Intuitive Design Workflows

Investigating the Feedback Cycles Between Physical and Digital Processes

Emrecan Gulay
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Abstract

Digital technologies have transformed the design process in various disciplines, including architecture. Architects now use digital tools not only for mundane tasks but also for creative processes. However, some conventional analog methods such as sketching and model-making have lost their prominence in the digital era. This thesis investigates the role of physical and digital techniques in the initial design stages and examines the feedback cycles of conception, revision, and evaluation. The main objectives are to understand architects’ current experiences, test the feedback cycles via tangible research prototypes, and propose approaches to create intuitive design workflows.

The thesis consists of three peer-reviewed articles that document the three main processes of the research. The first article is a literature review that defines the scope of the investigation. The second article introduces an exploratory design process based on Research Through Design (RtD) methodology. The last article presents contextual and online interviews with practicing architects and experts from Finland, Switzerland, Germany, and the UK.

The findings emphasize the importance of physical and digital techniques in the initial design stages and highlight the need for design and interaction methods to integrate physical and digital design workflows. The thesis suggests that architects value intuitive design experiences that allow for easy manipulation and understanding of design concepts, which can be achieved through the use of tangible and interactive design tools. The thesis offers several approaches to create intuitive design experiences, such as using interactive and tangible design tools, integrating physical and digital design workflows, and designing for ease of manipulation and understanding of design concepts.

The thesis provides a theoretical and historical framework for the research, with each study presented separately. The main findings and highlights of the research are discussed in the last chapter, which connects the three research processes and offers ideas for practitioners and researchers to create intuitive design experiences. These findings are useful for practitioners and researchers in the architecture and design fields who are interested in improving the design process and creating more intuitive and efficient design experiences.

Keywords intuitive experiences, digital technologies, design process, ideation

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Esseeväitöskirja

Tiivistelmä


Tulokset korostavat fyysisten ja digitaalisten tekniikoiden merkitystä alkuvaiheen suunnittelussa ja osoittavat tarpeen suunnittelu- ja vuorovaikutusmenetelmille, jotka integroivat fyysiset ja digitaaliset suunnitteluvirrat. Väitöskirja ehdottaa, että arkkitehdit arvostavat intuitiivisia suunnittelukokemuksia, jotka mahdollistavat helpon manipuloinnin ja ymmärtämisen suunnittelukonsepteista, mikä voidaan saavuttaa käyttämällä kosketelavia ja interaktiivisia suunnittelutyökaluja. Väitöskirja tarjoaa useita lähestymistapoja intuitiivisten suunnittelukokemusten luomiseksi, kuten käyttämällä kosketelavia ja interaktiivisia suunnittelutyökaluja, integroimalla fyysiset ja digitaaliset suunnitteluvirrat ja suunnittelemaan helpon manipuloinnin ja ymmärtämisen suunnittelukonsepteista.

Väitöskirja tarjoaa teoreettisen ja historiallisen viittekehynksen tutkimukselle, jossa jokainen tutkimus esitettäen erikseen. Tutkimuksen tärkeimmat tulokset ja kohokohdat käsitellään viimeisessä luvussa, joka yhdistää kolme tutkimusprosessia ja tarjoaa ideoida käytännön toimijoille ja tutkijoille intuitiivisten suunnittelukokemusten luomiseksi. Nämä tulokset ovat hyödyllisiä käytännön toimijoille ja tutkijoille arkkitehtuuriin ja muotoilun aloilla, jotka ovat kiinnostuneita parantamaan suunnitteluprosessia ja luomaan intuitiivisempia ja tehokkaampia suunnittelukokemuksia.

Avainsanat intuitiiviset kokemukset, digitaaliset teknologiat, suunnitteluprosessi, ideointi

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This journey has undeniably been one of the most interesting chapters of my life so far, testing my resilience, patience, and ability to reflect. My exploration into the depths of the human experience in the digital age has led me to encounter knowledge that profoundly influenced my understanding of life in unexpected ways and guided me through the often-turbulent seas of academia and self-discovery. I am filled with gratitude for the remarkable individuals who have played a pivotal role in shaping both my academic endeavors and personal development.

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I reserve this paragraph to thank my wonderful partner, Linyu. You’ve been my guiding star and provided me with a safe space through ups and downs. You encouraged me to challenge my beliefs and embrace my emotions, fears, and desires. Your presence in my life is a blessing, and our adventures together have created some of the best moments. I can’t wait for the future that we envision to build together.

And, to my mom, Servet, and dad, Emrah, thank you for the unconditional love and support you’ve given me over the last 31 years. You’ve been the best parents I could have asked for, and your love has been a constant source of strength.

To all the incredible people in my life, thank you for your impact on my journey. I’m sure there are many exciting moments ahead that’ll leave us with stories to cherish!
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Emrecan Gulay
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<tbody>
<tr>
<td>TUI</td>
<td>tangible user interface</td>
</tr>
<tr>
<td>GUI</td>
<td>graphical user interface</td>
</tr>
<tr>
<td>AR</td>
<td>augmented reality</td>
</tr>
<tr>
<td>VR</td>
<td>virtual reality</td>
</tr>
<tr>
<td>MR</td>
<td>mixed reality</td>
</tr>
<tr>
<td>RtD</td>
<td>research through design</td>
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<tr>
<td>CAD</td>
<td>computer-aided design</td>
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<tr>
<td>CAM</td>
<td>computer-aided manufacturing</td>
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<tr>
<td>3D</td>
<td>three dimensional</td>
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<tr>
<td>2D</td>
<td>two dimensional</td>
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<tr>
<td>S/RQ</td>
<td>study / research question</td>
</tr>
<tr>
<td>BIM</td>
<td>building information modeling</td>
</tr>
<tr>
<td>CNC</td>
<td>computer numerical controlled</td>
</tr>
<tr>
<td>NURBS</td>
<td>non-uniform rational Bezier spline</td>
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List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals.


Author’s Contribution

The author is the sole author of the present thesis and main author of Publications 1–3.
Abstract

The rapid advancement of digital technologies has led to significant changes in the representation, generation, and physical manifestation of design concepts in various design disciplines, including architecture. Digitalization has not only impacted architects' interactions within physical and digital realms but also transformed the design process itself. In the past, the design process relied on analog methods such as freehand sketching, physical model making, technical drawing on drafting tables, and manual rendering with markers. However, over the past 30 years, digital design technologies have become prevalent in architecture, not only for completing mundane tasks but also for supporting and enhancing creative processes.

As digital design technologies became more widespread, some conventional analog design methods such as physical drafting and model-making lost their prominence in design processes. With the influence of the makers' movement (Blikstein & Krannich, 2013) and digital fabrication technologies, there has been a growing interest in touch-based knowledge in recent years. Research in human-computer interaction and architecture domains has introduced design and interaction methods to integrate physical and digital design workflows. However, the separation between the physical and digital design platforms remains a research problem, and existing research presents a limited scope regarding feedback sequences in architectural design processes.

This thesis focuses on architecture and examines the role of physical and digital techniques in the initial design stages while examining the feedback cycles of conception, revision, and evaluation. The main objectives of the thesis are to gain an in-depth understanding of architects' current experiences, test the feedback cycles via tangible research prototypes, and propose approaches to create intuitive design workflows.

The thesis is a compilation of three peer-reviewed articles that document the three main processes of the research. The first article is a literature review that outlines the scope of the investigation. The second article introduces an exploratory design process designed and executed based on Research Through Design (RtD) methodology. The last article presents contextual and online interviews
conducted with practicing architects and experts from Finland, Switzerland, Germany, and the UK.

The findings highlight the importance of physical and digital techniques in the initial design stages and emphasize the need for design and interaction methods to integrate physical and digital design workflows. Through the research, it was discovered that architects value intuitive design experiences that allow for easy manipulation and understanding of design concepts, which can be achieved through the use of tangible and interactive design tools. The thesis proposes several approaches to create intuitive design experiences, including using interactive and tangible design tools, integrating physical and digital design workflows, and designing for ease of manipulation and understanding of design concepts.

Overall, the thesis offers a theoretical and historical framework for the research, with each study introduced separately. The main findings and highlights of the research are presented in the last chapter, which elaborates on the connection between the three research processes and offers ideas for practitioners and researchers to create intuitive design experiences. These findings provide valuable insights for practitioners and researchers in the architecture and design fields who are interested in improving the design process and creating more intuitive and efficient design experiences.
1. Introduction

1.1 Materiality and Digitalization

Interactions between designers and digital environments continue to take new forms through ongoing technological developments. With the expansion of digital capabilities, the connection between physical and digital realms became an exciting area for researchers in the human-computer interaction and architecture domains. Starting from the 1960s, early versions of computer-aided design (CAD) tools laid the foundations of more advanced and complex digital design platforms designers utilize today. As personal computers became ubiquitous, the adoption of emergent digital design tools accelerated gradually. Currently, immersive technologies, such as virtual reality and mixed reality (Arisandi et al., 2012; Sing & Xie, 2016; Yamamoto, Kawagoe et al., 2017), provide intuitive engagements in physical and digital environments beyond relatively traditional user interfaces (i.e., mouse and keyboard). Modern computer graphics, programming languages, and automated manufacturing techniques provide resources to plan and execute complex design concepts. The adoption of efficient digital tools resulted in the substitution of some physical architectural conventions. Over the years, various research proposed methods to integrate physical and digital processes (i.e., Golsteijn et al., 2014; Menges, 2015; Zoran, 2015). The need to unite the two realms stems from a lack of material feedback in the digital design processes, which can only be obtained through direct physical interaction. Although digital design systems are replacing many conventional physical techniques, several traditional methods retained their importance up until today (Gramazio & Kohler, 2014). Physical model-making and freehand sketching are two of these methods that have been explored throughout this thesis.
1.2 Background of the Research

This thesis investigates the influence of the material agency from a human scale. Throughout the research process, the main focus has become the initial design stages of architecture. As a trained architect, I have been fascinated by the recent advances in digital non-linear geometries, 3D design environments, and simulations.

With the influence of widespread digitalization, the understanding of architectural space and form has deviated from prior conventions and visual approaches. As Kolarevic (2004) describes, this new architectural thinking distinctly emphasizes building performance as a design paradigm. In other words, performative factors have become central to the design of cities and buildings. According to Hensel and Menges (2006), the recent research in architecture takes its roots “more from the realms of the physical sciences and engineering and less from the traditional trajectories associated with the profession.” With this scientifically rigorous and performance-oriented approach, testing and analysis through computational tools and technologies become integral for exploring new possibilities. Oxman (2008) explicated the term performative as a synthesis of the two features of digital design processes: a) Allowing an analytical evaluation of environmental performance based on physics simulations, b) enabling formation and manipulation of geometrical models.

a) Simulation

In various scientific fields mathematical models have been employed for predictions. In recent years, computational capabilities were exploited to create new methods allowing numerical predictions, including simulations, that can reveal the outcomes of more complex systems. “By these methods, outcomes of much more complicated systems, i.e. systems to which analytical closed form solutions are difficult to derive, could be predicted (Karlberg et al., 2013).” This expanded capability to predict and analyse complex systems resulted in an increase in simulation adoption in architecture. Verifying the design outcomes through simulation has been an extensive practice in some areas (i.e., product development.) “Simulation-driven design, however, as opposed to simulation-verified design, through a focus on driving development in early stages of design, enables evaluation (verification) of concepts/designs continuously as development progresses (Karlberg et al., 2013).”
b) Material Computation

According to Oxman (2008), performance can become a determinant and method for the creation of architectural form. Consequently, digital design separates from a paradigm “in which the formal manipulative skills and preferences of the human designer externally control the process to one in which the design is informed by internal evaluative and simulation processes.”

As digital fabrication technologies advance, digital material representations, such as voxels (3D pixels) and maxels, have come to represent material ingredients. Designers are now able to compute material properties and behaviour integrated into form-generation procedures (Oxman & Oxman, 2014). Such an exploration of shapes may expand the limited vocabulary of modern architecture. As Hensel and Menges (2006) state, materials and variables that are often overlooked as qualitative can potential do more than just accentuate and manage preconceived interior configurations; “instead they can be used to question and re-inform what constitutes boundary and edge in architecture other than that of surface geometry.”

The central theme of the dissertation originated from the project I completed during my Master’s studies. The physical outcome of the project was a 1:1 scale hanging structure prototype, which was later included in the first literature review article of this dissertation to demonstrate a transitional design approach alternating between physical and digital realms. The literature review unveiled that the existing physical-digital conversion methods do not offer adequate support for non-linear geometric operations. Results from the literature review also indicate a need to integrate physical and digital design processes to create more intuitive design experiences.
1.3 Contents of the Thesis

The research process consists of three stages (Figure 1.) that are built upon each other: First, a systematic literature review has been conducted to identify the existing body of knowledge and outline the scope of the research. Second, an exploratory design process based on Research Through Design (RtD) methodology has been carried out. Lastly, the data collected from 15 interview sessions with practicing architects and experts shed light on real-world architectural practices.

![Figure 1. Three stages of the research process.](publication1Publication2Publication3)

1.4 The Main Research Problems

The thesis centers around two main research questions derived from each process of the research. The first research question focuses on the divide between physical and digital design processes and integrating the two:

**RQ1:** How can we create intuitive design workflows that support architects to use both physical and digital design skills and knowledge in the initial design stages?

To address this research question, this thesis focuses on three key analytical criteria: feedback cycles, material agency, and design potentials.

Feedback cycles refer to the iterative process of exchanging information and ideas between physical and digital design platforms. By testing and experimenting with volumetric scanning technologies, this thesis has identified ways to enhance the feedback cycles between these two platforms. In addition, consultations with architects and experts in the field were conducted to gain insights into how to create more intuitive design workflows.
Material agency refers to the ability of materials to influence and shape the design process. To explore this criterion, the curved folding technique was used as a test case, examining research prototypes such as paper mock-ups and plywood prototypes. By doing so, a better understanding of how the material properties of these prototypes can impact the design process was gained.

Design potentials refer to the unique capabilities and affordances of both physical and digital design tools. Through this study, these potentials were explored and ways in which physical and digital design platforms can complement each other were identified. By leveraging the strengths of both platforms, more efficient and effective design workflows that result in better design outcomes can be created.

Overall, by using these analytical criteria, this thesis aims to develop a deeper understanding of how physical and digital design platforms can be integrated to support more seamless and intuitive design processes.

"Intuitive" is a description often used in technology advertisements and is associated with expressions such as "familiar, easy to use, easy to understand." According to O'Brien et al. (2008), intuitive technologies should support designers' current skills and experiences and cultivate new abilities through exploration and experimentation. Diefenbach and Ullrich (2015) suggest that intuitive systems are immediately usable by almost every person without requiring prior knowledge or instructions. Moreover, an intuitive experience may provoke feelings of "ease and proficiency, possibly even fun."

Contemporary performance-oriented digital design tools are becoming increasingly prominent in architectural design processes. Architects can access high-efficiency simulation, and material computation tools and utilize systematic form-finding methods. Despite their significant capabilities, performance-oriented tools may not be intuitive and straightforward for every architect. Some traditional physical techniques (freehand sketching and model making) are still being practiced, particularly during initial design processes, and taught in institutions offering architecture education. This may indicate that manual practices have essential qualities that can supplement or enrich the design processes. For example, in early design stages, sketching with a pen and a piece of paper “make it possible to present, with rapidly executed gestures, inner
images, most of which would be forgotten after a few minutes, to designers themselves or a second viewer, thus capturing and remembering them. (Ganshirt, 2012)” Modern performance-based digital design tools afford the generation of rapid, precise design outcomes that can be interchangeable and optimizable to meet requirements or to produce optimum results within existing constraints. One of the valued characteristics of manual ideation techniques (i.e., sketching on paper or with materials) is the lack of precision and flexibility that allows architects to experiment and try new ideas. Ganshirt (2012) also points out, “it’s the ambivalence of the sketch that opens up space for imagination.” Current digital design software operates within GUI paradigms which may not afford the suppleness of physical design tools when forming ideas. Accordingly, it may be necessary to establish intuitive design workflows that support the conventional skillsets of architects while enabling new digital capabilities.

This thesis approaches the issue by analyzing the feedback cycles between physical and digital design processes through testing and experimenting with volumetric scanning technologies and obtaining up-to-date insights from architects and experts in the field to identify the elements for creating intuitive design workflows.

Modern digital parametric tools and generative methods allow designers to produce many design probabilities in a short amount of time without requiring any physical involvement. Furthermore, advanced digital simulation techniques can provide valuable information regarding physical conditions and the performance of a structural system. However, various scholars from HCI and architecture domains argue that current digital design methods detach the design process from the physical space (Kolarevic, 2004; Melcer & Isbister, 2016; Stavrić et al., 2013; Vogel, 2012). A lack of feedback may result in a partial understanding of the real-world conditions that generate further issues when translating digital ideas into physical structures. At the same time, a design process that depends entirely on the digital tools may be missing out on the qualities and design potentials that the real-time physical exploration through material engagement could provide (Poulsgaard & Malafouris, 2017).

The following research question emerged from RQ1 and aims to explore how the material agency from a human scale can contribute to design exploration and enrich current digital design techniques:
**RQ1_mod**: *How can the material agency from a human scale contribute to the design exploration and enrich the current digital design techniques?*

Throughout the dissertation, the RQ1_mod is addressed by using the curved folding technique as a test case and examining research prototypes (i.e., paper mock-ups, plywood prototypes.) Moreover, the interviews included questions to comprehend the current digital design practices and the role of physical and digital techniques.

### 1.5 The Main Outcomes

This thesis addressed the research questions through a systematic literature review, an exploratory study with paper mock-ups, and an interview study with practitioners. Each process provided various indications and answers to how we can create intuitive design spaces and how physicality influences digital processes.

