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The Impact of Digital Fabrication as a Methodology in the Context of Design Practice

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PhD in Architecture of Contemporary Metropolitan Territories, specialisation of Digital Architecture

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E ARQUITETURA

Department of Architecture and Urbanism

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Resumo

Na prática arquitetónica contemporânea, a integração precoce do fabrico digital na conceção é frequentemente associada ao aumento da inovação. Ao aproximar o projeto digital da produção física desde as fases iniciais, torna-se possível explorar fluxos de trabalho mais experimentais, alcançar maior precisão construtiva e viabilizar soluções arquitetónicas que ultrapassam os limites dos métodos convencionais.

Esta investigação adota uma metodologia mista, combinando revisão crítica da literatura, entrevistas com profissionais e análise de estudos de caso de projetos e escritórios de arquitetura. Os resultados sustentam o desenvolvimento de um Quadro Estratégico para a Prática Arquitetónica Digital (SFDAP), concebido para orientar e avaliar a integração do fabrico digital na prática profissional.

O SFDAP é aplicado ao contexto arquitetónico português, permitindo avaliar o grau de adoção e as práticas correntes de fabrico digital nos ateliers nacionais. A análise comparativa com casos internacionais evidencia tendências partilhadas e desafios específicos do contexto português, contribuindo para uma leitura crítica do seu posicionamento no panorama global da inovação digital em arquitetura.

Os resultados demonstram que a integração precoce do fabrico digital transforma os fluxos de trabalho e os modelos de colaboração, promovendo maior proximidade entre arquitetos e fabricantes e facilitando a concretização de projetos complexos e criativos. Coletivamente, a investigação contribui para a teoria, a prática e o ensino da arquitetura, ao reforçar o fabrico digital como um motor ativo da conceção arquitetónica e como um elemento central na reaproximação entre projeto, materialidade e construção.

Palavras-chave: Fabricação Digital; Prática Arquitetónica; Maturidade Digital; Colaboração; Fluxos de Trabalho; Portugal

Abstract

In contemporary architectural practice, the early integration of digital fabrication into the design process is frequently associated with increased innovation. By bringing digital design closer to physical production from the initial stages, it becomes possible to explore more experimental workflows, achieve greater constructional precision, and enable architectural solutions that exceed the limitations of conventional methods.

This research adopts a mixed-methods approach, combining a critical literature review, interviews with professionals, and the analysis of case studies of architectural projects and practices. The findings support the development of a Strategic Framework for Digital Architectural Practice (SFDAP), designed to guide and evaluate the integration of digital fabrication within professional practice.

The SFDAP is applied to the Portuguese architectural context, allowing for an assessment of the level of adoption and current digital fabrication practices within national studios. A comparative analysis with international case studies reveals shared trends and context-specific challenges, contributing to a critical understanding of Portugal's position within the global landscape of digital innovation in architecture.

The results demonstrate that the early integration of digital fabrication transforms workflows and collaborative models, fostering closer relationships between architects and fabricators and facilitating the realisation of complex and creative projects. Collectively, the research contributes to architectural theory, professional practice, and education by reinforcing digital fabrication as an active driver of architectural design and as a central element in the renewed relationship between design, materiality, and construction.

Keywords: Digital Fabrication; Architectural Practice; Digital Maturity; Collaboration; Workflows; Portugal

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List of Acronyms and Abbreviations

2D — Two-Dimensional

3D — Three-Dimensional

AEC — Architecture, Engineering, and Construction

AI — Artificial Intelligence

AM — Additive Manufacturing

AR — Augmented Reality

BIM — Building Information Modelling

CAD — Computer-Aided Design

CAD–CAM — Computer-Aided Design / Computer-Aided Manufacturing

CAD/CAM — Computer-Aided Design / Computer-Aided Manufacturing

CAM — Computer-Aided Manufacturing

CAADRIA — Computer-Aided Architectural Design Research in Asia

CEAU — Centre for Studies in Architecture and Urbanism (CEAU/FAUP)

CNC — Computer Numerical Control

DFAB — Digital Fabrication

DfAM — Design for Additive Manufacturing

DfD — Design for Disassembly

DFL — Digital Fabrication Laboratory (FAUP, Porto)

DM — Digital Maturity

DM/RE Matrix — Digital Maturity / Research Engagement Matrix

EAAD — Escola de Arquitetura, Arte e Design (Universidade do Minho)

eCAADe — Education and research of Computer Aided Architectural Design in Europe

EDP — Energias de Portugal

ETH Zurich — Swiss Federal Institute of Technology Zurich

FAUP — Faculty of Architecture, University of Porto

FDM — Fused Deposition Modelling

FEA — Finite Element Analysis

G-code — Numerical control programming language for CNC/toolpaths

GSD — Graduate School of Design (Harvard GSD)

IAAC — Institute for Advanced Architecture of Catalonia

ICD — Institute for Computational Design and Construction (Stuttgart)

