# Understanding the Role of Physical and Digital Techniques in the Initial Design Processes of Architecture

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**Abstract.** Architecture has been taking new turns with rapidly developing digital design and fabrication technologies. Consequently, establishing a link between physical and virtual design methods remains an open area for investigation. This paper explores the contemporary idea generation methods and the role of physical and digital design techniques in the initial design processes of architecture. We report our findings from interviews conducted with 14 participants consisting of experts and practitioners from the architecture field. Then, we discuss potential application areas of the results in the context of HCI research.

**Keywords:** Conceptual design · Physical model-making · Digital design

## 1 Introduction

The contemporary understanding of the architectural form led to departing from traditional design techniques (i.e., physical model-making, two-dimensional drafting, etc.) towards digital design and fabrication processes [28,29]. This transformation has changed architects' interactions with physical and digital design platforms. With the influence of nature-inspired movements and complex free-form geometries, parametric design tools and programming languages became increasingly prominent in architectural design processes [16]. *"Parametric design"* implies a rule-based digital design approach involving algorithmic thinking to model geometries in a programming environment [21]. Current digital design techniques enable architects to manage large amounts of data and handle complex design tasks. Despite their distinctive advantage, digital tools may not support material engagement [40] and the direct sensual information that the physical world affords. Norman [33] states that material properties, such as strength, stress, and texture, can only be experienced in the physical world. Digital and automated fabrication methods offer resources for realizing design ideas in the physical space. The term *"fabrication"* refers to the production process of physical prototypes out of digital 3D models or 2D vector drawings via


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subtractive or additive methods. Although fabrication techniques allow seamless design workflows, the divide between physical and digital platforms remains an open research area for architectural design processes.

Initial design processes play a critical role at the beginning of a project, and the impact of early decisions carries over to the construction stages. According to Rice and Purcell [41], initial design stages are where the seminal ideas and intentions are tested and laid down. During initial design processes, architects develop rough conceptual ideas by producing two-dimensional (2D) hand-drawn sketches, physical mock-up models, and three-dimensional (3D) digital visualizations. Architects also comprehend programmatic requirements, analyze the construction site, and generate building masses [22]. The later stages of design require detailed technical drawings and architectural documentation to communicate design ideas with people from various areas of expertise that operate within the same project [41]. Consequently, decisions made throughout the early stages can significantly impact design development as the ideas progress further. In this paper, we answer the following research questions;

*1) What are the current idea generation practices in the initial stages of architectural design?*

*2) What roles do physical and digital design techniques play for architects while developing early design concepts and ideas?*

Prior research within HCI and architecture domains explored the physical-digital integration and idea generation methods. With a specific focus on the initial design processes of architecture, our work explores the current idea generation methods and the role of physical and digital design techniques. We contribute to the existing research by providing up to date knowledge about the physical and digital design methods and the current situation in leading architectural offices/studios.

This paper is structured as follows. Our first section introduces the relevant literature within the areas of HCI and architecture. Next, we describe our methodology and interview processes. Then, we present the two main sections of the paper and report our findings regarding current ideation practices and the role of physical and digital techniques. Finally, we discuss the implications of our findings concerning the HCI community.

## 2 Related Work

We introduce relevant literature that focuses on physical-digital integration (TUIs and fabrication approaches), and idea generation processes in architecture (sketching and physical model-making).

### 2.1 Integrating Physical and Digital Design Methods (TUIs and Fabrication Approaches)

Integrating physical and digital design platforms has been explored within the HCI domain (i.e., tangible user interfaces and fabrication approaches). In the context of tangible user interfaces, Terrenghi et al. [48] studied the physical and digital media manipulation through a puzzle and an image sorting task. The study has revealed that digital interactions may not naturally encourage bimanual hand interactions that can be seen in the physical world. Earlier studies [42,43] with urban planners also identified a mismatch between the digital processes and the real-world outcomes. With a focus on landscape architecture, Ishii et al. [23] introduced a dynamic sculpting method enabling physical form-exploration and real-time digital feedback. Two tangible systems were designed and tested with clay [38] and sand materials. As part of the *metaDESK* [24] system, *activeLENS* allows touch-based interaction with the virtual information displayed on a screen. Äkesson and Mueller [2] explored real-time structural exploration by implementing a multi-touch display that enables physical manipulation of 2D geometries and a 3D form manipulation system utilizing a Leap Motion[1] sensor. These two implementations enhance initial concept development processes by combining physical interactions with real-time structural feedback. Sheng et al. [45] presented a physical proxy technique that employs a sponge as a physical input to sculpt 3D geometries on a computer screen. Scerbo and Bowman [44] explored physical interactions with the digital realm through commercial 3D motion tracking systems. Modelcraft framework [46] uses freehand annotations to extract data from physical models and feed them into the digital design platform during the initial design processes.