The systematic literature review conducted in the initial phase of the research provided a theoretical framework and valuable insights into the first research question (RQ1), revealing the need for more intuitive support for non-linear operations and better physical-digital integration. These findings set the objectives for the subsequent exploratory phase of the research, where paper folding was chosen as a suitable method to address the second research question (RQ1_mod). Paper folding, as a well-established physical method, allowed for the rapid sketching of 3D ideas and volumes and helped to understand the generation of preliminary ideas from a human scale. Through paper folding experiments, we collected information on a human-scale, and demonstrated various functions of scanning and performance-based modeling tools. The final interview study mainly focused on answering the first research question (RQ1), but also provided critical data for the second question (RQ1_mod), demonstrating the efficacy of the paper folding method in addressing research questions related to physical-digital integration and non-linear operations.

The literature review conducted in the first year of the doctoral studies aimed to answer the RQ1, which focused on the physical-digital divide in design processes. The review uncovered that while the body of research, particularly in HCI, offers integrative solutions, it does not sufficiently address the
The second study looked into the influence of material agency in the early design stages from a human scale (RQ1_mod). While the findings of this study cannot be generalized to a larger population of designers, they offer insights into the potential of combining physical and digital modeling tools for a more intuitive design approach. The paper-folding method was a suitable approach for studying RQ1_mod because it enabled the creation of physical models from a two-dimensional material, allowing for quick and flexible exploration of design concepts at a human scale. While the method has limitations in terms of materiality and complexity, it offered a valuable means of generating and testing ideas in the early design stages, particularly in cases where digital tools fell short. As such, it provided insights into the importance of physical testing and the potential for combining physical and digital techniques in a more intuitive design workflow. One key finding was the gap between physical and digital operations and the critical role of physical testing from a human scale for verifying and understanding digital results. The example cases presented later in this thesis (Menges, 2007; OMA, 2005) further demonstrate this divergence between physical outcomes and digital simulation results. This finding demonstrated the importance of using physical modeling tools alongside digital models, no matter how advanced the digital tools may be. The paper-folding study showed the feasibility of a more intuitive design approach by combining existing technologies, such as 3D scanning, with traditional physical explorations.

Lastly, the interview study provided valuable insights from real-world practitioners on the exploratory and sometimes ambiguous conceptualization
stages of architectural projects. While modern architectural practices have embraced various performance-oriented digital design tools and equipped architects with new digital skill sets, participants noted that physical models are not widely used as idea-generation tools in architecture. However, this finding does not discount the role of material agency in design processes. Participants acknowledged that physical testing models embody exploratory qualities that can significantly impact design decisions, particularly in the early stages.

Based on the interview findings, physical techniques such as sketching provide a simple interface for expressing rough concepts on a planar surface using physical drawing skills. To achieve more intuitive design workflows, it is suggested that digital design tools capture a similar simplicity and ease of use, while taking into account the established approaches currently adopted by architects. The interviews also highlighted a lack of sufficient digital design training in diverse academic institutions, which forms the basis for providing architects with the option to use both their physical and digital skills through more intuitive digital design tools.

It is worth noting that the thesis does not focus on the latest technologies adopted in architecture, but rather on addressing fundamental questions regarding physical interactions in architectural design processes. The aim of this doctoral dissertation is to offer support and information to designers who may not be proficient in using digital design technologies, as well as design professionals with diverse experiences, students, and educators working with digital design tools.

1.6 Thesis Structure

The thesis starts by introducing a theoretical and historical framework of the research. The chapter combines existing research from the first literature review article with additional relevant works discovered throughout the research process. Next, the thesis concentrates on the plans and methodologies of the research studies. Each study is introduced separately. The last chapter presents the main findings and highlights of each study. The dissertation concludes by explaining the connection between three research studies. An appendix section is also included at the end of the thesis, which contains visual data and an example interview transcript from the second and third studies.
2. Theoretical Background

2.1 The New Digital Terrain

2.1.1 A Historical Overview of Computer Graphics and Modern Interaction Techniques

Between the 1960s and 1980s, the advent of computer graphics and personal computers (PC) were early milestones for the widespread adoption of digital design technologies. Sutherland's Sketchpad (1963) is considered one of the first computer-aided design (CAD) implementations. Sketchpad established the foundations of modern designer-computer interactions. This new graphical user interface (GUI) enabled designers to generate primitive geometric constraints on a display and optimize the visual representation to achieve desired outcomes. The system allowed designers to form new links between 2D geometries and modify them with precision. Similar interactions between user input and digitally generated geometries have carried over in today's widely used CAD software (i.e., AutoCAD, ArchiCAD, etc.) A noteworthy feature of Sketchpad was its support for interactive pen input for altering the displayed geometric forms. Digital pen input enabled direct manipulation of primitive geometries through manual hand movements. As in the pen and paper drawing process, digital pen input enables translating design intent into visual representations. Despite the aforementioned features, the practical limitations of the GUI-based design environment were prominent. Sketchpad supported the creation and manipulation of simple geometries. Consequently, the system did not support drawing intricate shapes that can be produced by using a pen and paper.

The graphical user interface of Sketchpad could be implemented into design processes without requiring programming skills from the designer. Hence, the system focuses on users' interactions within the digital design environment. Although computers progressively became capable of producing three-
dimensional (3D) digital models, two-dimensional representations, similar to Sketchpad, are still used in many CAD software.

Simple 2D graphics of Sketchpad evolved into more complex 3D models over the years. Moreover, the new rendering (Appel, 1967), rasterization (Gouraud, 1971) and global illumination (Whitted, 1980) techniques enhanced the visual presentation of 3D graphics considerably. Besides the representation of 3D visuals, physics-based modelling techniques started to become more prevalent. One of the notable contributions is the elastically deformable models that enable digital manipulation of 3D models based on attributed physical properties (Terzopoulos et al., 1987). Deformable models simulated the physical behavior of 3D objects by employing elasticity as a constraining material characteristic.

Researchers (Terzopoulos et al., 1987) implemented physics-based manipulation of 3D models to unify the shape and motion applied to an object. Through physics simulation, the static 3D model transforms into a dynamic digital object. Research on elastically deformable models demonstrate that implementation areas of computer graphics in architecture may not be limited to visual representation.

The architecture literature illustrates that during the the early 1990s, computers were not utilized as part of the design processes and the design process involved manual, more traditional approaches such as sketching with pen and paper, building physical models, and rendering by using brush markers. Lynn’s (1993) comparison between architecture and naval design has introduced the idea of incorporating force and motion into design processes:

"Traditionally, in architecture, the abstract space of design is conceived as an ideal neutral space of Cartesian coordinates. In other design fields, design space is conceived as an environment of force and motion rather than a neutral vacuum. In naval design, for example, the abstract space of design is imbued with the properties of flow, turbulence, viscosity, and drag so that the form of a hull can be conceived in motion through the water."

A neutral CAD environment may be a limiting factor for integrating time, motion, and physical forces into the design process. Lynn’s comparative argument about the development of form based on environmental determinants highlighted an important factor: In shipbuilding, the appearance is not solely an
aesthetical element but derives from the performance analysis and design decisions based on physical conditions. The early versions of 3D models were static objects in a bounded digital environment. In the physical world, 3D objects continually interact with external forces (i.e., gravity, wind, precipitation etc.) In digital design platforms, the same physical conditions may not be provided by default. Without the implementation of a physics simulation, the fixed 3D models remain representational on a computer display. Consequently, a static 3D model may not provide adequate information for designer to grasp the physicality of a design space. With the influence of Lynn’s ideas and works on digital design, more architectural practices began to explore design opportunities with unconventional geometries.

Towards the late 90s, one of the noteworthy leaps in computer graphics was the emergence of advanced free-form drawing tools. For example, Teddy (Igarashi et al., 1999) is a graphical user interface that allows production of 2D and 3D free-form surfaces based on a user’s hand input. Before free-form modeling systems, as illustrated earlier, the traditional practice was to build 3D models through primitive objects (i.e., a cube or a prism) and to carve basic shapes for achieving elaborate mesh surfaces. Teddy utilized a digital pen alongside a mouse input for transferring hand-drawn geometries into the digital design platform. The algorithm is capable of translating 2D section drawings into 3D models, and it enables diverse operations on models the designer creates, such as extrusion, trim, boolean, and surface smoothing. Teddy also allowed simple bending operations on 3D sketches to create curved surfaces. The system presents an early version of the digital operations that are available in many modern 3D modeling tools today (i.e., 3Ds Max, Rhino 3D). The introduction of free-form manipulations expanded the geometric variability within a bounded graphical user interface.

As the generation, representation, and physical manifestation of design ideas have transformed with the advancing computer technologies, three-dimensional systems have become capable of reserving large numbers of visual and structural data. This transition to digital design workflows has not been instantaneous in architecture. Throughout the adoption progress of computer-aided design and manufacturing (CAD/CAM) tools, physical techniques, and manual design skills played a significant role in design development processes.
In parallel with the technical innovations, over the last 20 years, scholars presented ideas regarding the historical progress, adoption, and current functions of computer graphics in architecture. Tornincasa (2010) pointed out the late adoption of computer-aided design and fabrication techniques and emphasized that these technologies had been utilized in the automotive, aeronautics, and shipbuilding industries years before they were used by architects. According to Dunn (2012), the late adoption of emergent technologies in architecture was due to social, cultural, and economic conditions. Hence, the digitalization process in architecture involves other factors than the technical advancements in computation and manufacturing.

Regarding the current understanding and role of computer graphics, Davis (2011) argued that computer graphics involve visualization methods that can enhance human-machine communication in a design process. CAD environments offer 3D and 2D graphical elements that facilitate the creation of architectural representations. However, Davis (2011) underlines that the CAD does not merely function as a drawing tool to generate static geometric visualizations "but can cover many other aspects of design work including optimization to improve productivity and derive other benefits at various operational levels."

In recent years, the ability to generate complex geometries (i.e., Non-Uniform Rational B-Splines), and physics simulations brought digital design space closer to the physical world. This provided architects with the tools to connect technical qualities of a project with its static representations (i.e., 2D drafts, 3D models.)

The expanding scope of application for computer graphics continues to inspire research studies incorporating physicality into digital design environments. The following sections will discuss other developments that contributed to the contemporary understanding of digital design and explore physical-digital integration with relevant examples and perspectives from scholars.

2.1.2 A Shift Towards Nature Inspired Forms and Parametric Design Environments

The world-renown architect Corbusier (1989) has seen the architectural plan as a central element for architecture to progress further. It is worth noting that, up until today, conventional 2D architectural plans, section, and elevation drawings are still being utilized, especially during the construction stages. However, dynamic 3D modeling approaches for form-finding procedures that became
prevalent in the 90s enabled the design of complex non-linear forms. Lynn’s (1999) Embryological House project, initiated in the late 90s, is one of the well-known cases among digital design researchers and practitioners. The project involved both physical modeling and digital form-finding procedures via animation software. Lynn’s technique allowed numerous iterations of a non-Euclidian design language, referred to as BLOb (Binary Large Object) architecture. The Embryological House remained a conceptual digital project, and besides scale testing models, the idea has not taken a full-scale physical form. As demonstrated in Lynn’s case, computational capabilities create new opportunities for testing non-standard architectural concepts. These organic concepts and large number of iterations may be challenging to develop only through traditional architectural plans. The architecture literature also supports the idea that, in the recent years, the understanding of architectural form has expanded beyond traditional drafting approaches.

Kolarevic (2004) remarked that the generative design processes are creating new opportunities for conceptual, formal, and tectonic exploration, and the focus of architecture is shifting towards the emergent and adaptive properties of the form. Later, Kotnik (2011) wrote that, the digitalization of design processes has led to "an understanding of form as a flexible expression of an intrinsic field of geometric interconnections instead of an extrinsic composition of stable basic forms." Hence, the focus of design processes has moved from the composition of static forms to the derivation of elaborate geometric relationships.

In recent years, new biology inspired aesthetic movements and digital design techniques have emerged in architecture research and practice. Knippers and Speck (2012) suggested that a connection between biological morphogenesis and the architectural form generation process leads to diverse design concepts. Morphology, a term coined by Goethe in 1797, refers to the structural deformations in living creatures. As Vogel (2012) points out, more than a hundred years after Goethe, mathematician and biologist Thompson examined the form alterations in numerous animals and plants through mathematical formulas. In the architectural discourse, Thompson’s idea of morphology influenced nature-inspired the recent bio-inspired movements and the conception of organic free-form geometries. The modern computational tools made incorporating biology concepts into the architectural design process more feasible.
Parameterized design tools, in particular, offered an adaptive design space for generating biological concepts via rule-based procedures. According to Jabi et al. (2013), parametric design refers to "a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between the design intent and the design response." A parametric digital design workflow extends the abstract CAD and 3D modeling space by allowing the generation and optimization of complex architectural systems. For instance, modern 3D modeling tools such as Rhino 3D provide a visual programming environment via Grasshopper plug-in and Python scripting language. Compared to well-known CAD software (i.e., ArchiCAD, AutoCAD), Rhino offers flexible toolsets for modeling complex 3D geometries. Furthermore, the addition of the algorithmic design plug-in Grasshopper provides generative form-finding capabilities to the base software. Similar visual programming systems enable the implementation of complex design approaches such as architectural morphology.

Various practice-based research projects have looked into the concept of biological morphogenesis, which also demonstrated the potential of parametric digital design techniques. For example, Reichert et al. (2014) analyzed the American lobster shell as a biological model for constructing a 1:1 scale fiber-reinforced polymer structure. The design approach involved digital structural simulation, analysis, and optimization techniques to generate geometric solutions. Finally, a fiber-reinforced physical prototype, employing a fabrication logic based on biomimetic principles, has been built and exhibited. Another interesting example is the Silk Pavilion (Oxman, 2015) which utilized domesticated silkworms called *Bombyx mori* to produce a 1:1 scale complex structure through their natural fiber generation process. Initially, researchers built a scaffolding structure with a computer numerically controlled (CNC) machine. Then, silkworms were placed at the base of a scaffolding structure. Finally, similar to a modern 3D printing method, silkworms completed 26 polygonal panels into a volumetric pavilion through a spinning motion. Oxman (2015) believes that it is possible to produce more pavilions by integrating this natural process into architecture. Both the cases incorporated biological concepts in different ways: Oxman (2015) utilized the natural production process as a fabrication method, whereas Reichert et al. (2014) used lobster shell formation as a conceptual basis. On the other hand, both design methods used biological concepts to establish a consistent design and fabrication framework starting from initiation to construction. The two examples from the literature demonstrate that, besides static
representation, computational processes can realize the idea of combining biology and architecture and offer a systematic form-finding method.

Recent innovations in CAD, digital fabrication machines, and structural performance analysis methods reemphasized the role of geometry in form-finding. According to Menges (2015), geometry has always been an important focus in architecture. The following section will provide an overview of the development of digital fabrication methods and how the new architectural styles and complex geometries take a physical form.

### 2.1.3 The Impact of Digital Fabrication and Physical Testing

Digital fabrication technologies enable quick prototyping or construction of design ideas. Yet, digital fabrication methods are not entirely separate from established physical and digital design procedures. On the contrary, fabrication technologies may have emerged from a necessity to test digitally generated design ideas with physical prototypes. This section will discuss the development of digital fabrication technologies by presenting examples from the literature.

Digital fabrication technologies are often associated with the instant conversion of digital data into physical objects, similar to a desktop printing setting. During the digital fabrication process, 3D models or 2D drawings that contain data for processing different materials are fed to the machine. Drawings are produced in CAD and modeling software operating in an abstract GUI design space. Willis et al. (2010) argued that the current digital fabrication systems are constrained within the GUI paradigm. However, existing examples, such as AA Component Membrane (Menges, 2007) (i.e., manually assembly of tension cables with membranes), digital fabrication processes and techniques can also involve physical procedures to expand GUI bound digital design environments. In later sections, relevant cases, including AA Component Membrane, are reviewed in more detail.

In 2012, Gershenfeld (2012) wrote: "A new digital revolution is coming, this time in fabrication. It draws on the same insights that led to the earlier digitizations of communication and computation, but now what is being programmed is the physical world rather than the virtual one. Digital fabrication will allow individuals to design and produce tangible objects on-demand, wherever and whenever they need them.” Gershenfeld depicts the growing
interest and anticipation from the architecture and HCI community as the digital fabrication technologies increasingly became widespread at the time.

Digital fabrication refers to diverse technologies that can produce physical objects by processing digital 2D vector drawings or 3D models. Digital fabrication technologies can involve subtractive and additive operations to reshape various materials. For instance, subtractive fabrication techniques, such as laser cutting and computer-numerically controlled (CNC) milling or routing, use 2D vector drawings to produce objects and surfaces. "Milling and routing are similar techniques since they both use a rotating cutter to subtract material. Milling is useful for metals amongst other materials, whereas routing is typically applied only to wood and plastics (Dunn, 2012)." To obtain physical objects, designers produce digital drawings illustrating which parts of the material will be cut, engraved, and moulded. Despite the infinite abstract design extent of digital design software, digital fabrication machines limited with physical and dimensional constraints. Producing large-scale physical prototypes may require additional manual building processes, particularly after a subtractive fabrication procedure.

Additive manufacturing has similarities with desktop printing logic. Nevertheless, some cases require designers' physical input. The additive fabrication processes create objects at a slower pace by building up layers of material. Dunn (2012) explains: "All additive processes work on the basis of translating digital information into a series of two-dimensional layers." The digital 3D model contains the essential data regarding the structural and geometric characteristics of the intended object. Accordingly, the additive fabrication machine translates the 3D model into individual 2D layers of material to accumulate and create the physical object. 3D printing is a widely-used additive fabrication and manufacturing technique. Similar to the subtractive fabrication method, the increasing scale factor can also impact the additive processes. For example, Yoshida et al. (2015) proposed a handheld fabrication technique for 3D printing 1:1 scale objects. The materials utilized for the fabrication process were chopsticks and a wood adhesive to keep the chopsticks together. Researchers adopted an aggregation approach to produce 1:1 scale prototypes. The handheld dispenser drops chopsticks with the wood adhesive and forms porous and lightweight surfaces. Such a human-assisted fabrication technique may enable the production of physical prototypes without design area or scale constraints. On the other hand, the increasing scale of the prototypes requires the manual involvement of
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designers. Accordingly, digital fabrication processes may not always follow a linear (digital to physical) order.

