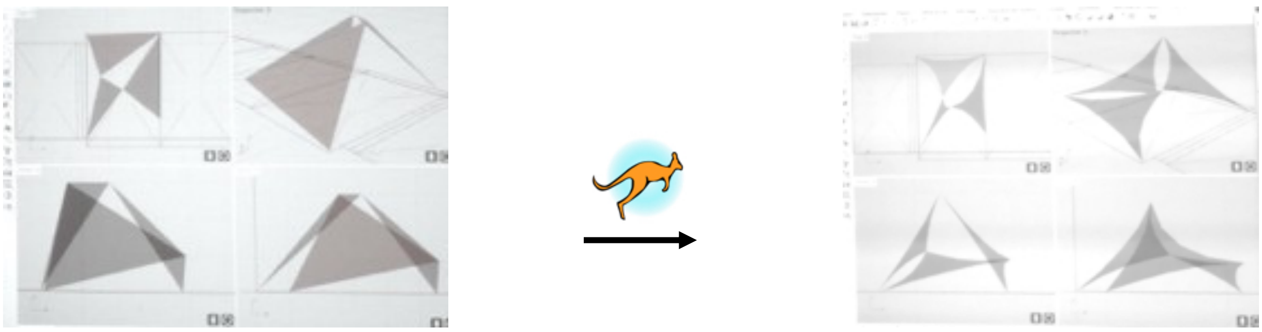


Fig. 5 : « plug-in » Kangaroo used in the parametric model in Grasshopper (group A3).

This plugin was used by all four teams in Case A but proved essential for groups A1 and A3. It allowed those groups to visualize the form after integration within the outline of the building, or to visualize areas with the highest deformation (Fig. 6).

Fig. 6: Photos of the computer screens of A1 (left) and A3 (right) groups' simulations of the deformation of the structure in Grasshopper.

The students therefore noticed the significant stresses at the anchor points of the canvases. These results pushed them to test the strength of the assemblies and of the material using a physical model. The elasticity of the chosen material was integrated into the digital model, requiring parameter adjustments. The statements captured in the video of group A3 illustrate this situation: "*We need to restrict the model parameter not to exceed a value of 2*" says one student. The student interacts with the model on the computer while the others watch implementations of an

[1] Kangaroo is a simulator for physical constraints that allows designers to integrate them into the 3D model and design a form under the influence of a constraint.

elasticity value of 3, and observe its effect on the digital model. They decide to change the elasticity to 1 and observe the shape of the digital: "*It doesn't require excessive pulling; it already gives us an interesting form*".

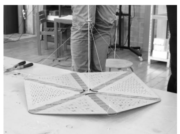
Once completed, the parametric model was used for formal research and exploring structural behaviours. Group A3 tested an extreme configuration where the attachment points of the canvases were located at the maximum distance. This digital test/verification process allowed group A3 to export precise geometric data provided by the model to materialize the form in a final physical model. Frequent interactions between the parametric models and physical models were thus observed during Case A. Parametric modelling makes it easy to modify the digital prototypes and to visualize different configurations but is followed, in each group, by a physical model for verification purposes using traditional models.

The use of analogue hand-made models in digital design may seem surprising in a context where rapid prototyping tools are available. This finding is particularly noteworthy in the context of the digital design-fabrication continuum supported by teachers.

4.3 The roles of the prototypes observed

In this section, we focus on the roles played by prototypes created either traditionally (hand-made/analogue) or digitally, in order to explore their contributions to the design process. The following analysis is based on a description of each consecutive prototype, retrieved from the observation grids of every group. An example of this description is provided for group A4 in table 1, below.

Table 1: Description of each consecutive physical model created by A4.