Prior HCI research introduced various fabrication approaches to address the separation between physical and digital design processes. *D-Coil* [36] is a handheld fabrication approach that uses an additive wax coiling technique to bridge the gap between CAD models and physical artifacts. *MetaMorphe* [49], a digital fabrication framework, supports the manipulation and transformation of 3D static models into physical artifacts. *ShapeMe* [53] integrates physical architectural models with the 3D CAD modeling environment via a rapid inkjet printing technique. Willis et al. [54] established a real-time link between physical and digital design platforms with prototype devices that can convert touch and audio inputs to physical artifacts. Moreover, prototypes allowed designers to fabricate physical objects interactively and receive simultaneous digital feedback. Mueller et al. [32] presented an interactive and rapid fabrication system that reduces the need for physical assembly procedures. Ashbrook et al. [4] developed an augmented fabrication system for supporting novices to produce functional physical objects. Alongside the HCI domain, within the architectural discourse, Menges [31], Gramazio and Kohler [14], Oxman [34], and Iwamoto [25] have made important practice-oriented contributions with a focus on digital and automated fabrication approaches.

### 2.2 Idea Generation Methods in Architecture (Sketching and Model-Making)

This subsection reviews relevant research covering the techniques architects employ for expressing their ideas during the initial design processes.

[1] https://www.ultraleap.com/product/leap-motion-controller/.

Hand-drawn sketches play a critical role in the conceptual development phases of architecture, as in various other design disciplines. Goldschmidt [13] states that *"the generation of architectural form, by definition, is a creative activity."* Sketching with pen and paper supports creative processes by offering a platform to transfer and communicate design ideas. Goldschmidt [13] investigated sketching and the role of imagery in the context of architecture. The results showed that the ideation process that shifts between figure and concept is as systematic as other dialectic processes. Tversky [50,51] identified a link between the mental processes of designers and the order of their sketches. An in-depth review [50] of prior research confirmed that the order of drawing elements unveils the thinking structure underlying the design process. Perrone et al. [37] conducted interviews with architects to investigate the influence of preliminary drawings when designing architectural solutions. Furthermore, Rice and Purcell [41] studied the role of sketching in the early design stages of architecture from an educational viewpoint. Buxton [8] suggests that sketching is a way of *"exercising the imagination"*, and there may be different forms of sketching beyond pen and paper.

Besides two-dimensional freehand drawings, previous research also looks into physical modeling as a method for idea generation in the initial design processes. As Gedenryd [12] states, *"the writings of design theorists imply that the traditional method of design-by-drawing is too simple for the growing complexity of the man-made world."* Although two-dimensional sketches can facilitate complex design ideas, mock-up models support three-dimensional design exploration in a physical space. Gursoy and Ozkar [17] investigated model-making as a form of sketching by testing three different mediums *(sketches, physical models, and digital visualizations)* with architecture students. Moreover, Heimdal et al. [19] conducted experiments with architectural students and explored the potential of architectural models produced from textiles as tangible three-dimensional sketching tools. Knoll and Hechinger [27] introduced a comprehensive visual guide for building physical architectural models. Material engagement framework [40] is another contribution that addresses the relationship between the mind and materials. There are relevant works that focus on touch-based knowledge and haptic perception [18,26,30,39]. Digital tools have become prevalent in architecture. However, physical models retain their exploratory and tangible qualities for the initial design processes[14]. According to Dunn [11], if CAD alone had provided an adequate replacement for physical models, there would be no need for models produced using digital fabrication methods.