Digital fabrication enables the physical manifestation and testing of design ideas that are conceived or modeled on digital design platforms. The design ideas move from the abstract design extent to the physical environment and are influenced by the flow of physical forces. Although it is plausible to understand physical performance to a certain extent through digital simulations, the conditions in the physical environment may pose unpredicted challenges. Digital fabrication methods can prevent expensive errors in the construction stages of an architectural design process by verifying digital design concepts. Moreover, additive and subtractive fabrication techniques facilitate an interplay between the physical and digital design spaces, which may be one of the central factors motivating further research and practical applications in this area.

Despite the increasing number of research and project implementations utilizing digital fabrication technologies in HCI and architecture domains, digital design methods have also had critiques throughout the years. The following section discussed the concerns and issues about digital design methods, particularly regarding digital design software.

2.1.4 Concerns about Digital Design Methods

CAD, 3D modeling, and parametric design software can increase the efficiency of design workflows. For example, when developing large-scale architectural projects, computational procedures can be less costly and more time-efficient than conventional design approaches (i.e., architectural hand-drafting, building physical representational models, etc.) Despite the advantages of digital design methods, some scholars raised concerns about the digitalization of design workflows and its impact on creative processes. Other scholars re-emphasized and reminded the significance of physical design techniques.

To exemplify, Frazer (1995) expressed that a fully computer-oriented design process may shift the focus to the final architectural outcomes instead of allowing a comprehensive examination of the design process.

With a focus on the physical aspects of the design process, McCullough (1998) asked: "What good are computers, except perhaps for mundane
**documentation, if you cannot even touch your work?**” McCullough (1998) emphasized that digital design technologies are unable to provide a direct physical experience. He suggests that new digital interaction methods (such as motion-tracking) could enhance constrained mouse and keyboard interactions and unite physical and digital realms.

Kolarevic (2004) later noted that before submerging ourselves in these technologies, we need to understand the design goals and implement digital techniques with proper planning.

To sum up, the most prominent concern among researchers can be outlined as follows; If the design workflow heavily relies on digital, numerically-controlled methods without a clear design intention and roadmap, creative and iterative thinking processes can be misguided.

According to Loke and Robertson (2011), by developing bodily knowledge, "designers can better articulate and advocate for the internal, perceived qualities of physical experience and new forms of interaction that value the lived body." Current digital design tools focus mainly on presenting ideas through visualizations in a GUI-based design environment. The user interacts with the visual representations through a mouse and keyboard and does not have any physical communication with the shapes and geometries. Although digital designs can be viewed in 3D on a planar computer display, they lack the tactile qualities that the physical space affords.

According to Vogel (2012), digital drawings do not have the same qualities as the drawings created by hand. Thus, despite their computing capacity, digitally produced designs and sketches remain an inadequate substitute for hand-drawn representations. Other scholars (i.e., Stavrić et al., 2013) also pointed out that a fully computer-controlled design process could lack the manual dexterity and material knowledge of designers.

To comprehend the contribution of physical involvement, Melcer and Isbister (2016) studied how emotions are conveyed through visual and tactile manipulations of shapes and forms. Three different design strategies, categorized as visual representation, metaphor, and motion, were implemented to understand the embodied process. Participants were asked to deform a clay material to generate 3D objects that express their emotions. The study has found that
movement and tactile manipulation play a central role in communicating ideas through forms and shapes. Participants’ interactions with the models indicate that physical engagement with the material adds tangible information to the design process that the visual representation alone may not provide.

Despite the above-mentioned issues raised by some researchers, digital design software and fabrication technologies can be beneficial for architects and design practitioners to speed up the design process and reduce the error margin. As Carpo (2017) said, digital tools enable the quick conception of complex design ideas, which requires a significantly longer time and more resources with conventional techniques (i.e., pen and paper drafting). However, existing research also indicates that the bodily knowledge, and physical interactions embody qualities that are lacking in the digital realm. Most digital design platforms emulate direct physical engagement through mouse and keyboard inputs. Hull and Willett (2017) asserted that such a limited interaction results in 3D models which "lack depth, texture and a sense of materiality, despite the most advanced digital modeling and rendering software."

Recent advances in haptics, virtual reality (VR), augmented reality (AR), and mixed reality (MR) technologies offer the potential for enhancing digital design practices with tangible interactions by providing high-fidelity physical and visual feedback. This thesis discusses the potential technologies in more detail in the concluding section.

2.1.5 The Changing Role of the Physical Model-Making

The previous section touched upon the significance of bodily knowledge and physical interaction in the current digital age. This section focuses on the role of the physical models in the digital design era.

Architectural model making is one of the traditional design techniques for developing concepts on various scales. The earliest documented use of architectural models dates back to the fifth century BC, when Herodotus, in Book V, Terpsichore, makes reference to a model of a temple (Herodotos: Terpsichore. V, 1894). However, it is not clear when scale physical models were employed during the design processes of buildings. Throughout the centuries, model making became prevalent and an essential design method for the architectural design processes. Today, physical models (such as representational models or
structural prototypes) are still a part of design processes. What qualities does physical model-making practice embody despite some intrinsic physical limitations?

To address the question, architecture and HCI scholars contributed a wide variety of ideas and perspectives. Conventional physical models (i.e., cardboard models) mainly rely on the manual dexterity of the designer, making them less precise than, for example, a 3D printed model. One of the main ideas behind digital design and fabrication techniques is minimizing the human error. Yaneva (2005) identified that while digital design methods reduce human error, they can also remove "moves that have unintended effects, with unexpected problems and potentials." Other scholars also support that the physical model-making process can assist the conception, testing, and revision of design ideas. For example, Pallasmaa (2006) pointed out that comprehending the architectural scale requires a projection of one's body scheme into the space in question. Physical models can act as tools for architects to project themselves into the extent they design and experience the space through scale physical elements.

According to Pallasmaa (2006), the sense of touch is the primary way of receiving data from the physical space. Hence, our vision acts as a subsidiary source of information and supports the tactile feedback we receive from the environment. Although such a claim may be debatable, omitting physical engagement from the design process could result in missing critical information from the physical space. In modern digital design environments and digital interactions, visual feedback is more predominant than auditory or tactile feedback. According to De La Torre (2006), somaesthetic information is necessary for quick and accurate interaction with our environment. Somaesthetic is a term that refers to "sensory systems that respond to stimulation of the skin and deeper tissues of the body (Hollins, 2010)." De La Torre (2006) writes:

"If the interface doesn't provide meaningful somaesthetic information about the environment's state, users are deprived of potentially critical information to learn and perform many tasks with speed and accuracy through their extended body. This would seem to be particularly so if users employ the interface to deal with a large number of degrees of freedom, as when working with tools or multiple objects with complex behaviors."
From an architectural perspective, Iwamoto (2013) suggests that engaging with physical models supports complex design processes by decreasing cognitive load. When manipulating materials manually, designers often encounter constraints due to specific material properties. Consequently, the physical model-making process can uncover any significant structural issues from an early conceptual phase. Iwamoto’s investigations have also revealed that discovering such material limitations prompts designers to consider and examine physical conditions from the initial steps of an architectural project, which could fundamentally impact the design process.

Modern physics -based form-finding techniques can emulate realistic direct interactions with digital models. Furthermore, the recent innovations in AR/VR technologies, and haptics offer life-like tangible experiences in the digital realm. Why do architects continue to employ physical models, despite the advanced computational resources for generating, optimizing, and engaging with design ideas? According to Dunn (2014), the most obvious answer lies in "the actual tangibility of such models that, unlike their cropped and flat counterparts, offer substance and completeness." Physical models and prototypes enable designers to convey and communicate their ideas through materials. In digital design environments, the models are intangible, created in abstract design space, and often rely on only one modality, the sense of vision. Without the touch, digital models can be misinterpreted by the viewer. Despite the recent AR/VR and haptic texture simulation capabilities, the experience of holding an actual physical model, and distinguishing fine details are still substantially different than viewing it on flat or stereoscopic displays.

As the digital models may not be able to materialize abstract ideas, scale models in particular can play a significant role in comprehending the real-world dimensions and the user experience. Scale physical models allow designers to manipulate materials through numerous hand movements without interface-related limitations in the physical design space. Previous works suggest that unrestricted physical interactions with the models can promote original design ideas (DeLanda, 2015). Besides the creative opportunities physical modelling affords, Agkathidis (2015) claimed that validating digital findings through physical model making can also assist students and practicing architects in evaluating the “spatial, aesthetic, and programmatic” qualities of a project.
To sum up, numerous academics emphasized and discussed the qualities physical models embody. A notable recent development in the area of physical model-making is the material engagement framework: Poulsgaard and Malafouris (2017) explored how computers and digital design methods influence the creative thinking processes in architecture and developed the material engagement framework. This framework is constituted on the idea that engaging with materials is an essential cognitive resource that changes "the projective flexibility and the material make-up of our minds." Thus, creative opportunities unveil themselves through comprehensive material and symbolic engagement. The imaginative qualities of a project may develop through physical involvement alongside extensive digital design knowledge. While stressing the importance of physical engagement with materials, Poulsgaard and Malafouris (2017) also acknowledge the importance of having an extensive knowledge of digital design tools.

The material engagement framework suggests that physical interactions with objects can create "meaningful connections through the ongoing sense-making between designer, tools, and materials." A series of physical studies conducted by Groth (2017) also demonstrated that engaging with physical materials can create a connection between the mind and material."

The general consensus in the literature is that physical model-making can facilitate novel, unpredictable findings and contribute to the ideation process. A recent survey (Sachanowicz, 2019) looked into why scale model is still critical to the creative process of architectural practices such as OMA, MVRDV and Neutelings Riedijk. The survey showed that physical models today remain as one of the most stimulating tools for architects. Sachanowics (2019) concluded that “architects need and enjoy physical contact with space, materials and masses they are shaping and designing to become real life objects - buildings constructed using real materials in the future.”

This section will conclude by clarifying the role of physical engagement in architecture through two example case studies from architecture. Both examples demonstrate how exploratory physical engagement can supplement digital design workflows from different viewpoints. In the first case, the specific point being investigated is the use of physical models as exploratory and critical investigation tools to drive the progress of an architectural project. The second case study looks into the use of digital fabrication technologies for generating
prototypes that help architects test and comprehend the physical conditions and constraints from the early design stages.

Case Study 1: Casa da Música

Casa da Música (2005) is one of the modern concert hall projects in Porto, Portugal, designed by OMA, a Rotterdam based international architectural practice. The construction of the concert hall was completed in 2005. Some publicly available documents published by the practice provide insights into how the team utilized different types of physical models as exploratory tools to drive the project progress.

Koolhaas, the founder of the practice, describes the ideation process as follows: “We experimented with a (physical) model for Porto (referring to the concert hall project) made of etched glass, with steel floors that would have created beautiful shadows, but I wasn't confident that it would have been interesting.” As the design ideas were evolving, the team of architects recognized that the original concept of the building was not going to work as intended. At this point, the architects decided to borrow conceptual ideas from another residential project they were working on and adapt them into the concert hall project. The residential project, named Y2K house, was designed for a private client. The designers describe the form of the house as “a laundry bag with a protected living zone in the middle of the bag.” The design team studied translucent, glass and solid physical models produced for the Y2K house when making decisions for the concert hall project. The process documents show that models produced with different materials presented unique spatial characteristics. A notable point in the conceptual development of the project is that building a glass model helped the team to recognize the complex spatial composition, referred to as the “laundry bag”.

Throughout the conceptual stages of Casa da Música concert hall project, the architects also explored solid-void, public-private relationships by building scale negative working models made of glass and white foam boards. There are documents (OMA, 2005) of more detailed scale physical models representing the main hall of the Casa da Música with scale human figures. Moreover, the team has studied the spaces through larger scale models. The design process of Casa da Música shows the role of physical models was not only limited to comprehending spatial relationships. Engaging with physical models from the conceptualization to completion provided creative inputs that improved the project.
with new ideas. Documentation of the project also suggests that physical models were utilized as practical communication tools for presentations (i.e., client presentations).

A noteworthy aspect of this project is the connection physical conceptual models have with the actual concert hall building. The conceptual framework in physical models has been translated into a construction project with minimal compromises. In this translation process, digital models and simulations (i.e., stress simulations) also played an important role besides the physical models. Nevertheless, the physical model making practices played a pivotal role during ideation, decision making, and even construction processes.

Case Study 2: AA Component Membrane

A permanent lightweight canopy structure was designed by Menges et al. (2007) to cover the roof terrace of Architectural Association in London. The project integrated physical testing and digital design techniques, and it was completed within seven weeks with an efficient fabrication strategy. AA Component Membrane is a notable example that demonstrates how architects take the physical conditions into account from early design stages and how the unforeseen physical constraints may impact the design decisions in later stages. Most importantly, AA Component Membrane exhibits the potential advantages of utilizing digital fabrication technologies for physical testing purposes alongside the digital form-finding methods discussed in the previous sections.

Although the lightweight canopy may resemble a shell structure, it is not an enclosed surface. Moreover, the final design allows light and wind to pass through while keeping and guiding the rainwater to a specific direction. Menges (2007) states that, “As the existing substructure of the terrace cannot withstand high torsional forces resulting from wind pressure, we decided to design a porous structure with a high degree of permeability for wind, light, and views.” Accordingly, the existing physical constraints and challenging conditions shaped the design and fabrication strategy of the design team from an early conceptual phase. This structural system consisted of various individual components of a steel framework and a membrane acting as a flexible loadbearing design element. The choice of materials and fabrication techniques resulted in a lightweight canopy that did not place excessive structural stress on the existing building.
In collaboration with a team of engineers, the architects studied the physical behavior of the structure in different seasons of the year through digital simulations. The information available about the project process indicates that the testing approach was not only limited to digital simulations but also physical prototyping. The main objective was to make the canopy a structurally significant element contributing to the load distribution of the existing building. The architects connected tension cables with custom fabricated membrane elements to achieve the structural system. Ultimately, each design element supported the whole structure.

AA Component Membrane case illustrates the influence of the physical conditions on the design and fabrication approaches. Physical forces, such as wind and water load, had a considerable impact on the final form of the structure. On the other hand, digital simulations alone were not sufficient to understand various physical factors. Architects had to test the physical behavior of the canopy by utilizing digital tools alongside physical prototypes. This process confirms that physical testing and prototyping may be necessary, particularly in a case like AA Component Membrane, where the physical forces need to be comprehended. This case also shows the benefits of the quick fabrication and prototyping techniques when designing a complex structural system.

Comparative Analysis of Case Study 1-2

The two case studies highlight the importance of physical models and prototyping in the design and construction processes of architecture projects. The architects utilized physical models to understand spatial relationships, public-private relationships, and the impact of physical forces, as well as to provide creative inputs and communication tools for client presentations. The connection between physical conceptual models and the actual building is notable in both case studies, as the conceptual framework was translated into a construction project with nominal compromises.

Based on the two case studies provided, it is apparent that physical models and prototyping play a considerable role in the ideation, decision-making, and construction processes of architecture projects. The evolving relationship between physical models and digital design skills and knowledge, and the challenges identified in these case studies, constitute the main research question for this thesis (RQ1) about creating intuitive design workflows that support...
architects in using both physical and digital design skills and knowledge in the initial design stages.

Casa da Música and AA Component Membrane were chosen as case studies because they represent different approaches to using physical and digital design skills and knowledge in the initial design stages. Casa da Música relied heavily on physical models to explore design options and communicate ideas, while AA Component Membrane made extensive use of digital design tools, such as parametric modelling software. The contrasting approaches of Casa da Música and AA Component Membrane demonstrate that both physical and digital design tools can play important roles in the design process, and that integrating them effectively can lead to optimal design outcomes.

Moreover, the case studies demonstrate the importance of physical models and prototyping in understanding various physical factors that cannot be comprehended through digital simulations alone. For example, Casa da Música provides a clear example of how physical models can be used to explore design options, communicate ideas, and engage stakeholders in the design process. In contrast, AA Component Membrane illustrates how digital design tools can be used to generate complex geometries and optimize designs for structural performance with the support of physical prototypes.

In the case of Casa da Música, OMA utilized different types of physical models, including glass and white foam boards, to explore solid-void and public-private relationships, spatial composition, and communication tools for client presentations. The architects borrowed conceptual ideas from another project, the Y2K house, and adapted them into the concert hall project. Physical models were also utilized to comprehend spatial relationships and provide creative inputs for new ideas.

Similarly, in the case of AA Component Membrane, physical conditions and constraints shaped the design and fabrication strategy of the design team from an early conceptual phase. The lightweight canopy structure was designed to be porous, allowing light and wind to pass through while guiding rainwater to a specific direction. Physical forces such as wind and water load had a significant impact on the final form of the structure, and digital simulations alone were not sufficient to understand various physical factors. Architects had to test the
The theoretical background outlines the physical behaviour of the canopy by utilizing digital tools alongside physical prototypes.

The two case studies indicate that physical models and prototyping are essential in the design and construction processes of architecture projects. They can provide architects with a better understanding of spatial relationships, public-private relationships, and the impact of physical conditions. Digital models and simulations play an equally important role but are not sufficient on their own, as physical testing and prototyping may be necessary, particularly in cases where physical conditions need to be comprehended.

For example, in the case of AA Component Membrane, the lightweight canopy structure was designed to be porous, allowing light and wind to pass through while guiding rainwater to a specific direction. Digital simulations were used to study the behaviour of the structure, but it was noted that physical prototyping was necessary to test the structure’s behaviour under different physical forces such as wind and water load. This was necessary to ensure the structural integrity of the final design.

Similarly, in the case of Casa da Música, physical models were used to understand spatial relationships, public-private relationships, and the impact of physical forces. Digital simulations were used in combination with physical models to refine the design and test the acoustics of the concert hall. However, it was reported that physical models were necessary to understand the spatial relationships, and digital simulations alone were not sufficient.

Therefore, the limitations of digital design tools in accurately simulating physical forces and their impact on the structure made the process not intuitive in understanding physical factors in the early stages of the project. Physical models and prototyping were used to comprehend these factors and refine the design, while digital simulations were used to test and refine the design further in later stages of the project.