N°	Description	Photo	Role
0	First hand-made model made of paper. Each bay of the chapel includes three chandeliers that fold on to themselves		Form exploration: Testing the folding/ the movement
1	Second model made of foam board, a wooden rod represents the fixed attachment point, and strings are used to fold a module		Testing the operationality of the mechanism
2	Model 1 is repeated to obtain the three modules, and a wooden structure is added to connect them		Visualizing the shape with the three hanging points
3	First generation of a laser-cut prototype and assembly to test the folding mechanism		Testing the operationality of the mechanism
4	Assembly of the final prototype with the mechanism: final model		Testing the operationality of the mechanism

All the observed roles in all eight groups are listed in the summary table 2, below. This table highlights recurring roles in each group.

We distinguish four main categories of roles played by prototypes that regularly appear: (i) Assemblies: involves evaluating the assembly between two elements; (ii) Appearance and Form: concerns the evaluation of the project's form; (iii) Functionality: involves assessing the overall function; and (iv) Fabrication/Materialization: studying the feasability.

We notice that the role of "formal research" is associated with the traditional physical model, while the role of "verifying fabrication" is rather related to rapid prototyping. This could be a bias due to the workshops' assignment. More research on this matter could further inform this hypothesis. Finally, the role of "testing an assembly" can be fulfilled either through a manually created prototype or a digital one.

Table 2: Roles played by the all the physical prototypes, per group.

Group	Hand-made physical model	Rapid prototyping using digital fabrication tools
A1	- Formal research - Support for parametric modelling - Checking fabrication feasibility - Test of materials - Test of assembly - Communication purposes - Test of the structural resistance	/
A2	- Formal/conceptual research - Test of assembly - Support for parametric modelling - Testing the operationality of the mechanism - Visualizing the appearance	- Test of assembly - Preparing the final fabrication - Visualizing the appearance - Verifying the operationality
A3	- Support for parametric modelling - Communication purposes - Formal research - Support for reflection on implementation - Visualizing the appearance - Test of materials - Test of assembly	- Preparing the final fabrication
A4	- Formal research - Test of the mechanism - Verifying the operationality - Visualizing the appearance	- Checking fabrication feasibility - Test of assembly - Visualizing the appearance - Choosing a material (by testing its structural impacts) - Verifying the operationality
B1	/	- Checking fabrication feasibility - Communication purposes
B2	/	- Checking fabrication feasibility - Communication purposes
B3	- Communication purposes	- Checking fabrication feasibility - Test of assembly
B4	- Communication purposes	- Test of assembly - Formal research - Checking fabrication feasibility - Verifying the operationality - Communication purposes

The results presented in this section demonstrate that the integration of rapid prototyping into the design-fabrication process is not systematic and requires a greater investment and mastering of parametric modelling. This lack of expertise represents an obvious barrier. The use of rapid prototyping, although not well-integrated yet into the parametric modelling process, can help students to test new techniques and be engaged in a rapid iterative process between ideating and testing. On the other hand, these results highlight the recurring roles played by physical prototypes created by students.

4.4 The students' perspective: physical vs. digital models

Here, we report on students' responses to the following questions: "Usually, what are the main stages of your architectural design process?", and "What tools are associated with each stage?".

Thirteen (of 18) students responded in Case A. According to them, the initial stages always involve "pencil sketches" or "hand-drawn sketches" to carve out "initial thoughts," "research," and "ideas". It is then said that sketches are always followed by the use of computer tools, which come into play in the later stages of the process. They are associated with keywords like "verification", "rendering", "finalization", "layout", and "refinement". Only three students mention physical models, either as "physical" or "draft" models. The use of models varies from one student to the other; one reports the use of models in the first stage, another in 3 out of 4 stages (they distinguish between two types of models referred to as "draft model" and "handmade model"), and the other exclusively in the final stage. Those surveyed consider physical models as rare, whereas sketches and computer tools as advanced drawing tools are mentioned in each case.