## 3 Methodology

In this paper, we present learnings, observations, and the visual data obtained from a total of 14 interviews conducted with seven experts (20 or more years of experience) and seven practitioners (between three to 20 years of experience) from leading architectural offices/studios in four countries. The first stage of the interviews took place in Finland. Then, we expanded our investigation in Switzerland, the United Kingdom, and Germany.

Initially, the study was planned as contextual inquiries to observe and comprehend how architects express and develop their ideas in the early design stages within their studio/work settings [6,20]. However, due to COVID 19 pandemic, we had to continue the study through virtual interview sessions. Before pandemic restrictions, we managed to conduct contextual interviews with three experts from three different companies in Finland. The contextual interview process (two hours in total) included an hour of participant observations followed by semi-structured interview sessions for covering relevant issues concerning our research questions. During the observation sessions, we collected photographs (i.e., sketches, conceptual drawings, physical models, 1:1 scale prototypes, digital visualizations) and drafted short field notes [10] without interrupting the participant's workflow. For the semi-structured interviews, fifteen questions have been prepared, with the addition of sub-questions, as a guide to utilize during the sessions. Hence, we did not follow a strict question order and conducted the interviews in a dialogue form. The rest of the interview sessions were conducted online (via Zoom and Microsoft Teams). Several participants shared images or sketches during the online sessions, and some participants sent them via e-mail after our discussions. Virtual interview sessions followed the same semi-structured format in a 45 to 60 min time frame.

The study aims to provide an up to date understanding of the early design stages and the role of physical and digital design methods in architecture. Therefore, while selecting participants, we focused on seven leading architectural practices that use cutting-edge digital design and construction methods and work with geometrically complex structures. We selected the participants based on publicly available portfolios and built projects. Through this selection process, we targeted to obtain relevant insights about the ongoing developments in architecture and the influence of digitalization on ideation processes. We reached out to participants via their work e-mail addresses. Before each session, participants were provided with an information sheet describing the study and the methodology. Alongside the information sheet, an informed consent form was sent to each participant. Participation was voluntary, and participants had the right to discontinue at any time without disclosing a reason.

Interviews were recorded and transcribed for data analysis. We used thematic analysis method [3,7] to comprehend emerging themes and relevant subjects. First, interview recordings and transcripts were transferred into ATLAS.ti, a qualitative data analysis software. Next, we found 11 main themes by going through transcripts, which included 42 sub-themes (codes). Codes were assigned to relevant sections of each transcript. Finally, we used the *"Smart Code"* tool to combine various themes and extract relevant quotes.

The following two sections present the interview outcomes by referring to participants' statements and relevant literature. We reference participants by using the letter P and a number (i.e., P3).

## 4 Current Idea Generation Methods in the Initial Design Processes of Architecture

For many architects, initial design stages are critical for exploring design solutions to fulfill programmatic requirements. Rice and Purcell [41] argue that conceptual stages are *"creative in the sense that the early expressions of thoughts and concepts need to give rise to spaces and forms often not seen before."* This section illustrates a variety of workflows and approaches architects adopt while developing initial design concepts.

### 4.1 Starting Points and Constraints

Physical and digital design techniques provide resources for early design exploration (sketching, physical modeling, digital visualizations). Although such design methods are widespread, architects do not always initiate the design process with blank papers or empty design spaces. One of the first questions we asked participants was their first starting point in an architectural project. The majority of the participants responded that before sketching up initial ideas, topology, scale, and surrounding areas of the project site needs to be comprehensively studied. P8 states, *"The initial task for the architect is to see how masses of the building can fit on the site to allow a proper site use."* Similarly, P3 says, *"You have to understand the program and also the site, the location, and the spirit of the place."* Statements gathered from participants imply that considering existing buildings and functional requirements is a significant first step in a new architectural project. During the early design stages, architects make many conscious and unconscious decisions. While making decisions, they also consider programmatic constraints. P9 elaborates, *"Well, you start with constraints because you are not on the moon or somewhere where there is nothing around you."* Other participants (P6, P2, P8, P9, P11, P14) also noted that their first starting point is understanding these limiting factors.