Casa da Música and AA Component Membrane are examples of projects where the design teams used multiple software tools. Casa da Música’s design team used AutoCAD, Rhino, and Catia, while AA Component Membrane’s design team used Karamba, Rhino, and Grasshopper. It is likely that the teams used multiple software tools for different tasks, such as 2D drawings, 3D modelling,
simulation, analysis, and fabrication. The use of multiple software tools allowed each team member to work in their preferred tool and then bring the results together. However, using multiple software tools can also make the design process less intuitive if the tools do not integrate well or if the team lacks expertise in some of the software tools. This can result in increased complexity, difficulty in transferring data between software tools, and potential errors.

In the case of Casa da Música and AA Component Membrane, there are no explicit indications that there was a lack of intuitiveness in the digital design processes. However, the fact that the design teams used multiple software tools suggests that there may have been some difficulties in achieving the desired results with a single tool. Additionally, the fact that physical testing and modelling were needed to validate the digital simulations suggests that the simulations were not entirely accurate or reliable. This could indicate that the digital design methods were not intuitive enough to fully capture the physical behavior of the structures. Finally, the fact that the design teams needed to work closely with engineers and other experts in order to optimize the designs further suggests that the digital design methods were not entirely intuitive or straightforward.

The changing role of physical models can be observed in the cases of Casa da Música and AA Component Membrane. Physical models allowed architects to experience the scale and spatial qualities of their designs in a tangible way, without the limitations imposed by digital interfaces. They were able to manipulate materials through various hand movements, promoting original design ideas. Moreover, physical models provided an opportunity for architects to test and refine their designs through the testing of acoustics in Casa da Música and the material properties and structural limitations of the membrane in AA Component Membrane.

Although digital tools have become more sophisticated and accessible, physical models remain a crucial part of the design process, as they provide a tangible experience and allow designers to convey and communicate their ideas through materials. Therefore, in the context of the main thesis research question (RQ1), these cases illustrate how physical models can offer advantages over digital models when it comes to experiencing the scale and spatial qualities of a design, testing and refining the design, and communicating ideas to others.
In conclusion, the two case studies highlight the evolving role of physical models in architectural design, showcasing how architects can use physical and digital models differently to enhance their design process. Understanding the advantages and limitations of each modelling approach is essential for architects to achieve their design goals.

2.2 Synthesis

The theoretical background section provides a comprehensive overview of the evolution of computer technologies and design methodologies in the fields of architecture and human-computer interaction (HCI). It establishes the context for the research questions by highlighting the advantages and limitations of both digital and physical design practices and emphasizing the need for architects to have skills in both areas to be effective in the current design environment.

The section identifies challenges associated with the integration of digital design and fabrication technologies, particularly the difficulties posed by parametric design methods that require knowledge of programming and mathematics. These challenges are linked to the main research question of how to create intuitive design workflows that support architects in using both physical and digital design skills and knowledge (RQ1).

To address this research question, the section proposes that architects may need more intuitive interactions with materials, digital models, and fabrication technologies. However, the limitations of existing design software and parametric design methods pose significant challenges for architects who do not possess programming or mathematical skills. Therefore, the section suggests that by offering more material and interaction choices, architects can enhance their ability to iterate through the design process and engage with both physical and digital components. These considerations are crucial to the development of intuitive design workflows and are central to the research question.

The second study of this thesis, which focuses on RQ1_mod, builds upon this foundation by exploring the potential of integrating physical materials into digital design practices using the curved folding technique. This technique offers potential for generating complex and versatile forms through the combination of physical and digital design processes. By exploring the role of material agency
in design exploration, the study addresses the integration of physical materials into digital design practices.

The study demonstrates that the curved folding technique enables the exploration of physical materials and their potential to influence and augment digital design. Furthermore, it showcases the benefits of a feedback-oriented approach to design that draws from both physical and digital design practices. While the case studies of Casa da Música and AA Component Membrane do not use curved folding techniques, they demonstrate the potential of digital and physical integration, specifically the use of algorithmic modeling, physical experimentation, and prototyping to generate complex geometries and optimize structural performance.

Together, the two case studies and the second study of this thesis contribute to addressing the research questions by showcasing the benefits of an integrated approach that draws from both physical and digital design practices and highlighting the importance of considering material agency in design exploration. By doing so, the thesis aims to bridge the gap between physical and digital design practices and facilitate the development of intuitive design workflows that support architects in utilizing both types of skills and knowledge.
The research process of this thesis centered around three studies carried throughout my doctoral education. To determine the research topic, I initiated the investigation by conducting a literature review (Publication 1.) The literature review provided perspectives from HCI and architecture domains and built a theoretical framework. The review focused on the entire design process of an architectural project from the start to the completion. Findings of the literature review highlighted a need for studies focusing on the feedback exchange between physical and digital design processes (Gulay & Lucero, 2019). After the literature review study, I narrowed my scope into the initial design processes instead of examining the whole design process. Early intentions and creative ideas take their first shape during the initial design stages (Rice & Purcell, 2004). Hence, concentrating on the initial design stages was relevant to understand how existing physical and digital methods interact. I carried an exploratory study incorporating physical paper-folding activity with digital design methods (Publication 2.) A feedback-oriented design workflow was examined through physical prototypes, volumetric scanning technologies, digital simulation, and fabrication technologies. The design process brought new questions regarding the current practices in the initial design stages of architecture. To understand the recent developments and the role of physical and digital techniques in the early stages, I conducted interviews with practicing architects and experts in Finland, Switzerland, Germany, and the UK (Publication 3.) Outcomes of the interview study included elements that supported some of the findings from the previous studies. The following sections elaborate on the different methodologies utilized during each study and how they connect.

3.1 Literature Review (Publication 1.)

3.1.1 Study Design
Understanding physical and digital design gap is a broad research area that comprises diverse viewpoints within the human-computer interaction (HCI) and architecture fields. During the first year of my studies, my first task was to
search for relevant resources that focus on the physical-digital relationship and establish a theoretical framework. Before going through the literature, I determined the scope of the search. As a trained architect, my main interest was the impact of digitalization and the changing role of physical techniques on architectural design processes. Examining prior research in architecture was essential but not sufficient for understanding the full extent of the research problem. At this point, the literature in the HCI domain offered outlooks beyond architectural discourse. Related works in the HCI field included research approaches from various disciplines (i.e., industrial design, fashion design, computer science, etc.) Consequently, I conducted the literature review (Gulay & Lucero, 2019) based on prior research within HCI and architecture domains.

Although digitalization in architecture is one of the main focus areas, the literature review also included methods that are not directly associated with architectural design workflows. Obtaining information from two different fields provided support for comprehending the digitalization in architecture through HCI concepts and related works. Prior research in HCI and architecture focus on several common themes for integrating physical and digital design platforms. To exemplify, digital and automated fabrication methods, tangible interactions, and hybrid techniques are some of the themes identified throughout the literature review.

With the advancements in digital design techniques, integrating physical and digital design processes sparks interest within HCI and architecture research communities. As Poulsgaard and Malafouris (2017) state, it is critical to investigate how we can comprehend this "new digital terrain" and its impact on creative processes. Prior research discusses digital design methods as an efficient way of producing complex ideas and workflows. On the other hand, numerous research suggests that depending entirely on computer-based methods may disconnect design ideas from the physical world. For instance, Lynn (1993) points out the necessity to develop "a systematic human intuition about the connective medium" rather than developing artificial intelligence with critical thinking skills. As the literature review progressed, it became apparent that there is room
for further research on integrated approaches that unite computation with manual design skills.

Figure 2. Existing literature in the domains of HCI and architecture have been organized and assessed under four categories.

3.1.2 Methodology

Defining the scope of the research was the initial starting point of the literature review process. First, the search started by determining the initial keywords. Keywords, such as "computational design, digital fabrication, physical modeling, and tangible interactions," were used for identifying the relevant literature. Throughout the review process, ACM Digital Library was the main engine to extract literature. On the other hand, we also benefitted from Google Scholar, ProQuest E-book Central, and Aalto University's Library database to obtain literature from various publishers in the field of architecture and haptics.

Using the keywords alone returned thousands of papers and books. However, not all the results were relevant to the research questions (Figure 2.). To refine the search results and reduce the number of literature, related keywords were combined. For example, connecting "computational design" and "digital fabrication" returned 478,996 papers. Similarly, merging "physical modeling" and "tangible interactions" returned 289,071 papers. Combining broad keywords did not result in a considerable reduction in terms of the number of available literature. The initial results indicated a need to narrow the scope through more specific and targeted keyword groups.

To identify the core literature and establish an anchor point for investigating the connections between different research exploring physical and digital design environments, existing review papers and books were examined. Relevant contributions in architecture include reviews on digital fabrication methods (i.e., Dunn, 2012), works on digitalization in architecture (Frazer, 1995; Kolarevic, 2004), and physical design methods (Yaneva, 2005). In the domain of HCI, we looked into the research of Hull & Willet (2017), Ishii & Ullmer (1997), Weichel et al. (2015) to expand the literature collection. This scoping methodology was chosen because it allowed for a broad and systematic exploration of the physical
and digital design gap in the field of user experience. The methodology was deemed appropriate for our research question, as it enabled us to identify and map out the existing literature on this topic in a comprehensive manner. Similar approaches have been adopted in prior literature reviews. For example, a systematic assessment of national artificial intelligence policies was conducted by Niels van Berkel et al. (2020) using a comparable approach.

As the number of literature increased, new keywords emerged such as "computer-aided design, physical modeling, creativity support tools, digital simulation, haptic feedback." These specific keywords resulted in outcomes that were relevant to the physical-digital relationship. However, relying solely on keywords to structure the literature review process was insufficient for classifying the necessary data. Therefore, further refinement of the search method was necessary.

A systematic approach was adopted to exclude the literature that is not within the scope of the review. Hence, search engine results were organized under three main categories: 1) architecture, 2) human-computer interaction, 3) haptic principles. Throughout the review process, the information collected from related works was entered into a spreadsheet. The spreadsheet included three color-coded sections dedicated to each category. Each column of the spreadsheet was used for specifying a data type (i.e., author, title, year of publication, number of citations, keywords). Alongside the raw data extracted from the papers and books, the spreadsheet also includes a column for entering personal
notes and learnings from the readings. Information regarding each literature was added inside individual rows pairing with the related columns (Figure 3.)

The first category, "architecture," covered works that present a historical overview of the digital transformation in architecture (i.e., Menges, 2015; Kolarevic, 2004). Moreover, research outputs related to digital design and fabrication methods, physical scale models, and direct contributions to architecture from the HCI community were also a part of this category. Among 249 returns from search results contributing to architecture, 41 sources were included in the literature review.

The second category, "human-computer interaction," is a collection of research papers involving tangible-user interfaces, physical-digital manipulation, and prototyping systems. Out of 203 returns, 50 most relevant contributions were included in the literature collection.

The third category incorporates research areas, such as touch-based design knowledge, cognition, and creativity under the title of "haptic principles." This category mainly focuses on the processes and interactions within the physical design space and connects the research conducted within both architecture and HCI domains. Selected research outputs discuss the link between the hands, materials, and the mind in the context of design processes.

The primary focus of the literature review was the feedback obtained from physical and digital design processes. Therefore, the selection process centered around works that incorporate digital and analog design methods. Digital fabrication, computational design or, tangible interactions are broad areas of research. Thus, sources that do not relate to the main research question were not included in the review spreadsheet. Although literature in HCI and architecture approach the same research problem in various ways, there are intersection points between different research methods. Several practice-based works in architecture address the physical-digital integration by studying design and fabrication systems through 1:1 scale prototypes and research pavilions. HCI researchers approach the same problem by utilizing tangible user interfaces, fabrication approaches, and hybrid techniques. Literature in both domains provides valuable knowledge to answer the research questions.
3.2 A Feedback Oriented Design Approach (Publication 2.)

3.2.1 Study Design

The research study commenced with a thorough literature review, which culminated in the development of the Transitional Method. Initially, this method was a cyclical process that alternated between physical and digital design methods for testing physical designs using digital technologies. However, the method was later refined into the Feedback-Oriented Design Approach to better accommodate the complexities of the design process. This approach prioritizes an iterative process that involves continuously gathering feedback to improve the design. It places emphasis on generating rough ideas without committing to a particular design decision. To narrow the range of the design exploration process, the study implemented three curved folding strategies. The study specifically focused on exploring complex non-linear geometries through existing methods of curved folding in architecture. This was a potentially challenging test case for investigating physical and digital feedback cycles. In traditional design, paper has been a cost-effective material for creating mock-ups, which enables designers and creators to experiment with complex ideas without the need for more expensive materials. The use of paper can save time, effort, and resources.

Following the literature review process, the scope of the research became more specific with the addition of new sources to the existing list of relevant literature. Prior studies in HCI (Balakrishnan et al., 1999; Follmer et al., 2010; Hartmann et al., 2010) and architecture (Chandra et al., 2015; Laing et al., 2015; Oosterhuis et al., 2004) looked into conversion techniques that blend physical design skills with digital software knowledge. Translating digital data into physical artifacts can be achieved through digital fabrication methods (Dunn, 2012). Although current fabrication technologies may introduce material and scale limitations, they facilitate physical engagement and testing of digital concepts. On the other hand, the transition procedure from a physical to a digital design workflow may be relatively more convoluted. For example, earlier studies (Kus et al., 2009; Niiyama & Kawaguchi, 2008; Weichel et al., 2015) explored volumetric 3D scanning technologies to trace a physical artifact and generate digital 3D models. By obtaining visual information through a camera, scanning systems create virtual reference points to define traced physical objects, which can also be referred to as "point cloud" data. According to Remondino (2004), the 3D scanning approach results in digital models that are
"incomplete and noisy." Reconstructing digital models from point cloud data remains a problem due to inadequate physical information and technical limitations. With the recent advances in physical sensor and camera technologies, a more consistent level of precision can be achieved when tracing physical models. Conversion processes continue to improve based on emerging technological solutions. At the same time, the necessity for a translation procedure may be indicating a disconnect between the current physical and digital design methods.

Among practice-based works in architecture, curved folding (Huffman, 1976; Kilian et al., 2008; Koschitz, 2014) is one of the relevant and potentially challenging test cases to investigate physical and digital feedback cycles. Existing studies focus mainly on primitive shapes (Song et al., 2006; Tian et al., 2018) or functional objects (Zheng & Nitsche, 2017) in a translation process. Moreover, fewer studies (Yoshida et al., 2015) examine non-linearity and the impact of utilizing more complex geometries when linking physical artifacts with digital 3D models. After discovering the open area in research, I focused on translating complex non-linear geometries via existing methods.

In architecture, the concept of folding has been explored since the beginning of the twentieth century (Dunn, 2012; Lynn, 1993). However, folding has been a long-standing physical modeling technique before its introduction in architecture. One of the common materials for form-exploration through folding is a sheet of paper. The tractable nature of sheet paper allows creating a variety of 3D volumes in the physical space. The act of paper folding offers hands-on knowledge about concepts such as motion and transformation (Gregg Lynn, 1993; A. T. Olson, 1975). Olson (1975) explains the relationship between mathematics and paper folding as follows: “One intriguing way of adding an active element of interactive experience to a mathematics class is to fold paper. Once a relationship has been shown by folding paper, formal work on it later does not seem so foreign.” Furthermore, engaging with a sheet of paper to search for new geometries can create an intuitive design environment to understand mathematical relations. Paper folding can also simplify and materialize complex ideas during the initial design stages. Due to their flexibility and suitability for free-form exploration, paper sheets were utilized as mock-up materials in the study.
As Dunn (2014) remarks, “The ability of paper and cardboard to incorporate curvilinear geometry in two directions is significant in relation to other materials. These materials are particularly useful at the early stages of the design process when the form of the building is unknown and the designer may not want to waste time, effort and money testing out such ideas with more expensive and labour-intensive materials.”

A simple sheet of paper can generate numerous complex folding mechanisms and facilitate volumetric exploration. Hence, implementing simplicity into more intricate digital design processes has become the central idea behind the study. Another important concept was the non-linearity of the design vocabulary, which added complexity to test the capabilities of existing physical form-finding, digital optimization, and fabrication tools.

The first step aimed to create rough ideas without committing to a particular design decision. However, there could be countless possibilities without a clear design intent and direction when folding a planar paper surface. Three curved folding strategies were planned and implemented for narrowing the range of the design exploration process. Outlined folding approaches established rules for the idea generation and assisted the design process.

After translating the physical paper mock-ups, the design process continued in the digital realm. In this study, the digital process comprised two operations: First, paper prototypes were translated via 3D scanning technologies. Second, generated 3D models were optimized and used for both simulation and fabrication processes. The paper mock-ups produced during the first step were imprecise. Consequently, switching to a digital design environment rationalized handmade paper surfaces and provided a platform to examine architectural qualities. The idea behind shifting to a digital design space is to incorporate efficient tools and simulate real-world conditions before using different materials than paper. As the paper models have limited contribution, the digital design procedures present technical data and enrich the ideation stages. Mock-up models are relevant, tangible resources to study the gravity and external physical forces that can influence an architectural concept. For further physical testing and construction processes, the information from a mock-up may not be adequate.

Apart from the data (physical prototypes, photographs, observation notes) obtained from paper-folding activity, parametric simulation tools were adopted to
extract further information regarding the physical performance of curved surface geometries. Modern simulation techniques present the technical data in the form of numerical and visual representations. The finding of digital simulations and experiments can be applied to make design decisions in later stages. However, as discussed in previous sections, designers can only observe the physical performance in a simulation environment based on predefined conditions. In another saying, an accurate examination of the design idea may not be possible by solely relying on digital results.

The switching procedure from digital to a physical design workflow entails an equal understanding of both realms. After shifting from a physical to a digital design workflow, a second physical testing process was required to verify digital outcomes. Finally, optimized digital design concepts took a tangible form via digital fabrication and manual assembly techniques. For the second prototyping stage, plywood has been chosen as the primary material to rebuild improved versions of physical models. Thin plywood stripes hold material properties similar to a sheet of paper (Sellers, 1985). Yet, unlike paper surfaces, predetermined folding strategies may not apply to plywood stripes. Constructing a curved folded surface via plywood involves implementing new manual assembly solutions alongside a fabrication logic. By utilizing digital fabrication technologies, the objective was to establish a physical re-engagement with the design ideas. While shaping and refining design concepts, architects engage with a 2D display and an abstract design extent. However, producing physical prototypes involves a tangible envisioning of the design concepts, different from the neutral setting of the software.