Case B shows more variation among the ten (of thirteen) respondents. The analysis of the profiles reveals that the students' backgrounds, experience in architectural design, current level of study, mastery of parametric and digital fabrication tools are indeed quite variable. Similarly to the Case A, the sketch is the most mentioned tool by participants from Case B, followed by CAD software and 3D modelling. The physical model is only mentioned once among the 10 respondents. Parametric tools and digital fabrication are said to be occasionally used throughout the design process. It highlights even more the limited consideration for physical models in their traditional design process.

Students were then questioned about the use of digital tools during the early stages of their design processes. In Case A, 9 of 18 students consider parametric modelling to be "adequate" or "very adequate" for modelling their project. 7 (of 18) believe that parametric modelling does not offer more than any other tool, yet 5 of these 7 had never used parametric modelling software prior to the workshop. In Case B, 8 of 12 considered parametric modelling to be "adequate" for modelling their project, while four reported "somewhat inadequate".

Those who consider parametric tools as "adequate" or "very adequate" highlight its flexibility; the ease to change a shape at any point in the project, the possibility to create variants, and the ability to explore different forms. One student also mentions its suitability for a repetitive framework, while another highlights the relevancy of these technologies for a dynamic process including fast iteration.

Those who responded "No impact", or "not adequate", explain that they are not proficient enough to fully exploit its potential. Additionally, one student mentions the extensive modelling time. This echoes field observations, particularly with the example of group A4. Perhaps these reactions indicate a reluctance towards the tool, particularly the time investment it requires. We also believe that students do not receive enough training (particularly in teacher-assessed pedagogical settings).

The questionnaires' results highlight the main reasons that justify the use of digital fabrication. The first reason is to model "complex shapes", and the second is to quickly implement numerous repetitive tasks, tests, or fabrications. The results also show that, in this context, the design is developed and discussed with sketches first, without resorting to digital tools.

When it comes to the need to physically fabricate models to validate choices, two thirds of the participants in the Case A workshop state that they "greatly/strongly" feel the need to manually fabricate their digital model. This finding confirms the observations made during the workshop week regarding the extensive use of physical models. The observations of Case A indeed highlight a strong use of hand-made physical models by certain groups. Moreover, the majority (10 out of 17) of the Case A students believe that their project is easily achievable with said "traditional" tools.

In Case B, a third of the participants said they did not feel the need to fabricate the physical model. During the observations, all Case B students used digital fabrication tools and very few relied on physical models. The responses to the questionnaire also show that 10 of 12 say the digital and physical prototypes would have been very difficult or even impossible to model and fabricate without parametric software and digital fabrication tools.These differences reflect different pedagogical approaches in the two Cases.

After the workshops, students were asked to rank a list of tools according to the following question: "Among the following design tools, which one has most stimulated your creativity: the hand-drawn sketch; architectural references; 3D digital model with Grasshopper; Digital fabrication tools?".

Table 3: Ranking of the tools stimulating creativity, as perceived by the students.

Rank	*Case A*	*Case B*
1	*1/ hand-drawn sketch*	*1/ architectural references*
2	*2/ architectural references*	*2/ 3D digital model with Grasshopper*
3	*3/ 3D digital model with Grasshopper*	*3/ hand-drawn sketch*
4	*4/ Digital fabrication tools*	*4/ Digital fabrication tools*

In both cases, architectural references seem to stimulate creativity over the use of digital tools. Parametric modelling has a greater perceived impact in Case B. The table shows that digital fabrication tools have little impact on creativity in both cases. This finding, contrasting with the Case B responses attesting that participants considered relying heavily on these tools to complete their project, brings some nuance: perhaps the tools are not expected to support creativity.

Finally, table 4 below summarises the response to :"What difficulties did you encounter during the fabrication of your model?".

Table 4: Summary of the difficulties and barriers faced by students ("x2" meaning that two students mentioned it).