Participants who are fluent with digital design methods (P1, P5, P13) suggested that constraints and external factors can be seen as parameters that are components of a larger framework. P1 explains, *"If you have a strong concept and a structural framework, the logic behind that framework will make your design process very fluid."* Some participants emphasized that an architect's primary focus is to define parameters concerning the environmental, structural, social, economic impacts of the building. Such a parametric approach is essentially similar to the core logic of more conventional design approaches (P4, P8, P9). Remarks of P1, P5, and P13 indicate that modern parametric design tools have been influencing initial design approaches for some architects.

Several architects expressed different viewpoints towards parametric design thinking in the initial design processes. P8 and P4, who have more than 20 years of experience in the field, believe that architects also make visual decisions beyond parameters. P8 explains, *"We don't think much about the colors, textures, size or shape of windows at the beginning of the design. But, we think about how the building looks in the image of the city and the urban environment."*

Beyond parameters that address programmatic requirements, initial design processes of architecture may involve visual and spatial design decisions. As P4 states, *"Architects produce something to be seen, felt and touched. If you are making a physical object or a physical space, there's always an element of aesthetics."* P12 thinks that fixed parameters or visual inclinations will limit other potential outcomes: *"You just put some parameter, and something comes out. That is not an informed design."* Similar viewpoints (P2, P9) suggest that narrowing the process down to parametric definitions or a visual style may limit further design exploration.

## 4.2 Team Dynamic and Work Environment

By conducting three contextual inquiries and 11 online interviews, we gained insights into architects' team dynamics and work settings (Fig. 1) during idea generation processes. Conversations with participants unveiled that teamwork is a significant element of the initial design processes. Participants stated that they develop initial ideas as a team. For example, P5 describes how their team created early design concepts for a high rise project: *"We were three of us in the team. We sat around the table, and we developed maybe 10 to 20 initial concepts in half an hour."* Although each member can contribute individually during idea generation processes, final design decisions are made as a team. According to P3's description, architecture teams are led by a head designer. In some projects, specialists responsible for the restoration of old buildings can also be involved as decision-makers. The number of people in the group can vary (between three to eight architects) based on the project (i.e., commercial, residential, high-rise, etc.) P3 says, *"It's good to have a small team in the beginning. In our current project, we are three people. That's quite ideal."* 10 out of 14 participants agree that the team dynamic and workflow with the people involved in the project can influence initial design processes.

**Fig. 1.** Architects work with a variety of drawing equipment, computers, and material samples throughout the design processes.

In our contextual inquiries, we observed the participants and documented their work settings in three different architectural offices. Our observations and photographs show that there are individual and collective working areas. For instance, we observed a similar work setting in three of the offices we visited. Most architects utilize a large desk, or two desks, containing equipment for both digital and physical design processes. Computers, tracing papers, pens/pencils, material samples, and modeling tools are the types of equipment that can be found in architects' work-spaces. Some architectural offices work with physical models and 1:1 scale prototypes in separate workshop areas that contain digital fabrication machines. During the interview session, P8 stated, *"I think the physical modeling has its limitations. It takes more time to create them, but it also takes more time and space to transform, transport and store."* However, our observations show that architectural practices invest and create space for physical modeling despite limitations.

There are also architectural teams that prefer handling physical workflows and digital workflows separately. An executive of an architectural company (P7) explains, *"I see how much time and effort highly-trained architects show to keep up with the CAD development. My goal is to build our company in a way that we have a specific team of BIM (Building Information Modeling) experts."* Hence, a team of digital design experts could support architects for translating ideas into the software environment during the early design stages.

## 5 The Role of Physical and Digital Design Techniques While Developing Early Design Concepts

The previous section presented some of the core information obtained from the interview sessions. We looked into different initial design approaches and work settings. In this section, we focus on the role of physical and digital design techniques during the initial design stages.