To sum up, the exploratory stage of this research concentrated on conventional physical operations and existing digital techniques. The transitional approach employed throughout the design process demonstrates how widely-used design methods and tools can support intuitive non-linear explorations in the initial design stages.

Both physical and digital modes of design present resources to support the design thinking process. Physical models enable tangible exploration and testing through hands-on engagement with materials. Digital tools supplement the design process by form generation, calculation, and simulation capabilities. Switching between two design platforms can aid human memory limitations and reduce excess cognitive load by transferring the information to an external
design platform. Thereby, physical and digital design spaces afford an archive
where architectural and aesthetic qualities can be continuously assessed and
modified based on programmatic requirements.

3.2.2 Methodology

In the second phase of my research, I examined a feedback-oriented design ap-
proach alternating between traditional and contemporary methods and tools. I
initiated my studies by establishing a theoretical framework through a literature
review. However, hands-on investigations were needed to understand the phys-
ical-digital integration adequately and identify the issues when operating in
both realms. As a trained architect and the first author of Publication 2., it was
essential to participate actively in this process and collect experiential infor-
mation. The objective of following an exploratory design process was to promote
new research questions and expand the scope further.

The feedback-oriented process is developed based on the Research through
Design (RtD) approach (Frayling, 1993; Zimmerman & Forlizzi, 2014) and the
material engagement framework (Poulsgaard & Malafouris, 2017). Establish-
ing a connection between research and design has been an ongoing challenge.
In Research through Design (RtD), researchers produce new knowledge by en-
gaging in design activities, and the outcomes can manifest in the form of physi-
cal models, artifacts, or research prototypes. Such a design-oriented research
method involves reflection and iteration to grasp "the people, problem, and con-
text around a situation that researchers feel they can improve (Schön, 2017)."
Zimmerman and Forlizzi (2014) define Research through Design as "an ap-
proach to conducting scholarly research that employs the methods, practices,
and intention of design practice with the intention of generating new
knowledge." Therefore, researchers contribute to studies by bringing their de-
sign knowledge and skills. Prior research points that direct engagement in de-
signing or making processes allow researchers to discover new opportunities,
research areas, and methodologies that could otherwise go unrecognized. As a
result, "the processes of design and design thinking" become the profound con-
tributing factor and high-fidelity research prototypes stimulate future research
endeavours. Design thinking is a term used to explain the contribution of de-
signers in a project or process. However, there isn’t a clear definition. Zimmer-
man (Zimmerman et al., 2007) believes that "in some respects its ambiguity is
part of its strength, allowing it to be the right thing at the right time." When
planning the study, I approached *design thinking* as an ideation process that progresses through iteration and links design knowledge with technological skills.

The concept behind the feedback-oriented design process was to produce knowledge by purposefully employing physical and digital design methods and presenting the contributions through physical prototypes. Hence, RtD was an appropriate method for anatomizing each design operation and understanding the feedback cycles. Although RtD constituted a methodological framework for the feedback-oriented design process, another significant element of the study was using different materials to produce research prototypes. The feedback-oriented design process starts by engaging with sheets of paper and deforming surfaces to create 3D volumes. After a digital simulation and optimization phase, the physical workflow continues with plywood sheets. Before implementing the design approach, it was essential to understand the critical role of engaging with materials and physical models. The literature review (Publication 1.) showed that concretizing abstract ideas and gaining touch-based information from materials support formulating initial design ideas. Employing *the material engagement framework* extended the RtD approach by focusing on materials and continuous physical interaction. Accordingly, when designing the study, I kept the physical engagement with physical mock-ups and prototypes at the core of the design process. In digital design processes, interacting with a 3D volume may be limited to point and click actions on a computer display. At this point, the second prototyping (laser-cutting) stage with plywood stripes maintained the material engagement and continued physical exploration initiated with paper folding while benefitting from computational tools.

### 3.3 Interviews with Experts and Practicing Architects (Publication 3.)

#### 3.3.1 Study Design

The first two stages of my studies consisted of a comprehensive literature review (Publication 1.) and prototyping (Publication 2.) through an exploratory design process. The literature review provided extensive knowledge regarding the research in the field and getting involved in a design process offered first-hand insights. As I progressed with my studies, it became clear that I needed more information about the current situation in the industry and academia.
Prominent studies on the idea generation and initial design processes indicate the elusiveness of the thinking structure that shapes design concepts. Architects envision and communicate design ideas through sketches or preliminary mock-ups in the physical design space. However, going through existing literature provided less clarity about the process of idea generation and conceptualization. The ambiguous essence of the initial design steps may be due to a diversity of approaches adopted by architects.

Earlier research looked into sketching and model making in architecture. Nevertheless, there is a scarcity of up-to-date research investigating contemporary idea generation techniques and the role of physical and digital tools. As I reviewed the relevant literature and talked to my colleagues and supervisors, it became apparent that there are not many recent contributions focusing on ideation techniques (i.e., sketching, model-making processes, 3D modeling) in the initial design stages of architecture. The feedback-oriented design process (Publication 2.) guided the focus of the research into the initial design stages, and the new questions that developed from the design process formed the starting point of an interview study (Publication 3.) One of the main issues with the previous exploratory investigation was the applicability of the feedback-oriented design approach in architectural projects. Based on the initial literature review, Publication 2. began by assuming a gap between physical and digital design workflows. The missing component of the research was a comprehensive examination of the most recent digital design techniques and their impact on physical procedures. Consequently, the next step was to interview practicing architects and experts in digital design and fabrication methods to understand the current situation and feasibility of an integrated design approach.

Initial design processes are where architects explore and examine new design ideas and plans. The process is creative in the sense that the early expressions of thoughts and concepts need to offer unconventional and novel spaces and forms (Rice and Purcell, 2004). Sketching and model-making are some of the traditional physical techniques architects implement to express and convey initial design ideas. Although sketching and model making are two different methods, they may contain similar features in the initial design stages of architecture (Gursoy, 2010). According to Goldschmidt (1994), pen and paper sketching contributes to initial design processes differently than other idea generation methods. Suwa and Tversky (Suwa & Tversky, 1996) claim that
extracting different types of information from sketches is the driving force in revising design ideas. Sketching connects interactive representation through a constant production of images with clues "to visually reason not about something previously perceived but about something to be composed, the non-existent entity being designed (Goldschmidt, 1991, 1994)." The uncertainty regarding the final result constitutes the creative aspects of the initial design processes. Buxton (2007) states, "sketching in the broad sense, as an activity, is not just a byproduct of design. It is central to design thinking and learning."

On the other part, physical mock-ups are rough scale models that facilitate architects to create quick 3D volumes, often via inexpensive and readily available materials. Dunn (2014) refers to such models as "design development" or "process models" that are essentially "three-dimensional sketches through which novel ideas are explored and tested but not necessarily concluded." Therefore, preliminary mock-ups allow experimentation through physical deformation and function differently than comprehensive models built in later design stages. These imprecise physical models are produced concurrently with sketches and drawings, and "they do not require special preparation, as it would most likely delay rather than support design development (Knoll & Hechinger, 2007)." As in sketching with pen and paper, mock-up modeling involves a perpetual conversation between design ideas and tangible artifacts to create new solutions. One key hallmark of mock-up or process models is that the designer physically engages with the model to achieve envisioned forms or volumes. As Dunn (2014) explains, facilitating direct physical engagement is a characteristic that differentiates mock-ups from "other types of models that may be subcontracted to professional modelmakers."

Apart from hand-operated design methods, by utilizing CAD software and recently developing parametric tools, architects can create photo-realistic 3D representations and accurate physics simulations. On the other hand, designers continue to apply conventional approaches (such as model-making and sketching) throughout the architectural design process. In this interview study, one of the primary research problems was the impact of new computational capabilities on more traditional physical workflows.

One central objective of the study was to understand architects' motivations, values, emotions, strategies, workarounds, real-time interruptions and interactions with others, and the limitations inflicted by real-world conditions (Buxton,
More specifically, it was essential to observe and develop an understanding of how architects express and develop their initial ideas in the early design stages within the context of their studio/work settings. Therefore, observing and interviewing architects in their work environment has become the focus of the study to find answers to the formulated research questions.

Before preparing the interview questions, I determined the types of research data required to address the research questions and planned the data collection procedures (Figure 4.) The required data were classified as follows: a) interview recordings, b) field notes and sketches, c) photographs, d) publicly available project catalogues, portfolios, and 3D visualizations.

<table>
<thead>
<tr>
<th>Data Collection</th>
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<tbody>
<tr>
<td>a) Interview recordings</td>
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<tr>
<td>Interviews will be recorded by a digital voice recorder during the sessions. Recordings will later be transcribed for analysis.</td>
</tr>
<tr>
<td>b) Field notes and sketches</td>
</tr>
<tr>
<td>Expanded Notes: Descriptive Notes (Musante and DeWalt, 2010) There will be no inference or analysis while taking notes.</td>
</tr>
<tr>
<td>c) Photographs</td>
</tr>
<tr>
<td>Sketches, conceptual diagrams, mood boards, etc. Physical models / Prototypes Digital models / processes (i.e., Rhino, Grasshopper, Python, Maya, Revit, AutoCAD, ArchiCAD, etc.) Architectural plans, sections, elevations, etc. Work environment Workshops / Studios</td>
</tr>
<tr>
<td>d) Publicly available project catalogs, portfolios, and 3D visualizations</td>
</tr>
<tr>
<td>If available, additional visual and written material will be collected.</td>
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Figure 4. Based on the research questions, necessary data has been organized into four groups. The figure shows a part of the original research plan, including short notes about important details and specific data types.

The original approach was to start with one-hour-long workplace observations without interrupting the daily routines of participants. The total duration of observation and interview sessions were planned as two hours in total. The observation sessions provided time to take photographs, write short field notes (DeWalt, 2002), and draw sketches. Besides collecting data, the observations aimed to create an opportunity to get familiar with the office/studio environment, meet with team members and executives, and tour workshop spaces.
Photographs offered concrete examples of the tools and methods architects employ to develop and communicate their first ideas at the beginning of a project. Initial design sketches, material samples, physical models and prototypes, digital models were among the photographed content for the study. Images captured during the observations provide accurate and objective visual information that can later be utilized for the data analysis. Field notes (DeWalt, 2002) and sketches aided the data collection process, even though they may not be as objective sources as the photographs.

One of the purposes of using field notes and sketches as a data collection approach was to document my thinking process and formulate alternative ways to approach the issue. In some architectural offices, obtaining images of the ongoing projects was not possible due to company policies. Therefore, notes and sketches were employed to collect data while protecting confidential information about participants and design ideas. Moreover, drawing sketches and taking notes can be an efficient way of noting relevant remarks from casual conversations with the study participants.

After outlining the observation sessions, I started planning semi-structured interviews to cover relevant points about physical and digital design methods and their influence on the early concept development. The observation sessions formed a contextual basis, whereas the interviews intended to obtain specific information by facilitating in-depth discussions with participants. The interview setup included one main digital voice recorder and a backup recorder to capture audio data during the sessions. The backup recorder was used for continuing the data collection in case of a technical failure with the primary device. In addition to the data collected during observation and interview sessions, publicly available project catalogues, portfolios, 3D visualizations supported the analysis stage of the study.
When drafting the semi-structured interview sessions, I determined several subjects as a basis for the questions. The interview questions covered four specific issues that connect to the research questions (S3/ RQ1, S3/ RQ1_mod). The first part of the interview sessions focuses on the starting point of a new architectural project (Figure 5.) Before getting into more specific topics, the plan was to learn more about the workflows that different architectural practices adopt when expressing ideas, assessing programmatic solutions, and deciding on architectural forms. The next subject was the influence of early academic training on initial design approaches. Focusing on education could provide new perspectives regarding which skills and knowledge architects obtain in universities or schools. Hence, architecture education was incorporated as a focus area to gain more information about how such skills and knowledge are being used in current practices. Later in the study, including academic training as part of the interviews opened up new discussions about the changes in architecture education from the early 1990s up until now.

After gaining insights into the ideation processes and the background of the participants, the following objective was to focus on physical and digital design techniques. The physical-digital relationship is a critical component of the study. Accordingly, understanding the influence of the current digital practices
on early creative processes was the initial focal point before concentrating on conventional methods. Besides gaining insight into the latest digital tools, the idea was to identify positive impacts alongside shortcomings and limitations of adopting digital techniques in the early design phases. The next step was to gather information, through a similar approach, about the design techniques architects practice in the physical realm.

The final portion of the interviews was designed to switch the focus to current issues with digital and physical design techniques. One important topic to cover was the flexibility of various physical and digital design platforms. By using the expression "flexibility," I refer to the ability to perform complex geometric operations without the constrictions of physical design spaces or digital user interfaces. As Zhang et al. (2019) states, in a flexible method, "uncertainty is not viewed as a risk but as an opportunity." Addressing the flexibility of physical and digital platforms instigated another discussion regarding participants' ideal design workflows in the future. The inclusion of the future design approaches allowed participants to finalize the interview session by envisioning the future of architecture and speculating about new design methods. The interview plan also included an additional five minutes for talking with participants about various relevant subjects, apart from the interview questions, at the end of each session.

3.3.2 Methodology

The previous subsection elaborated on the planning stages of the observation and interview sessions. As the investigation aimed to analyze how architects utilize physical and digital tools, an essential part of the study was to determine a suitable sampling method. Oxman (2008) argues that digital design methods promote novel formal content and various new architectural concepts. Hence, building new educational frameworks may be necessary due to the pedagogical challenges and opportunities that digital design methods embody. Over the years, digital design frameworks became widespread in design education as well as in architectural companies. In this study, the initial step of understanding the role of physical and digital techniques was to observe, gain insights and comprehend the ongoing digitalization in the academic environment and its impact on architectural practices. Hence, a suitable participant selection approach had to be chosen for the study. Before establishing the participant selection guidelines and the recruitment procedures, the scope of the study has
been defined. Computer-oriented processes are becoming prevalent over traditional physical design techniques in many architectural practices (Gulay & Lucero, 2019). Consequently, comprehending the digital transformation in architecture was a fundamental component of the study. The interview participants were recruited among architectural practices that utilize the latest digital design and building methods and work with geometrically elaborate structural systems (Gulay & Lucero, 2021).

The interviews were initiated in Finland through a pilot session involving an architect with several years of work experience. This pilot interview aimed to test the open-ended questions, timing, and conversation flow. The pilot included comprehensive data regarding the modern digital design technologies and some physical techniques architects use during the initial design stages. Thus, the pilot session was incorporated into the study. I continued to search for relevant architectural practices in the Helsinki area that fit the scope of the investigation. Most well-established architectural companies own a website showcasing their projects and profiles of the architects working in the company, sometimes with a concise description of their area of expertise (Gulay & Lucero, 2021). Company websites classify the positions of the architects (i.e., junior architect, senior architect, intern, etc.) to indicate the level or years of experience. Architects' profiles were reviewed based on the publicly available information to identify and extract contact details for potential study participants. The recruitment method was to reach out to each participant individually through their work e-mails. The e-mail included a brief explanation of the study, the role of the participants, and how they can contribute to the research study.

After the first three contextual interview sessions, the methodology had to be re-adapted for pandemic restrictions. Due to a transition to an online interview format, obtaining observation data, such as photographs, sketches, field notes, was not feasible. The lack of physical interaction with participants has been compensated through available online tools. The interview questions were designed to drive our discussion through available online tools. The interview questions were designed to drive our discussion through available online tools. The interview questions were designed to drive our discussion through available online tools. The interview questions were designed to drive our discussion through available online tools. The interview questions were designed to drive our discussion through available online tools. According to the initial inquiry, several participants shared images, screen captures, slide shows to enrich the interview sessions through visuals. Several participants showed their work settings, 2D sketches, and 3D rendered images in real-time during the video call. Furthermore, some participants shared visual documents via e-mail after the interview sessions.
4. Research Outcomes and Synthesis

My doctoral studies consisted of a literature review, exploratory research through design process, and an interview study. Each research approach contributed to unveiling the connections between physical and digital design platforms and their influences on the creative processes of architecture. The literature review (Gulay & Lucero, 2019) examined the existing works in the related fields that focus on the divide between physical and digital realms. Doing a review of the prior research also provided an opportunity to discover my research interests which gave shape to the following studies (Gulay et al. 2021; Gulay & Lucero, 2021). This chapter will present the notable findings of three studies and articles included in this dissertation, discuss the connections and outcomes.

4.1 Developing a Comprehensive Understanding of the Digital Realm with Material Knowledge (Publication 1.)

This section compiles and discusses the main findings from the literature review conducted during the first year of my doctoral studies, which is also the first publication (Publication 1.) included in this dissertation.

As initially discovered in the literature review (Gulay & Lucero, 2019), excluding architects’ physical engagement from design processes may not improve the design workflows or outcomes. The architectural design processes consist of idea generation, evaluation, reflection, and testing cycles. Reviewing the existing literature showed that design processes that rely solely on digital or physical techniques may hinder a more extensive understanding of the digital design platforms with the material knowledge (Gulay & Lucero, 2019). To exemplify, most HCI studies on physical prototyping depend on GUI-based design environments. The lack of physical engagement constitutes a non-iterative, linear
workflow. Hence, the focus shifts from the creative process to transferring digital files into fabrication machines for producing physical objects. One of the notable findings of the literature review is the critical role of material engagement for design exploration. Prior literature obtained during the review process point that even digital processes that simulate material properties or touch-based interactions may not be an adequate substitute for physical engagement. Physical materials embody generative features on their own, and they also provide accurate tactile feedback which may not be possible to obtain only through digital models.