Assembly issues	Assembly of parts
	Joining different panels
	Assembling unnumbered parts
	Element assembly
	Panel connection
	Hinge connection
	Shape junction
	Fabric connection
	Assembly difficulties due to curves and distance between frames
Scale issues	Small scale for canvas joints (Patterns—scale)
	Scale problem (x2)
Computer-related issues	Issues with Grasshopper
	Export problems, mainly with Grasshopper
	Difference between 3D model and reality
	Modelling an idea in Grasshopper without altering the concept
	Transition between software platforms
Digital fabrication-related issues	Lengthy 3D printing process
	Excessive printing time
	Faulty printing (poorly printed piece)
	Laser cutting issues (inaccurate cuts)

Overall, the results of the questionnaires provide insights into the importance of sketching and architectural references for creativity in an architectural design process, even in the context of digital-oriented workshops. Other difficulties mentioned sporadically include the materialization of artifacts, but they are not necessarily related to the machines.

5. Discussion

The results reveal different levels of integration of digital technologies in modelling processes, with a tendency for the Case A students to be more favourable to the use of analogue tools, whereas the Case B students were prone to adopt the parametric tools earlier in the process. Several factors can explain these differences, including the cultural context, the overall curriculum and classes previously taken by this small sample of participants, or perhaps by the assignment itself. Nevertheless, these results suggest the continued relevance and need for non-digital supports in the digital era of architectural design. Architecture students might still benefit from sketches and (hand-made) model making experiences, as they value and utilize traditional tools alongside digital ones, indicating a unique approach to parametric modelling.

The analysis of prototypes created both traditionally and digitally reveals four main categories of roles: assemblies, appearance and form, functionality, and fabrication/materialization. Hand-made physical models often play a role in formal research, while rapid prototyping is rather associated with verifying fabrication. Testing assembly can be fulfilled through both manual and digital prototypes. These roles demonstrate the value of prototypes in evaluating different aspects of the design, from structural integrity to formal qualities. However, the research also highlights the need for a more systematic integration of rapid prototyping into the parametric modelling process, which requires greater expertise and mastery of parametric modelling tools.

This research also highlights specific limitations and struggles the students face regarding the adoption of digital fabrication tools. In comparison to analogue practices, computational methods still are a key element of their thinking, designing and communicating processes.

These drawbacks could inform architecture teachers to approach the use of both analogue representation tools (hand-made models, sketches) and digital design fabrication as a holistic and complementary workflow, thus leveraging the strengths of both digital and physical models.

Digital tools in architectural design require a change in design practices and thinking. This is a substantial challenge, even more so in time-constrained pedagogical settings. Students are not yet trained enough for the use of these technologies. Furthermore, teachers should be aware of students' perceived insecurity about their mastery of the technological tools made available to them.

Overall, the findings suggest that there is still a gap between the potential of rapid prototyping and its integration into the parametric modelling process. Students may feel limited by their software proficiency and the investment required to fully utilize these technologies. Further research could investigate ways to bridge this gap by providing training and support to students in using parametric modelling tools more effectively. Additionally, exploring the benefits of combining physical and digital models in a more systematic and integrated manner could lead to enhanced design processes and outcomes.

6. Conclusion

This paper highlights the interconnectedness and interaction between analogue representation tools (hand-made models, sketches) and digital design models and fabrication. Two pedagogical settings are analysed, with results able to inform the development of integrated workflows that leverage the strengths of both digital and physical models, allowing beginner architects to explore and iterate on their designs more effectively.

The research demonstrates the use of digital simulation and physical verification in the design process, particularly for groups of students utilizing uncommon materials such as tensioned fabric in their designs.

By addressing the students' perception of physical models and the difficulties they encounter during fabrication, the research sheds light on the experiential aspects of architectural training. Understanding students' perspectives and challenges could help educators and practitioners develop better support systems, resources, and training programs to improve the students' fabrication skills and overall design processes.

This research contributes to the advancement of architectural training by uncovering the roles and significance of sketches and physical models throughout digital design processes, informing pedagogical approaches, and promoting a holistic understanding of the relationship between digital and physical representations in architectural training, which in turn could inform future landscapes of practice.

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