### 5.1 Physical Design Techniques

Conversations with participants show that architects benefit from physical design skills by sketching and physical modeling. All participants stated that they use pen and paper sketching to express their initial design ideas. For instance, P1 elaborates, *"All of us start with the sketching. Even the offices working with just parameters and numeric factors of architecture start with sketches that you can see on their booklets."* Nevertheless, some participants noted that they mostly produce 2D sketches (i.e., plans, sections, elevations, etc.) but not 3D perspective drawings. P3 says, *"I don't do 3D sketches or perspectives by hand. During the (academic) studies we had quite a lot of drawing and artistic courses, but I don't draw like that so much anymore."* According to P5, sketching establishes a connection between the hand and the mind while creating spatial concepts. The participant (P5) adds that it is difficult to find a viable alternative to freehand sketching in the digital realm, and digital drawing tools are not offering the

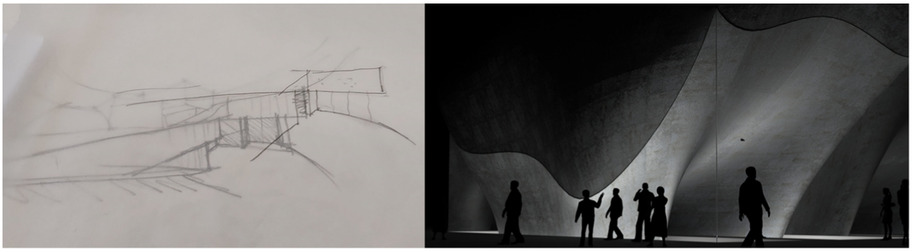

**Fig. 2.** Example hand-drawn and computer-generated drawings documented during the observation sessions. Initial design sketches are translated into digital 3D models as the detail level increase.

convenience of a pen and paper. P2 suggests that the initial design phase requires a high level of abstraction, and a freehand sketch can provide information about designers' thinking process. Freehand sketching is one of the essential techniques to generate and develop ideas. Interviews reveal that most architects express their ideas through sketching with a pen and paper. Another interesting finding is that most of the sketches are transferred into the digital platforms as the ideas start to become more concrete (Fig. 2). P8 describes the process: *"I might put a tracing paper on top of the site plan and start sketching quickly. When I think I have something that looks good, I will go into the software and start building my massing model."* Several architects (P2, P4, P5, P8, P13, P14) reported similar workflows that shift from the physical form of drawing to a digital design environment.

Another essential design method is physical model making. Architects build physical models throughout the different stages of a design process (Fig. 3). P7 is one of the participants that utilize physical models for client meetings to display

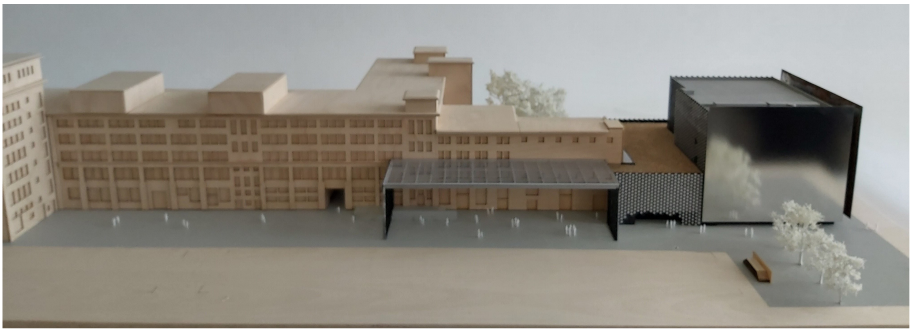

**Fig. 3.** An example representational physical model that is built in a later stage of design.

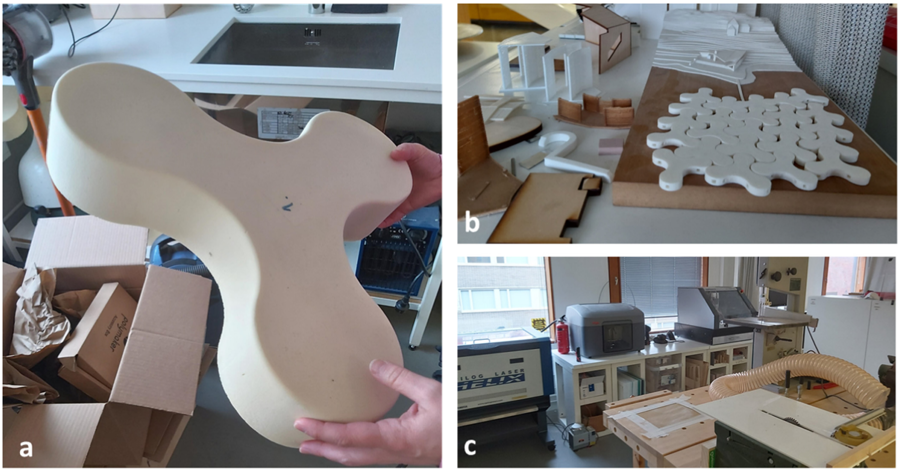


**Fig. 4.** a) 1:1 scale prototype produced for testing a curved structural system in early design stages, b) digital fabrication methods and traditional physical modeling techniques are being used in workshops, c) digital fabrication and physical model-making workshops include various tools for production and assembly.