The literature review (Gulay & Lucero, 2019) also identified design approaches that promote or allow interactions with physical design models and prototypes. The current digital fabrication machines do not support a real-time link with the digital model once a physical design prototype is produced. The physical object separates from its digital origins, and alterations on the materials do not influence the digital model. Thus, the design process mainly centres around the digital model and its completion before the fabrication procedures. As an outcome of the literature review, several real-time fabrication and design exploration methods have been classified as suitable techniques for re-establishing the link between digital and physical models. Each of these techniques simultaneously converts the physical alterations performed on an object to rebuild digital models. In the review, the bidirectional fabrication (Weichel et al., 2015) and computational building blocks (Anderson et al., 2000) method have been highlighted due to their implementation of 3D scanning technologies. Both methods utilize a rotary table setup to enable real-time digital geometry reconstruction based on the manual rebuilding of models in the physical design space. The bi-directional fabrication approach supports non-linear modifications on objects, whereas the building block approach is suitable for relatively more primitive geometries. Prior research demonstrates that 3D scanning may be a potential area to investigate an intuitive design environment that mixes both physical and digital design procedures.

Examining the existing literature concerning the role of physical engagement and potential implementations formed a theoretical basis for the exploratory research through design (RtD) process, which became the second article of this dissertation (Publication 2.) The literature review process started with the assumption of a divide between physical and digital realms in a design process. Findings of the review pointed that different approaches also interpret the
physical-digital separation in different ways. For example, some HCI research on tangible user interfaces understands this divide as digital and physical object manipulation. On the other hand, research on automated and robotic fabrication addresses the issue from a wider lens by re-integrating physical models as explorative design tools into digital design processes. One of the common grounds of relevant works is the necessity to integrate physical and digital design workflows. The physical-digital divide is an extensive area that continues to develop in HCI and architecture literature through new concepts, methodologies, and technical advances.

### 4.2 Physical mock-ups as exploratory design tools (*Publication 2.*)

Section 4.2 presents the notable findings from the research through design (RtD) study conducted during the second year of my doctoral studies, the second publication (*Publication 2.*) introduced in this dissertation.

One significant finding of the literature review was that the existing physical-digital conversion methods do not offer adequate support for non-linear geometric operations. In some cases, the issue is related to limitations inflicted by the digital hardware or software solutions. As elaborated in previous chapters, the feedback-oriented design process began by producing a range of mock-up models based on three folding strategies. The idea of initiating the design process by creating mock-ups was inspired by the material engagement framework proposed by Poulsgaard and Malafouris (2017). Design processes develop incrementally and usually originate from rough concepts. The second article examined the conception of architectural ideas by using simple and widely available material, paper. The paper folding activity played a central role in the design exploration stages and resulted in 42 design ideas for a multipurpose structural system. The mock-ups were produced on a table surface with conventional modeling tools (i.e., modeling knife, rulers, drawing pen, etc.)
Utilizing paper as an ideation tool enabled an intuitive design space allowing material engagement by the physical constraints and forces.

The paper-folding procedures provided surprising outcomes and unveiled new design potentials. Material properties and the flexibility of the physical design space may have a role in generating unexpected results. Although paper as an exploratory material has its inherent limitations, an extensive number of design operations can be executed by altering its shape (Figure 6.)

Material properties are a significant element in physical form exploration. However, the intuitive aspect of the design process stems from the designer's direct engagement with a particular material. Material engagement supports architects to comprehend a structural system physically while developing initial ideas by obtaining real-time tangible feedback regarding the physical conditions.

At the second stage of the investigation, 3D scanning technologies were tested and implemented as a physical to digital translation method. 3D scanning outcomes showed that current scanning technologies have the capability to form a more intuitive design environment by expanding material and modification
opportunities. Older generation point-cloud data gathering technologies (i.e., Kinect) may not accurately convert physical objects to digital models. Lower accuracy 3D scanned surfaces require a significant rebuilding in the modeling software. On the other hand, more recent scanning (i.e., structured light scanner) setups incorporating high-resolution cameras and sensors provide precise details when capturing material information. 3D scanning tools are continuously improving and becoming more applicable for architectural design processes. However, the physical data is essentially the visual information captured by a camera. The 3D scan data does not contain information about material characteristics and performance. Curved folded paper surfaces captured during the 3D scanning operations confirmed a hardware-related limitation. As an outcome of a lack of material data, the digital optimization process relied on physical conditions simulated in the digital design environment. Yet, scanning tests demonstrated the applicability of the 3D scanning technique to create an intuitive design space, where the designer can apply manual design skills alongside digital software knowledge. The ability to integrate traced paper mock-ups into digital software facilitates physical engagement with design prototypes and has valuable potential for future implementations.

The last stage of the RtD process concentrated on re-establishing the physical engagement with the mock-up models by employing digital simulation and fabrication technologies. Although the 3D scanning method afforded a flexible design environment by allowing physical alterations without material constraints, the divide between digital and physical processes became apparent once the translation process was complete. At this point, the focus of the design process shifted to the digital file rather than the physical models. The digital simulation process allowed testing physical conditions by assigning different material properties to a surface geometry derived from the paper-folding activity. The digital feedback was provided in the form of visualizations on the surfaces of 3D geometries. Obtaining structural performance data enabled examining various materials without the need for physical testing, hence, saved from time and costs. Observations throughout the digital optimization and simulation processes revealed that detaching digital models from their physical counterparts may hinder exploratory operations. Material engagement presents numerous design opportunities through direct physical alterations. The point to be emphasized is not the abundance of design possibilities but the interactive process that enables concentration, observation, and reflection: an essential
advantage of utilizing physical prototypes alongside parametric design exploration tools.

Structural issues found during fabrication and assembly procedures, the final stage of the study, demonstrated why structural systems need to be tested and apprehended physically from early design stages. Although curved folded geometries were investigated and optimized under simulated physical conditions, recreating the conceptual models with sheets of plywoods required physical modeling skills and an understanding of the material behavior through hands-on interactions. Digital simulation procedures provide results based on the entered parameters and assumptions about the physical conditions. However, as demonstrated in the initial paper folding, fabrication, and manual assembly processes, the physical outcomes may not match the digital simulation results.

The choice of curved folding as a case study for experimental study was made due to its potential for creating complex geometric forms and structural systems using a simple material and a limited number of folding strategies. The curved folding technique allowed for the exploration of non-linear geometries that are difficult to achieve through traditional modeling methods. The experimental study demonstrated the value of physical mock-ups in exploring and generating new design ideas, as well as the limitations of current digital scanning and simulation technologies in capturing the full range of material characteristics and performance. The findings of the study highlight the importance of physical engagement with design prototypes, alongside digital simulation and optimization tools, for achieving better design outcomes.

The use of physical mock-ups and curved folding techniques in design can offer several benefits to the field of human-computer interaction (HCI). This approach highlights the importance of physical interaction and material engagement in the design process, which can lead to more intuitive and engaging user experiences. HCI requires user-centered design and usability, making this approach particularly valuable. Moreover, using physical mock-ups and an iterative design process can help to reduce the time and costs associated with traditional design methods, while enabling designers to develop more complex and innovative designs.
Moreover, the integration of physical and digital tools and techniques provides a valuable opportunity to explore the strengths and limitations of each approach and to leverage the unique affordances of both. This can lead to new insights and design opportunities that may not have been possible using either approach alone.

Finally, the study's focus on non-linear geometric operations and the limitations of current physical-digital conversion methods has implications for the development of new tools and technologies that can better support these types of design processes. This research contributes to the ongoing dialogue within the HCI community regarding the importance of physicality and materiality in design, and highlights the potential benefits of integrating physical and digital tools and techniques in the design process.

4.3 Current Idea Generation Approaches in Physical and Digital Design Realms (Publication 3.)

This section sums up the notable findings from the research study consisting of 3 contextual and 12 online interviews conducted with practicing architects and experts from leading companies and research units in Finland, Switzerland, Germany, and the UK. The section also introduces relevant findings that were not discussed in the publication. The interview study is a part of the third article included in this dissertation (Publication 3.)

The third study looked into the current idea generation methods in architecture. The first interview questions investigated various starting points to an architectural project. Interview statements suggested that developing a conceptual framework is a fundamental element of the initial design processes in architecture. Architects examine external factors such as the construction site and topology, environmental conditions, and scale. The opening questions of the interviews aimed to obtain information regarding the different procedures architects follow at the beginning of a project. Consequently, two distinct design strategies, classified as parametric and visual approaches, have been identified. A parametric design approach considers the social, economic, environmental impacts of the building from early stages. Interview statements indicate that, in a parametric process, the shape of a building develops in later stages after defining parameters. To exemplify, one of the participants describe the process through an existing project as follows:
"An example would be the X project, it’s a cable net, and we decided that it's going to be a quad network so that you have cables running through in two directions. That means you wouldn't have nodes where you have three or five cables coming together. So it's a very balanced mesh. That's one of the starting points. We'll come up with a design for it, but it has to be within these parameters."

Accordingly, in the parametric approach, the starting point is not the geometry. Geometric operations are executed within the parameters determined at the beginning of the design process. Hence, the parameters need to inform the geometry that develops throughout the design process. Another initial design process is a visual approach that involves aesthetic decision-making alongside programmatic considerations. In the visual and spatial design approach, the process also comes from the program. However, there may not be an intertwined relationship between programmatic parameters and the form of the building. One of the expert participants argues that architects make aesthetic decisions all the time: "Even if somebody says that they only solve the problems and what we are doing is not an aesthetic thing, it definitely is. We produce something physical, and then you think about the aesthetics. There are aesthetics in everything you see, feel, and smell." All participants’ statements imply that there is a creative contribution of the architect to the design outcomes.
Regardless of their fluency in digital design software, all participants utilize pen and paper sketching for formulating initial design ideas (Figure 7.) In several cases, tangible mock-up models are also produced to test design ideas in the physical space. The interview findings show that pen and paper drawing is perceived as an uncomplicated interface to express rough concepts on a planar surface by using physical drawing skills. Drawing sketches do not require any technical skills, and the interview data shows that most architects acquire essential drawing skills as part of the architecture training.

On the other hand, physical modeling is mainly employed to create a tangible 3D embodiment of conceptual ideas, understand the physical conditions, and conduct structural tests. Some theories consider mock-up modeling processes a form of 3D sketching in the physical design space. The second article of the dissertation (Publication 2.) also demonstrated that physical mock-ups facilitate complex non-linear explorations and offer an intuitive design environment. Yet, the interview outcomes indicate that, currently, utilizing mock-ups as idea generation tools may not be a common practice in architecture. Physical mock-up modeling is practiced predominantly for testing purposes during the initial design stages. However, participants also state that such testing models also embody exploratory qualities, which shows that mock-
ups are used as part of the idea generation process and can inform the design decisions.

Architects apply their manual skills and digital design knowledge in various stages of an architectural project. Study outcomes show that practicing physical sketching and model-making techniques is valuable for forming, expressing, and experimenting with early design ideas. Participants think that the current digital drawing tools do not offer an adequate substitute for the pen and paper drawing practice (Figure 8.) Current tangible user interfaces and digital simulations also do not provide sufficient feedback to understand complex structural systems physically. Many participants produce physical scale models or conduct full-scale tests before constructing a project in the physical space. Study results confirmed that physical models are indispensable tools for testing structural systems, especially when the design involves non-linear complex geometries. As observed in the previous studies (Publication 1., Publication 2.) of the thesis, physical models can only provide limited information about the system.

At this point, depending on the proficiency level, digital design tools can both support or limit a design process. An experienced architect explains as follows: "If you ask my managers, they would say that digital tools are restricting, and they think that those tools take too much time for you to learn them, and that..."
Research Outcomes and Synthesis

takes time from your design skills and concentration on the design. Yeah, but at the same time, we need them." Participants proficient in digital software view the physical methods as time-consuming, whereas architects who are skilled in physical techniques think the other way around. The interviews also unveiled that most architects do not receive sufficient digital design knowledge during their academic training. The majority of the participants, even the comparatively recent graduates, developed digital design skills after completing their architectural education. Although digital design training is becoming more widespread among educational institutions, the graduates acquire additional skills later in their professional careers.

4.4 Creating Intuitive Design Spaces for Architects

The previous sections briefly summarized the most notable findings of each study. This section clarifies how the three research processes connect. I also introduce ideas for establishing intuitive workflows in the initial design stages of architecture. The insights and outcomes of this dissertation can assist architecture companies, software developers, designers from other domains, and HCI researchers working on tangible and interactive systems. The thesis is aimed particularly at designers that are not digitally native. However, the findings may also support diverse design professionals, students, and educators working with digital tools.

Over four years, cumulatively, this research has acquired new knowledge through a literature review, an RtD process, and an interview study. The literature review started with a hypothesis that there is a gap between physical and digital design processes, and the separation can be narrowed by integrating physical and digital design processes. All three research processes pointed that the ongoing digitalization influenced the ways architects engage with their design physically. One causative factor to the divide between physical and digital design workflows is the changing functions of traditional manual techniques (i.e., sketching, model making, 2D drafting, etc.) Each research process highlights that, with the extensive adoption of digital technologies, some physical design workflows are substituted by digital procedures. Digital design tools provide cost and time-effective solutions in an architectural design process. The feedback-oriented design process (Publication 2.) and the interview study (Publication 3.) have unveiled that both physical and digital techniques possess limitations and opportunities in different design stages. In the initial design stages,
rough design ideas take shape. It is crucial to evaluate the constrictions and the impact of physical and digital design tools on the design intent.

The first main research question of the thesis focuses on the integration of physical and digital design platforms to create more intuitive design experiences for architects. Concerning the initial research question, in the literature review, 3D scanning was identified as a potential method to achieve an intuitive design space. The idea was tested by utilizing research through design (RtD) approach. The interview study also supported a need for an intuitive design platform where architects can receive real-time material feedback during the digital design processes. Most architectural design software operates within GUI paradigms, which creates a clear separation between the physical and digital models. GUI-oriented computer-aided design systems need to be enriched with the implementation of TUIs to create more intuitive design experiences. However, current TUI systems focus on replacing material engagement with technological solutions rather than capturing the physical activity, generating a real-time feedback cycle. An ideal digital design process should recognize the physical design techniques architects employ and continuously adapt the digital model based on the physical feedback obtained through material interactions.

The interview study showed that skill levels of architects are a determinant when deciding which physical or digital tools to apply during initial design processes. Several works in HCI literature tackled the issue by proposing design environments and tools set up for testing the concept of connecting physical artifacts with digital models in real-time. Intuitive experiences entail familiarity and ease of use. Existing approaches improve the current digital design environments by introducing physical interactive systems. However, there may be more research needed to address the familiarity aspect. To illustrate, in the second process of this research, the feedback-oriented design process adopted a rotary table setup for examining the conversion of physical feedback into the digital design platform through 3D scanners. When adequate lighting and scanning conditions are provided, 3D scanning technology can trace the physical alterations on mock-up models accurately in real-time. Yet, the interview findings suggest that architects may not operate in fixed table setups, such as a rotary table setup. There is a need for technology and software development beyond the current GUI paradigms, for simultaneously capturing physical design operations and feeding the tangible information back into the digital design platforms in-real time. A significant limitation of the 3D scanning technique is that
the physical objects are converted based solely on visual data. The image capturing technology embedded in 3D scanners offers the potential to provide a design space where architects can utilize physical and digital skills based on their proficiency level. However, visual information alone contributes only a limited amount of feedback regarding material properties and physical conditions. The existing research demonstrated the feasibility of implementing proxy technologies and tangible tools that obtain material data. Combining the image capturing techniques with physical instruments that provide real-time feedback is a potential area to explore for future research and technology development. As the interview process also pointed, when developing intuitive design systems for architects, it is crucial to comprehend the current practices and tailor the user experience accordingly.

Both the RtD process and the interview study supported the initial hypothesis of the dissertation formed during the literature review process regarding the separation between physical and digital design processes. As interview participants also expressed, there is a need for more fluid design workflows. Even the most advanced digital simulation software may not precisely predict how a structural system will behave under physical circumstances. Consequently, receiving physical feedback by producing mock-ups and prototypes can enrich digital design processes. Architects’ physical involvement through sketching or model-making remains an essential intuitive element of design workflows despite the modern computational capabilities. Current digital design solutions do not facilitate material engagement or integrate physical procedures architects go through to obtain tangible feedback. In response to the second main research question of the thesis, the study results showed that physical mock-ups allow quick testing and materialization of early design concepts. Testing the early ideas can prevent costly mistakes and inform digital design workflows. An interview participant’s description illustrates this finding as follows: "In the Project Z, how these tiles are put onto this free-form shape was tested out in a 1:1 prototype. There you notice what can go wrong and what you need to take care of before starting the real installation of the tiles. So in that sense, you save time, and you get a better result when you have tested it.” Integrating physical mock-up models can supplement the digital design processes by validating the findings from digital 3D models or physics simulations. Moreover, physical mock-up models also provide an opportunity to understand structural systems physically while at the same time allowing hands-on design exploration and material alterations.
Recent parametric modeling tools offer generative design processes that can lead to numerous design solutions. Study outcomes show that the quantity of the design options may complicate the process rather than provide support. Interviews with architects pointed that most digitally generated designs are not used in a project, and these options also create confusion due to excessive information. Physical mock-ups help stabilize a complex design process by supporting architects to focus on one design concept at a time rather than choosing one among numerous options. As materials hold generative qualities, a direct physical engagement also unveils design opportunities that may otherwise go unnoticed in the digital realm. Consequently, model making can be considered a more exploration-oriented approach when compared to digital form-finding processes that focus more on decision making and optimization.

It is necessary to communicate the differences, advantages, and shortcomings of operating in physical and digital realms during the early design stages. The interview findings suggest generational differences between architects that influence their attitude towards physical and digital methods when producing preliminary designs. More importantly, the interviews show a lack of sufficient digital design training in academic teaching. Many institutions provide basic digital design knowledge such as 3D modeling or pure software training. A revised teaching approach integrating existing conventions with the latest digital design techniques can equip students for the ongoing digitalization course in architecture. Furthermore, implementing additional training programs in architectural offices and academic institutions may support architects to distinguish which physical or digital tools to implement when developing early design concepts.

The table below (Figure 9.) provides a summarized overview of the main contributions of the articles included in the thesis, current limitations and potential open areas for future research:

<table>
<thead>
<tr>
<th>Main Contributions</th>
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<td><strong>Publication 1:</strong> The study identified a need for an integrated workflow combining physical and digital design procedures and proposed a cyclical approach.</td>
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</table>
Publication 2: The study found that a feedback-oriented design process that integrates iterative physical and digital models with user feedback can facilitate creativity and exploration in design while also enabling designers to refine and validate their ideas.

Publication 3: The study found that physical techniques were more frequently used than digital ones in the initial design processes of architecture, and that physical techniques facilitated exploration and iteration of design ideas, while digital techniques were preferred for representation and communication of design concepts.

Limitations

- The effectiveness of intuitive workflows in complex and dynamic systems is still an open question.
- The role of emerging technologies such as AI and machine learning in creating intuitive workflows has not been explored extensively.

Open Areas for Future Work

- The extent to which intuitive workflows can be automated needs to be examined.
- There is a need for more comprehensive guidelines and standards for designing intuitive workflows.
- The impact of intuitive workflows on user engagement, satisfaction, and retention needs to be further explored.

Figure 9. An overview of the main contributions, limitations, and future work.

4.5 New Vision and Touch-based Technologies and Future Implications for Architecture

Throughout the thesis, the main argument centered around overcoming the shortcomings of digital design environments through manual model making and direct engagement with materials. It is worth noting that this thesis does not necessarily endorse re-adopting traditional methods or disregard the substantial role of digital design tools. The main takeaway is developing intuitive digital design technologies with the insights gained from long-lasting physical practices. The embodiments of this idea have materialized in research and commercial applications in recent years.
The earlier theoretical background sections briefly touched upon the recent developments in immersive technologies (i.e., AR, VR, MR). In addition to vision-oriented technologies, the latest research in haptics offers considerable potential to simulate real-world interactions in the digital realm. The sense of touch is one of the modalities that the ongoing technological developments target, alongside vision, smell and hearing. Ideally, an immersive and intuitive digital environment would stimulate multiple senses, but most existing technical solutions focus primarily on the visual feedback. Vision-based technologies, such as head-mounted displays (HMDs) for VR, AR, or MR applications, created a natural inclination to establish tactile contact with digital objects. As a result of the growing research and development interests in touch-based interactions, today, it is possible to see numerous innovative techniques that aim to bring the physical and digital worlds closer. In the HCI literature, the most prominent ideas can be listed as follows: a) Providing mid-air haptic feedback via ultrasonic transducers. b) Simulating textures via electrostatic or vibrotactile feedback. c) Connecting human intention with computers through wearable technologies (i.e., muscle-computer interfaces, haptic gloves, and suits) d) Utilizing tangible proxies to manipulate digital objects. Although the itemized techniques can improve interactions with the digital realm, they have not been used extensively in architectural design processes.

For the architectural practices, some of the latest technological concepts, such as mid-air haptic sensations for virtual reality (Marchal et al., 2020), wearable physical proxy (Jiang et al., 2021), and tactile texture rendering (Otake et al., 2022) are among the most promising advancements. The links between VR, AR and MR environments and the commonly used 3D modelling software can pave the way for such techniques to be integrated into architectural design processes. Immersive technologies, such as VR headsets have already been utilized in conjunction with haptic data gloves for training simulations by various industries.

Despite the existing robust vision and touch based technologies, a wide spread adoption has not been achieved yet. Two major factors may be contributing to the slow adoption of the immersive vision and touch-based technologies. First, most solutions are still relatively invasive for daily use: For example, commercial VR headsets and haptic gloves can be uncomfortable to wear for extended simulation experiences. Secondly, as articulated throughout this thesis, a comprehensive understanding of how people interact with their physical
environments may be necessary. The three processes of the thesis, anatomizing architects’ connection with the physical space, can be utilized to extract insights and aid the conception of new ideas for vision and touch-based technologies.
5. Appendix
5.1 Visual Data from the Exploratory Study (Publication 2.)

FOLDING STRATEGY A – Connecting the edges of two curved lines
- Shortlisted designs are highlighted with green frames.
FOLDING STRATEGY B - Arranging parallel curved lines with similar of different radius

- Shortlisted designs are highlighted with green frames.
FOLDING STRATEGY C – Combination of both types of curved lines

- Shortlisted designs are highlighted with green frames.
Rotary Table Setting for 3D Scanning
Initial Scanning Outcomes
5.2 Example Interview (Publication 3.)

Interview 3

Interviewer [00:00:40] Thank you so much for accepting this request and taking your time. How long have you been working as an architect in the industry?

Participant 3 [00:00:49] I started to work already in 1997 as a student in an architect's office. In fact, the first office I went to work in was already in 1995. As a first-year student. But then in 97 I went to work for X's office. And from that point on, I've been working quite, almost all the time.

Interviewer [00:01:18] So how long have you been working in this office?

Participant 3 [00:01:22] I have been working since 2004. And then I was away for about four years when I did my PhD.

Interviewer [00:01:31] So that was more of a process that you wanted to learn more about the profession?

Participant 3 [00:01:36] Yes. Yes, I was interested in what affects design decisions. That's why I decided to approach the question through the concept of esthetics, which I used in my thesis.

[00:01:53] Yes, very interesting. What I'm interested in this research is the initial design processes actually maybe it also touches on the topic that you're interested in that sense. And I'm wondering, when you start a project, how do you go about at the beginning and how things work in the very initial phase?

[00:02:16] Well, I think well, first you study kind of all the facts and information you have about the design task and then.... Well, yeah, that's one point. For example, now at the moment, I am working on the design of the new National Museum. It's based on a winning competition entry. So in that competition brief, we had a quite good description of the design task. And also a description of the site and all the
functional demands and what the museum wanted from the new extension. So in that case, what you started with is to get into the... Kind of start processing all this kind of basic information you have to start with.

**Interviewer [00:03:24]** Does this starting point help to develop the design concept further?

**Participant 3 [00:03:30]** Well, of course, you need to adjust the design to all the demands in a way that’s one thing. But then I think what is quite important is that when you develop the concept is that you need to have something plus. That’s what we can give as an architect and designers. We can give them content that goes beyond what's given in the starting point. I think we [work to] get the most of the new building.

**Interviewer [00:04:14]** So understanding the architectural program I think is a significant starting point.

**Participant 3 [00:04:20]** Yes. You have to understand the program and also to understand the site, the location and the kind of them ....what they call... Kind of the spirit of the place. And how you want to develop that place. For example, I worked for several years with Amos Rex art museum. And there, it was very important to consider the impact of the new building on the whole city structure. And we wanted to both change the city in that spot, and then in a way, also kind of preserve the valuable things in that area. So I think the site is very important.

**Interviewer [00:05:14]** The spot is also very central, very important to Helsinki. When you were starting to Amos Rex project, how did you start expressing your initial ideas? Or was there any process that, you followed within an agenda?

**Participant 3 [00:05:35]** Well, that case. In the really early stages, we simply put the spaces. Well, we studied also there, for example, the existing building and the surroundings. And then we placed the functional program on the site. And in that case, we knew quite early that the new museum needed to be underneath the square because the old building was protected. Lassipalatsi building is very important as kind of a modernist monument in Finland. So we realized that we can't put a contemporary art museum in the old building. So that’s why it's under the square. But then, we developed this idea that we wanted the art museum to be present on the square. And that’s why it kind of rises up, so you can also see it outside. Because we didn’t want to kind of hide it under the square.
Interviewer [00:06:46] So it was sort of a way of externalizing that.

Participant 3 [00:06:52] And in a way, also, it's in line with the functionalist or the modernist kind of approach to architecture where you show things as they are. So what do we do in the Amos Rex is that you show where the exhibition spaces are underneath the square. For example, the biggest hill underneath there you have the biggest dome in the exhibition hall. So it's kind of transparency with kind of a logical approach to architecture.

Interviewer [00:07:29] So the exhibition spaces, did they sort of shape the building?

Participant 3 [00:07:36] Yes, yes. Yes, very much.

Interviewer [00:07:41] Since we talked about the esthetics of the building, I'm wondering how have you been designing the form of this project?

Participant 3 [00:08:01] Well, then it's in a way the shape comes from the exhibition spaces and the demands. And the function... In a way, they stem from these functional demands from the exhibition spaces. We wanted to have a certain... Well, the exhibition halls are divided into three main areas which are all different in size. So these three spaces you can see them on the square. There are three hills which are different sized. So but otherwise it's kind of quite a free shape which we have studied quite a lot with 3D modeling. And so the shape of the hills was studied very thoroughly in the 3D world. And then, of course, after later on, we also had real 3D models. Physical models. Yes. We worked quite a lot with both digital and physical models.

Interviewer [00:09:18] So both ways of working kind of contributed to the form shaping and volumetrically exploring this space.

Participant 3 [00:09:30] Yes. Yes. For example, in Amos Rex the biggest hall was quite a lot bigger in the earlier phases of the project. And then there were some technical pressure to make it smaller. And then also we realized that... Although we didn't notice it on the drawing board, then when you start to look at the 3D model, it really looked huge, the biggest hill. So now, in fact, when it's smaller, it's better.
Interviewer [00:10:07] How does this decision-making process work? Do you work as a team?

Participant 3 [00:10:12] We work as a team and depending on the project there is one head designer, lead designer. And in the Amos Rex project that was one of the partners of JKMM. There my role was... We had two what we called project architects who lead that kind of the actual drawing. I don't know how you would call it. So I was kind of the project architect of the new museum part which is underground part. And then we had one project architect who was in charge of the restoration of the old building. And she's very... Her name's Katia Savolainen and she's very talented, has very long experience of this restoration of old buildings. So and then we had several other people in the team, in total perhaps around eight persons who were involved in the project. And then depending on the phase, we were not all the time working, perhaps from four to eight [working hours] depending on the phase.

Interviewer [00:11:34] It's interesting to sort of... Because it's a building project and I think it's very interesting to use this as an example. Is this [process] working in every project like this?

Participant 3 [00:11:49] Basically, yes. Also, we will have the same kind of team in this new National Art Museum project. So there X is a lead architect and he's also a partner in X. And then I'm the project architect. And then we have, at the moment, only one other person. Well, you met him. So we're at the moment only three persons in the team. I think the decision making is... We have a very open atmosphere so that everybody kind of contributes by telling their opinions, their viewpoints. Sometimes, if we have very different opinions then it's the lead architect who can decide in what direction we continue. I think that's in a way necessary. Perhaps architecture can't be a totally democratic process because people have kind of different opinions.

Interviewer [00:13:07] Could this be also because of the level of abstraction that you're working with?

Participant 3 [00:13:17] I don't know. Perhaps not. I don't know. Well, it depends perhaps on your experience as an architect. If you can kind of see the whole the different levels of abstraction kind of in your head, you are thinking about a project. Because there are very detailed technical considerations that affect the whole project. And still, we are, for example, now it's a quite interesting phase we are now working on, at the very beginning of this national museum project. Although are the whole
layout of the building and the concept, it's quite on an abstract level yet. But then the whole time, we were kind of also going very deep into the details. And then we just then again, you go up to the main concept because you need to kind of control the details in order to get what you want in the end.

Interviewer [00:14:29] I'm wondering, for instance, about the effort you spend during that time. How is it clustered like from the beginning of a project until the end in terms of effort and time?

Participant 3 [00:14:45] I don't really have the statistics. I know how much time you put on which phase of a project. Well, in the end of the project, when you're supervising the building process, the actual building, Then it's a lot of less work. Most of the time compared to when you [start]. Well, when you start with a project and then decide it's good to have the design team small. Because then, you know it's difficult to kind of split up the tasks in the beginning of the project. You need to know. Everybody that works in the projects needs to kind of in a way, have knowledge of the facts so that they can kind of work, do their initial design. So it's good to have a small team in the beginning, like we are now in the new national museum, three persons. That's quite ideal. And then later on when you start to come to this building permission phase and then you do that kind of the technical drawings, then you need more people and then it's easier to divide the tasks also.

Interviewer [00:16:21] So there are several kinds of processes. I think the drawings that you're producing in the beginning and the later processes are also different in that sense.

Participant 3 [00:16:31] Yeah. Yeah. So it takes quite a lot of time to do the technical working drawings with all the kind of definitions that are needed for the building so that they can be built.

Interviewer [00:16:58] How does your early academic training influence your current practice in the company?

Participant 3 [00:17:07] I think it influenced quite a lot because I was working a lot with... Or in my study studies. I had the building design which was my main theme and I did kind of public building design and housing. So in that way, in my work, I just continued what I've started in the studies. Also, I worked during my studies from the third grade onwards. So I had constantly this kind of connection to the office world.
Interviewer [00:17:53] And how did it shape your approach towards the initial design process, this early education?

Participant 3 [00:18:01] Yes, I think it’s shaped very much. I was fortunate to have in the freshman year, Juhani Pallasmaa as my professor in architectural theory. And he was so... There we really moved on quite abstract levels and a very conceptual approach to architecture. And I think that has influenced me very much. And I also, later on, read quite a lot of Pallasmaa’s text. I agree with him on most things. I think that has formed [my practice] very much. But also I think because I worked at X’s office and he was a professor in housing design. He has quite a different approach than Pallasmaa. He starts much from very functional things and technically very precise designs. So I think that influenced me also quite a lot. At the office they had quite a strict kind of what we call "laatujerjästelmä", kind of a quality control system in the office. So very strict rules about how you draw and how do you use the AutoCAD programs and so forth. So I think in an office work it is quite important also to have quite well-defined rules of how we work and how you use the different computer programs.

Interviewer [00:20:11] Did you learn using these computer programs during your school years?

Participant 3 [00:20:16] I guess I’m quite old. I studied in the 90s and then at that time AutoCAD came to schools, to the universities. And so, I learned to draw in AutoCAD in the university. But for example, I did my master’s thesis by hand. It was kind of a changing point at the end of the 90s, beginning of the year 2000.

Interviewer [00:20:53] It was becoming more widespread.

Participant 3 [00:20:56] Yeah, but after from 2000 onwards, I used computer programs in the offices.

Interviewer [00:21:13] You have a lot of experience in this office and in other offices. When you look at the younger generation who are becoming architects recently, how do they approach the initial design processes and how do they use digital tools, for instance?
Participant 3 [00:21:28] Well, of course, they know how to use digital tools. Let's say that that's a way of working in the universities already, that you produce quite a lot of renderings and computer drawings and nobody draws by hand anymore. So, of course, I think it affects the way you understand or approach the design in the beginning. Do you do it with a computer or do you just do it by hand? It’s simple. When you do it by hand, you don't. You're quite free to do whatever.

Interviewer [00:22:24] In terms of design space.

Participant 3 [00:22:27] Yeah. Yeah. Because it's so easy to just... You take a new paper and then you start again.

Interviewer [00:22:37] Which of the design skills and knowledge do you still use from your early academic training? Do you have specific sort of skills and knowledge that you still use?

Participant 3 [00:23:08] I think I'd like to draw by hand, to exemplify it, do a floor layout and think about how the spaces are right. Start by doing it drawing by hand and then after that, I do it with the computer. But then again, for example, I don't do so much kind of 3D sketches by hand. I don't do perspectives by hand. I think during the studies we had quite a lot of drawing and kind of artistic courses as well. But I don't really draw in that sense so much anymore.

Interviewer [00:24:03] What are the advantages of, for instance, using these drawings and doing quick sketches?

Participant 3 [00:24:09] Well, the first computer kind of you can visualize the building when you do sketches. I think when I'm drawing through 2D world, then I kind of imagine how they are in 3D. But in my head without drawing them. So if you see a floor plan you kind of rethink how you move in the space.

Interviewer [00:24:45] Plasma also has a very interesting point that we project our own bodies into scale models or drawings while exploring.

Participant 3 [00:24:55] Yeah. Also do that quite a lot. What I do also is that I imagine the situation in reality. For example, we have been thinking about the size of the
main lobby in the new museum. So I have kind of a very long measure [measuring tool]. So I put it here. We have been measuring here in the office. For example, we have now the main entrance lobby. It will have a six-meter-high glass wall. So we took the measurement [tool] and we started measuring here in the office how high is six meters physically just inside. It's really quite a high glass wall. And I like to do that so that I take the measure and then I start to measuring here for example, the office space, it's about eight-meter wide. So then you can imagine, ah, I have this much space in the lobby if it's eight-meter wide. Well, yeah, I like to do that.

Interviewer [00:26:07] Trying to understand the three-dimensionality of your own designs basically.

Participant 3 [00:26:14] Yeah. Yeah. You start to kind of imagine. Or we can simulate the situation of two people meeting in a corridor. So then you take two people and then you think, oh, is this enough space to really meet without feeling awkward if you're really close to somebody you don't know in a corridor for example.

Interviewer [00:26:46] I want to learn what is the role of the digital tools in the initial design processes especially?

Participant 3 [00:26:55] Well. We used here at the office quite a lot of 3D because we have ArchiCAD and it's made to have a three-dimensional [drawing]. So now although for the new National Museum, we are in a very early stage of the project we are already working in 3D model in the ArchiCAD. It is quite a wonderful tool because you have a three-dimensional space, but at the same time, you can have a very precise 2D drawing.

Interviewer [00:27:31] So it's integrated.

Participant 3 [00:27:32] It comes from the same motto. So we use that really a lot. And now in the project, we are very soon going to receive quite precise, a measured model of the existing national museum and all the small buildings that are on the lot. So then we can really study in this 3D world how we connect to the old buildings from the new building. So in that way, the digital work model and way of working is really very helpful. It gives a lot of possibilities.
Interviewer [00:28:22] Do digital design practices, especially in recent years, do they somehow influence the way you approach the initial design processes? How do they influence in any way?

Participant 3 [00:28:36] I think they influence in the way that you can really try out different options like in the Amos museum. We could really try out with these digital shapes. What you could fit in, for example, in the Lassipalatsi square? Because of the renderings and images you get from it, they really are very informative about space and what kind of possibilities you have to use the space in 3D. So I think it has really a lot of possibilities and in a way, in a good way [it] affects the design.

Interviewer [00:29:29] What would you say about the offices who are kind of resisting the digital and try to do things in a more traditional way?