their ideas in the physical realm. P7 says, *"The physical model is a strange thing. We bring our clients videos, cool rendered images. But if you show them a physical model, they go crazy. They can't stop looking and touching it."* In P7's case, physical modeling is used in later design stages to showcase and materialize the ideas created via CAD, 3D models, and sketches. However, physical models can also be employed as tangible design tools for structural exploration and form-finding (Fig. 4). As Gursoy and Ozkan [17] argue, physical modeling could be a three-dimensional way of sketching with materials during the initial design processes. P13 states, *"Hand-drawn sketches and physical models are exploratory tools. They can inform you in an early stage. If you are encountering problems already while doing small scale mockups, it is likely that the idea is not going to work."* Our conversations confirm that physical models are beneficial exploratory resources for architects, especially for creating complex non-linear structures. To exemplify, P2 is fluent with parametric design software and prefers a digital design workflow for architectural projects. P2 noted that one of their previous projects, a tensile structure made of wood plates, required extensive physical testing with models. Similarly, P1's team tested a curved windows system in a high-rise building via physical models before construction. P13 also benefited from physical models for their fiber-based complex structure: *"It is important to start this process with a small physical mock-up by taking the threads, making a scaffolding, and placing them on the scaffolding."* For some participants (P2, P4, P5, P6, P8), compared to 3D models on a computer screen, it is easier to understand the scale of a building through physical models. Furthermore, P10 and P14 suggest physical modeling is a more intuitive design approach than 3D modeling on a computer. P14 describes physical models:

*"I think it is really about intuition, right? It is not this abstract thing that you are looking at. You are involved in it. It is like talking to the material rather than just talking to a block of geometry or a default material in the modeling environment."*

Physical models form a link between the mind and materials [15], and they can offer an intuitive design platform to test, explore and materialize initial design ideas. Although there are various digital visualization and simulation techniques, physical models retain their significance for representation and structural exploration.

### 5.2 Digital Design Techniques

In recent years, parametric design tools and programming languages are being adopted by architectural practices due to their capability to generate and handle complex geometries. However, many architectural teams continue to use CAD and BIM (Building Information Modeling) software to produce 2D and 3D architectural drawings. Parametric design is mainly used for digital design exploration, whereas BIM is utilized in the later stages of a project to increase the efficiency of the construction process [21]. Moreover, CAD tools support producing 2D representations. Some of the most commonly used programs include ArchiCAD[2], AutoCAD[3], and Revit[4] for drafting (i.e., floor plans, sections, orthographic drawings, etc.) On the other hand, Rhino 3D[5], 3Ds Max[6], and Maya[7] are the software used for 3D modeling and photo-realistic rendering (i.e., V-ray[8]). Several participants (P2, P9, P10, P11, P12) utilize Rhino 3D in conjunction with Grasshopper plug-in, C Sharp, and Python frameworks. According to P3, 3D digital models provide valuable data during the initial design stages: *"Digital models are very informative for understanding the possibilities you have to use the space in 3D."* Experienced architects, P2, P3, P4, and P7, believe that digital design platforms are just tools that architects utilize for the initial design processes: *"We have to understand that digital tools are just tools for us, and they are developing all the time (P7)."* Nevertheless, some architects use computation to build dedicated design environments allowing a coherent design and fabrication logic. P9 explains through one of their projects: *"We set up tools that come from digital form-finding, but as importantly from the physical exploration based on how we want to control tolerances and aesthetics for specific fabrication strategies."* Therefore, beyond architectural drafting and representation, digital

[2] https://graphisoft.com/solutions/products/archicad.
[3] https://www.autodesk.com/products/autocad/overview.
[4] https://www.autodesk.com/products/revit.
[5] https://www.rhino3d.com/.
[6] https://www.autodesk.com/products/3ds-max.
[7] https://www.autodesk.com/products/maya.
[8] https://www.chaosgroup.com/.

techniques are employed to generate and manage an entire structural system from initiation to completion.

Advanced parametric techniques enable a flexible design environment where architects can create specific toolsets for projects by taking programmatic requirements and constraints into account during the initial design processes. However, participants also point out that digital methods should not be separating architecture from the physical realm. For example, P12 states, *"I am a very digital-oriented person. I believe we should be doing things digitally. But I think you cannot disconnect architecture and construction work or the physical building."* Furthermore, P9 describes the need for physical feedback through a specific case:

*"Gravity. What you see on the computer is still a simulation, there is no gravity. When you are simulating gravity there is always an unknown because the outcome depends on your input and the assumptions that you make in the beginning. When you model the structure on your computer, you have perfect boundary conditions, perfect support, blocks that are contacting each other perfectly. But the reality is completely different."*

P9 also notes that the simulation techniques they use are considerably advanced. Despite their capabilities, the cutting-edge parametric techniques and simulation engines may not provide sufficient information that the physical world affords. At this point, digital fabrication and automated construction technologies offer an integrated design workflow linking physical and digital processes. During our visits to architectural offices, we documented a workshop for building architectural models and 1:1 prototypes. In fabrication workshops, architects use various techniques (i.e., CNC milling, laser cutting, 3D printing, etc.) to transform digital models into physical prototypes. Apart from scale models, 1:1 prototypes inform both the early and later design stages by facilitating physical testing. P6 points, *"For us, prototyping is important to understand what type of solutions, even shapes are appropriate for a certain kind of fabrication strategy."* Custom computational resources allow the design and engineering of complex structural systems with the necessary fabrication data. Although a few participants point out (P2, P3, P8) that digital and physical design platforms complement one another, others think there is a divide between these realms. For instance, P6 illustrates,

*"I see this in our team. People who are good with digital are often too disconnected from getting their hands dirty. That is why I keep saying that we have evolved towards a process where we want to make sure that we understand the system physically."*

Participants described ideal digital workflows that can be developed in the future to facilitate intuitive initial design processes. As P4 reports, *"Maybe in the future digital drawing tools might be a way of incorporating hand drawings more into the design."* From a digital design perspective, P6 states, *"I believe we need to have a rule-based strategy. I would argue that computation can help us to discover exciting solutions, good designs starting from something that achieves and maintains a structural efficiency."* All participants expect that digital design techniques will become more prevalent in the future. P2 suggests that implementing artificial intelligence (AI) can provide efficiencies during the initial design processes. On the contrary, P8 believes that the parametric design and AI systems are not useful during the initial design stages. Several architects (P7, P9, P10, P11, P12, P13) emphasized the importance of an integrated physical and digital design process. As P12 elaborates, *"It would be quite nice if there is a feedback loop between what you are doing in the digital world and what is materialized."* Descriptions of the participants imply that an integrated design approach could support idea generation processes. Specifically, structural systems that utilize complex non-linear geometries require extensive physical testing. Connecting efficient digital frameworks with the physical design skills of architects could generate an intuitive design environment.

## 6 Discussion

In this paper, we presented our findings of the contextual inquiries and online interviews conducted with experts and practitioners within the field of architecture. The interviews uncovered some noteworthy points regarding initial design processes. In response to our first research question, the current idea generation practices in architecture mainly focus on developing a conceptual framework by analyzing the building site, physical conditions, topology, and scale. Although architects employ different approaches (parametric and visual) based on their computational or physical design skills, all participants initiate the process by comprehending the programmatic requirements and limitations. Therefore, constraints play a crucial role in the initial design processes. As prior research [13,41] and interview recordings suggest, initial design processes involve the creative input of the designer. Our results show that architects incorporate their creative inputs by considering constraints (i.e., construction methods, site, urban environment, etc.) instead of generating ideas in an unbounded design space. This finding could be a potential application area while developing tangible design tools for supporting architects. For example, tangible form manipulation methods (i.e., Song et al. [46], Sheng et al. [45], Ishii et al. [24]) could be expanded by focusing on the constraints in early architectural design processes. By considering the modern digital techniques, design constraints could also be explored as a part of fabrication frameworks (such as MetaMorphe [49], or ShapeMe [53].)