Participant 3 [00:29:38] I would say that the digital... It's good but it's kept as a tool. It's kind of a tool. It's a working tool to design. For designing It's not kind of the goal in the end. But of course, good architects can also in traditional ways by drawing, for example, by hand, if they are good, they can imagine the situation. You don't need to put it all into a computer program.

Interviewer [00:30:21] So basically, it just acts as an aid to enhance the process.

Participant 3 [00:30:28] Yeah, yeah. To kind of try out different options.

Interviewer [00:30:32] What are some of the limitations that you're experiencing while using these digital tools currently, in the case of ArchiCAD for instance?

Participant 3 [00:30:43] Well, for example, free shapes. Like in the Amos Rex, the hills and this kind of very free-flowing shapes are impossible in ArchiCAD. Then we use Rhinoceros and then everything is possible there. But these two things work together quite well. So we take from the Rhino model, shapes and take them to the ArchiCAD.

Interviewer [00:31:18] The working mechanisms of this two software are quite different. You have to understand the algorithmic logic in one software. Do you work with a lot of parameters in Rhino when you're working?
Participant 3 [00:31:37] In fact, I don’t work with the Rhino. But we have very talented people in the office who work with that and they can do anything with it. For example, at the beginning of projects, I work quite a lot with those who do that kind of graphic images in the Rhino. For example, we do images of the sketches in Rhino and Photoshop quite early on in the project so that we study what looks good.

Interviewer [00:32:33] Interesting. Is there something you miss when you’re working with the recent digital tools? Is there something you missed from the past?

Participant 3 [00:32:47] No, not really. In the ArchiCAD, it makes possible in the 3D and doing working drawings. It’s so much better than it used to be when you are in the AutoCAD and the 2D world. It’s really great. I really like ArchiCAD. I was talking at there. They were launching this new ArchiCAD version a year ago. I made kind of a speech there where I had to say in the end that I love ArchiCAD. Organizers were really... They liked me.

Interviewer [00:33:38] Can you tell me a bit about the role of non-digital design methods or anything that you still do by using non-digital tools? This could be physical tools or this could be sketches...

Participant 3 [00:33:53] Well, I like to sketch, for example, floor layouts. Then I use a pencil and sketching paper and I try in that way the layout of the rooms. But then also what I do for handle [reffering to the staircase handle]. Always I’m counting things when I design the staircase, for example. And then I simply counted on small pieces of papers. So then you get it kind of right. You don’t need to use the computer or anything.

Interviewer [00:34:38] Do you use any other physical techniques?

Participant 3 [00:34:48] Well, the measurements of the space. That is quite physical. In the office, we try out with 3D physical models, so I can show you, for example, that we have a workshop where we do the models. For the Amos Rex, for example, we have done a 1:1 model, kind of a prototype for quite a lot of things. For example, we design this kind of technical units that are in the exhibition spaces’ floor. So we did kind of really a 3D one to one prototype for this floor unit. This Is, just one example. Then we did 1:1 prototypes for the concrete tiles that are on the square. This spinner shaped tile. And then there’s we tried out different details, shape, size of the tiles.
Interviewer [00:36:05] How did these 1:1 prototypes help you during the process?

Participant 3 [00:36:13] Well, if you want to design a new product that we did, for example, for the floor unit in the museum space, I think the 1:1 [physical] model was the only way to do it. Because in the this floor unit we integrate these technical components. It was kind of [like] millimeter adjustments to have them fit in the small space.

Interviewer [00:36:51] So physical model was basically a driver there.

Participant 3 [00:36:54] Yeah. In the Amos Rex project as in many other projects, we were [working] with the contractors so that they do also 1:1 models of, for example, the ceiling in the exhibition spaces in the museum.

Participant 3 [00:37:14] It was kind of almost the size of this room where they tried out how to attach the ceiling panels and technical solutions. We didn't do the model ourselves but they did it in a warehouse in Estonia. So we went there and then with the contractor we discussed how to continue. And I think we do this quite a lot on different surfaces and different components.

Interviewer [00:37:55] Why is that exactly?

Participant 3 [00:37:57] Because the details and how they are realized are very important if you want to have this very pure space. For example, like in the Amos Rex museum, we really wanted to control every technical appliance, every kind of installation, so that if it's under control, then we get this space that is as pure as possible in the end. Because otherwise, if every technical contractor or designer, if you allow them to do what they want to do, the end result will not be this kind of a pure space. And also, I think [to understand] how materials function as they are installed, you have to try it out, otherwise, you can't imagine all the things. For example, you have the main lobby space in the Amos Rex museum. There we work together with a lighting artist. His company is called X. They tried out, they did these real lampshades and real lighting. And then we went also to a warehouse and they kind of installed them in the same manner that we will be seeing them in the museum. So then we could check that what it looks like, really.
Interviewer [00:39:47] So you were able to basically understand in the physical environment.

Participant 3 [00:39:53] Yeah, that is quite a very physical.

Interviewer [00:40:00] You talked about these 1:1 physical models. Are there any sort of shortcomings of producing them like cost-wise or production times?

Participant 3 [00:40:11] I think that in the end, you can also save quite a lot of money by doing it. For example, in the Amos Rex, the hills and how these tiles are put onto this free shape, that was also tried out in a 1:1 kind of testing situation. And there you kind of notice what can go wrong and what you need to take care of before starting that real installation of the tiles. And then so in that sense, you really save time and you get a better result when you have tested it.

Interviewer [00:40:53] Would you say that the digital tools fall short of identifying this or is it better with the physical making this identification?

Participant 3 [00:41:03] I think they complement each other.

Interviewer [00:41:14] Can you tell me some of those challenges when you’re working with any kind of physical tools in the initial design processes?

Participant 3 [00:41:27] Well, the challenge is, of course, if you, for example, work with a 3-D model, then it takes time to do it. And so you don’t do it. Or not too often, perhaps, if you really want to have a model.

Interviewer [00:41:50] What would be the opportunities, for instance, if I would want to implement physical models a bit more in the Initial processes?

Participant 3 [00:41:59] Yeah, well... Probably, there are quite a lot of ways to use them. For example, if you have a complicated room program and you want to see how different functions connect to each other. I saw it once in hospital design where you have quite a lot of functions there. I’ve seen just pictures of it, for example, where you use Lego pieces to try to figure out how the different functions connect
like that, but probably you could use models more also than we do here in the office. I've been once in a lecture by Frank Gehry. He showed how they really work with this 3-D pieces at that time. It's quite a long time ago.

**Interviewer [00:42:55]** He's a very influential figure also in modern architecture. Worked quite a lot with the physical models, especially for form exploration and volumetric exploration at the beginning of the processes. Have you seen this happening also in other offices other than Frank Gehry's office?

**Participant 3 [00:43:16]** I think a lot of offices use models [physical]. For example, my friends, they have this X Architecture office. I think they use quite a lot of models really as this kind of working models that they don't do finishing in models. They look really like work models. For example, for competitions, I've seen that. We have also worked together in some competitions so that they really try out the volume of a building in that kind of a working model.

**Interviewer [00:43:58]** In terms of the flexibility of the design space, what would you say about this type of exploration at beginning of the design process compared to, for instance, the digital process?

**Participant 3 [00:44:14]** I think that they are quite difficult. Do you mean the flexibility of space or the design?

**Interviewer [00:44:24]** The design space, for instance, the platform that you're basically designing something and ideating.

**Participant 3 [00:44:32]** Well, I think the digital is also ready to study the flexibility of the ideas. And so it is quite difficult to compare.

**Interviewer [00:45:00]** What would be the opportunities that digital tools can bring in the initial design process in terms of exploration, ideation, for instance?

**Participant 3 [00:45:10]** Well, yes, they can visualize different situations with digital solutions. You can really do it so that you can see the different concepts. And also in the three dimensional. So that's very... I think that's very useful because you can kind of... You can kind of rule out bad solutions by testing them in the digital world.
Interviewer [00:45:52] in such a process, how would digital tools fall short in the current practices? Or what would be the point that the digital tool does not provide further information? A point where you might need a physical model or a sketch.

Participant 3 [00:46:15] Perhaps to show the concept... to get to this tangible way of the concept. [information that the digital tools may not provide]

Interviewer [00:46:31] So it's kind of not showing as tangible as other types of models?

Participant 3 [00:46:37] Because in a real 3D physical model, then you can touch the volumes and the blocks, and the material set. So you can kind of put in real materials that you can get the feel of the material in a different way. Of course, in the digital world, you can't feel the tactile surfaces of the concept. Because the concept also touches all the senses. For example now the museum we're working on, the concept is such that we have different building volumes that we want to have quite a monolith and that they are really kind of our example... Well, I can show you the competition proposal for that one. It's a part of the globe, which is kind of a bowling ball that is held up with this kind of a golden box. We are working for having the golden, not real gold, but kind of a golden color. Now we want to have the golden box real so that it doesn't get destroyed by all details. So we kind of work on making it so that we can really have it like a simple gold and boxing band. And this golden box is standing on this kind of granite volumes. It needs to be really simple and these volumes need to be kind of discernable. So I think that we will be working with models, also physical models in this case, but not at the moment.

Interviewer [00:48:50] So basically at some point you might need the physicality. I'm very curious about why the touch and the sensual information is important in some cases for architecture.

Participant 3 [00:49:06] I think it gives quite a lot of content, or it gives kind of touch to the building volumes and kind of this materiality.

Interviewer [00:49:26] And this materiality, I think is often maybe a bit more difficult to comprehend with the digital tools. In that sense maybe. You mentioned, that it's complimentary. Would it be beneficial to sort of integrating these two realms or at least two platforms, design platforms?
**Participant 3** [00:49:47] Well, of course, we do renderings where we have real materials in the digital world. Then when we do this kind of marketing pictures we put a lot of effort in selecting the materials so that it kind of supports the concept. But then, of course, it's not so easy to make rendering and drawings with real materials that look good. They kind of start to...

**Interviewer** [00:50:30] Maybe there's a risk of misleading the client. For instance, if you use something or the lighting could be looking different from the real building.

**Participant 3** [00:50:38] Yeah. Because some pictures you look at it is also in a small scale. It is a quite difficult world to do it. But what was I supposed to say, yeah, well.... For example, what do we do also at the office when you go further on the projects that we use real materials in the digital ArchiCAD model. I can show you that on our project. We're so early on, so we haven't applied that yet. But I've seen in other projects at the offices that in your working 3D drawing world model, you can really go in and you have the real materials, you have the real lighting fixtures, fixtures. You have the real kind of cupboards, the furniture. Everything is kind of in the way we have defined them for the building. So it takes design on another level. So we will do that in this new project.

**Interviewer** [00:51:53] So you're also beginning recently to this project.

**Participant 3** [00:51:57] This is a new national museum. Yeah, the competition was decided in December. So now it started in the beginning of the year.

**Interviewer** [00:52:10] I came in the right time.

**Participant 3** [00:52:12] Yes.

**Interviewer** [00:52:14] It's very, very nice. What would be the ideal ways of working in the digital platform for you in the future?

**Participant 3** [00:52:23] I think it's important that digital programs are very adaptable to what we need in the design. For example, the shapes. As I said that the ArchiCAD
doesn’t do free shapes so well. I think that they need to work on that. I mean, of course everything should be possible so that the digital world doesn’t kind of limit your design.

**Interviewer [00:53:09]** So do you think the current digital tools, when you think about their graphical user interfaces... Are they kind of limiting in that sense?

**Participant 3 [00:53:19]** Well, for example, in the sense that ArchiCAD doesn’t really bend to all these free shapes so that’s a limitation. We avoid that limitation by using other software. But of course, it would be easier if it’s all in the same software could kind of do a bend to all these needs.

**Interviewer [00:53:52]** In terms of Rhino, would you say it also has certain limitations or can you basically produce anything?

**Participant 3 [00:53:57]** I think I can’t comment so much on that. I think I’ve noticed the limitation with Rhino when you bring it into ArchiCAD is that it’s not so... You get the feeling that it’s not so precise because you, for example, in the ArchiCAD world, you have to make these surfaces so that they are not completely kind of free shapes because it takes so much, it gets so heavy. So then you kind of split into this kind of triangular.

**Interviewer [00:54:28]** Yes. Polygons.

**Participant 3 [00:54:30]** Yeah. So that’s kind of a limitation. Then you can’t adjust anything.

**Interviewer [00:54:41]** So the translation process is not so fluid.

**Participant 3 [00:54:47]** But another thing I think... Because I think about digital software. They are like tools that make the design easier and quicker. Because when you do, for example, work drawings, when you did them before you had to draw everything. Like you had a window, then you need to make it kind of a facade of the window and then you do all that kind of definitions in those drawings then. So you had to do everything separately. So now in the ArchiCAD, you have a model and you have a 3D window and inside the window, you do all the definitions and then you kind of
get a list of all the windows automatically and all the door locks and handles. You can get it automatically. So I think that's a very useful thing we get from the digital world is that we get automated, these work phases that take a lot of time if you do them manually. So it makes the design quicker, the real building design [phase]. But I don't know if that's quite far away for them from the initial phase of a project where you are more of a free and you don't need to go so [much] in detail.

**Interviewer [00:56:17]** That's correct. But do you think what you decide on the initial design first process influences the later processes in any way?

**Participant 3 [00:56:27]** Yes, yes in a lot of ways. That's why I think that you need quite a lot of knowledge about the real building phases. Afterward, when you're doing the initial drawings, then you can kind of make good decisions in the beginning that will affect later on.

**Interviewer [00:56:54]** So have you had any experience, for instance, the decision that you made in the initial design process caused an issue later?

**Participant 3 [00:57:04]** Yeah. Yes. I think we are constantly doing mistakes that [we] know later on. For example, one very concrete thing is that you decide to put a floor level on a certain level and then the room height is certain. Then when all the technical drawings are made and you see how much technique you have in the space and you realize "ahh it so low because the technique takes so much space". Then you think, oh, we really should have had one and a half a meter more. So this kind of situation is... Because you can't really perhaps know all the technical equipment that comes along in the building. One thing with that which is very interesting now at the moment, is that when we work in the team with the engineers. Now we're really at a point where you can work together so that... Because they also work now in the three-dimensional digital world and then we combine all our work models and then we can really early on see everything in the three-dimensional world. So now, for example, in the design of the museum, we have very, very kind of difficult... What do you call it? The ground... foundation. These circumstances are very difficult on the site and we need to connect to these old buildings underneath them. It's an underground museum. So now we're really seeing all the good things about this three-dimensional one, because now the engineers can simulate, for example, what level the groundwater is. So we have the water in that model and then you have the rock levels in this 3D model. So you see that if I put the underground museum here, then I have to excavate all this amount of rock. And what happens with the water? They're very technical. They are very technical issues. But they affect, for example, the costs of the project very much.
Interviewer [00:59:50] And I think the soil is one of the main problems when you're building something under the ground. What would be the ideal ways of working in the physical platform for you in the future? Should we integrate physical? Or should we just forget about it?

Participant 3 [01:00:15] I think it’s very good to have the physical world or do also kind of simulations in the physical world so that, for example, if you're designing a new space and you think that, oh no, space could have this kind of dimensions. So what? One very useful thing is to go somewhere where you have approximately the same situation and then you kind of go there and you feel this. Is this what we want in our project? I think in that sense, a physical [model] is really kind of...you can skip it. And that’s what we do a lot also for when selecting materials. For example, you go somewhere and you look. How have they done this? How have they used this material? Is this what we want? Or is it not?

Interviewer [01:01:15] Do you receive a kind of feedback about the way material behavior?

Participant 3 [01:01:21] Yeah. Yeah. For example, now already for the Amos Rex museum we did quite an extensive tour of museums in Finland and we went abroad also to museums. And for example, we interviewed the staff and asked how they use the backspaces is a museum and what they need. I did these memos, for example, here in Helsinki of the museums. How many spots do they have? How do they built their walls when they have an exhibition? And then so you get you collect these kinds of experiences from different buildings and users. Then we try to kind of make good choices in our design.

Interviewer [01:02:16] Is there anything you would like to add to this discussion?

Participant 3 [01:02:23] I think well... I think I’m a bit old fashioned in the way that I think. In digital simulations and virtual reality there is a limit... It’s not applicable to the real world, I think because it lacks this sensual dimension.

Interviewer [01:02:53] So it’s not that connected to the real world.

Participant 3 [01:02:56] So because some research projects, for example, they compare the virtual reality and the real [world]. They simulate in the virtual reality
situations and then they ask a participant to make choices in the virtual world. Then they say as a finding that "Oh, people in a hospital would like to have a horizontal window", for example. So I think that to project in that sense from the virtual to the real, I think you’re kind of missing out really on a lot of dimensions if we don’t go to the real world and do research there.

**Interviewer [01:03:52]** So this there is a certain in a way divide between the virtual and the physical. Although we have all these tools.

**Participant 3 [01:04:02]** The way the building and architecture affect us in the physical world, it kind of affects us in many ways that are very difficult to measure. For example, kind of you feel, you smell and you feel the scent of things. I don’t know, the heat of the sun. It's a very sensual experience and also the way people interact. The kind of social... What I talk about, for example, in my thesis is this social dimension. So that it’s kind of the way people behave in spaces and in buildings. That’s very difficult to have in the digital, virtual world.

[01:04:54] **Exactly. So simulating that would be difficult. What would you say to the people who are, for instance, saying we should go all digital and basically and in digital we can do everything?**

[01:05:07] **I don’t believe it. I don’t think it’s true.**

[01:05:11] **All right. Thank you so much for your insights.**
5.3 Physical Processes from Contextual Interviews (Publication 3.)
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In the rapidly evolving realm of digital technologies, design disciplines, including architecture, have undergone a significant transformation. This thesis explores the dynamic interplay between physical and digital techniques in the initial stages of design, analyzing the feedback cycles of conception, revision, and evaluation. Through a comprehensive examination of designers' experiences, it introduces innovative proposals for intuitive design workflows and the seamless integration of physical and digital methods. The findings underscore the significance of interactive and tangible design tools, empowering designers to effortlessly manipulate and grasp complex concepts. This thesis offers valuable insights for practitioners and researchers seeking to optimize design processes and unlock more intuitive, efficient experiences.