Another finding of the study is that even the participants that are fluent with digital tools utilize pen and paper sketching techniques while generating early design concepts. Consequently, participants use their manual design skills before benefiting from the efficiency of computation. To illustrate, P2 uses parametric design software and photo-realistic rendering tools to generate early design sketches. Although P2 mainly utilizes digital design software throughout the project development, the ideation process starts with freehand sketching. As the level of detail increases, hand-drawn conceptual drawings are translated into digital 3D models. Some participants also conduct testing via physical mock-ups or 1:1 scale models before establishing a computational framework for their designs. For instance, physical mock-up models play a central role in P10's non-linear structural systems. P2 and P3 tested the material behavior of complex structures by building scale models and 1:1 scale prototypes. Our findings indicate that architects extract information from sketches and physical mock-ups that they may not obtain from digitally generated models. Previous HCI studies [1,5,9,35,47] propose 2D and 3D sketching systems to enhance the initial design processes of architecture. We believe that these systems can be developed for promoting 3D and 2D explorations by incorporating various physical skill sets (i.e., drawing, model-making, assembling, etc.) of designers. One example is Rhino, a widely used 3D modeling software that integrates the Grasshopper plug-in and Python scripting language to generate intricate geometries. However, the software is still bound to a 2D graphical user interface and an abstract Cartesian design space. Consequently, participants prefer using physical models to discern the three-dimensionality of their initial designs. Implementing a tangible input (i.e., shape-aware materials [53]) or a proxy approach [45] into the Rhino would improve its current visual programming environment by allowing real-time intuitive physical and digital manipulations beyond a fixed coordinate system.

Architects work both with physical and digital design platforms in different stages of a project. Our second research question focuses on the role of these two platforms during idea generation: We learned that physical sketching and model-making are convenient methods to formulate, express, and test initial ideas, whereas digital processes support generating and managing complex architectural systems. One of the highlights of our investigation is the integration of physical and digital design methods. As in other design disciplines, the architectural design process progresses with iteration. From initiation to completion, architects develop their design ideas by taking the 1:1 scale performance and the construction site into account. Consequently, the feedback obtained from the physical realm is crucial for validating digital findings. Throughout the study, we documented physical 1:1 scale prototypes and mock-ups that architects use for materializing their ideas. Participants (P6, P9, P12) see physical prototypes as valuable resources for testing physical forces (i.e., gravity) that may not be precisely simulated in the digital realm, especially while working with non-linear geometries (P1, P2, P13). Observations and interviews also confirm that architectural practices continually invest in digital fabrication equipment and physical prototyping workshops. The results show that physical engagement with prototypes is becoming increasingly prominent despite the continuing digitalization in architecture. However, it is necessary to distinguish representational physical models from exploratory, structural test models or mock-ups. Detailed representation models are built for the client or public presentations, mainly in later design processes. On the contrary, exploratory physical models inform and impact the design process by providing data about the structural performance and material behavior. Participants pointed out a need for a more fluid initial design process that establishes a feedback loop between the physical and digital models. One method to achieve such a feedback loop could be through a bidirectional fabrication system (i.e., Weichel et al. [52]) by implementing 3D scanners to trace physical models in real-time.

We presented and discussed our findings from the interview sessions with architects. However, we acknowledge that there may be some limitations. For example, we conducted interviews in four different countries in Europe. The results may not represent the current situation in each part of the world. Despite the geographical limitation, this research can contribute to ongoing HCI research by adding up to date knowledge about the early design stages and the role of physical and digital design techniques.

## 7 Conclusion

This paper studies the current idea generation methods and the role of physical and digital design techniques with a focus on the initial design processes of architecture. Based on observations and semi-structured interviews, we presented and discussed the potential application areas of our findings. We contribute to the existing and ongoing research by providing up to date knowledge about physical-digital design workflows and the current situation in leading architectural practices. Our research can be adopted in the HCI domain to develop interactive systems and fabrication techniques to support architects during the initial design stages. By considering the feedback physical and digital platforms provide, intuitive tools, design workflows, and frameworks can be explored.

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