ISCTE-IUL — Instituto Universitário de Lisboa

ITKE — Institute of Building Structures and Structural Design (Stuttgart)

Lab2PT — Laboratório de Paisagens, Património e Território

LCA — Life Cycle Assessment

LSBU — London South Bank University

MAS — Master of Advanced Studies

MIT — Massachusetts Institute of Technology

ML — Machine Learning

NCCR — National Centre of Competence in Research

NURBS — Non-Uniform Rational B-Splines

R&D — Research and Development

RE — Research Engagement

RIBA — Royal Institute of British Architects

ROI — Return on Investment

SFDAP — Strategic Framework for Digital Architectural Practice

SIGraDi — Ibero-American Society of Digital Graphics

SOM — Skidmore, Owings & Merrill

TUM — Technical University of Munich

UCL — University College London

VFabLab — VITRUVIUS FabLab (Iscte-IUL)

VR — Virtual Reality

Introduction

The evolution of architectural practice has long been shaped by technological change, affecting both how projects are conceived and how they are realised. Over the last two decades, computational design and digital fabrication have expanded the discipline's capacity to work iteratively, test performance, and explore complex geometries through methods such as parametric modelling, algorithmic design, and emerging machine-learning tools (Carpo, 2023; Lloret-Fritschi & Jenny, 2024; Burry, 2016; Kolarevic, 2003). In parallel, contemporary debates suggest a shift from predominantly efficiency-driven digitalisation toward approaches that emphasise human agency, adaptability, and collaboration across design and construction (Ayres, Thomsen, Sheil, & Skavara, 2024).

Robotic fabrication and additive manufacturing have strengthened the feedback loop between design intent and material execution, enabling more direct translation from digital models to constructed components and assemblies (Carpenter et al., 2023; Oxman, 2017; Gramazio & Kohler, 2008). These developments support new modes of practice in which experimentation, iterative prototyping, and human–machine collaboration become part of the design process rather than isolated technical services (Mortati, 2023). In this context, digital tools function not only as representational and coordination media but also as decision environments in which material logic, assembly constraints, and tectonic intent can be tested and iterated.

Despite these advances, digital fabrication remains peripheral within much of everyday architectural practice, often concentrated in academic laboratories, specialised research groups, or limited prototyping workflows (Burry et al., 2020; Yuan et al., 2017; Sheil, 2012). Fabrication is still frequently positioned as a downstream phase, an operational step that follows design, rather than as an integrated driver of architectural workflows and decision-making (Picon, 2010; Singh, 2024). This thesis addresses that gap by examining how fabrication knowledge can be embedded earlier within office workflows, and what organisational, cultural, and practical conditions enable that shift.

Motivation

This research is motivated by the rapid advancements of computational design and fabrication technologies alongside their surprisingly limited uptake in everyday architecture practice. On one hand, architects increasingly recognise that digital fabrication offers opportunities for greater innovation, precision, and sustainability in building; on the other, many offices remain hesitant or face barriers to adopting these tools. This misalignment has practical consequences: it limits opportunities for iterative design-to-production feedback, constrains material and constructive exploration, and can increase the separation between design authorship and material realisation.

By identifying the barriers that keep fabrication at the fringes - be they technological, organisational, educational or cultural - and exploring strategies to overcome them, the thesis seeks to bridge innovation in academia with implementation in practice. For instance, recent analyses show that emerging fabrication methods (like 3D printing or robotic automated construction) require new skill sets and mindsets that many practitioners have not yet developed, highlighting the importance of upskilling and design workflow adaptation. This upskilling is not only a technical requirement but also an organisational transition: it concerns how offices distribute expertise, coordinate collaboration with machines and specialists, and create conditions in which digital fabrication augments professional judgement and authorship. There is also a need to clarify the value proposition of earlier fabrication integration, including its implications for design quality, coordination, risk management, and office capability development.

The uneven adoption observed in different contexts provides further motivation. In global terms, some leading offices have embraced in-house digital fabrication teams or research-oriented design practices, whereas others lag behind. In Portugal specifically, the architectural community is navigating a broader digital transformation of architectural practice (understood here as changes in workflows, organisational structures, and design–production relations) but at an uneven pace (Brimet & Paio, 2013). This contrast between experimentation and hesitation offers fertile ground to study how and why innovation diffuses (or fails to diffuse) into practice.

The motivation is both intellectual and practical: to contribute to architectural knowledge by understanding this contemporary transition in practice, and to provide practice-relevant insights that support more coherent links between design intention and material realisation.

Moreover, this research takes the view that re-centring digital fabrication within architectural office design processes has cultural and creative ramifications, particularly in how it reframes material intelligence, responsibility, and authorship within digital workflows. Embracing digital fabrication as a design driver encourages architects to engage more deeply with materials and making. It aligns with the notion of material agency – the idea that materials have inherent qualities and behaviours that actively participate in the design process (Leopardi, 2024). By treating materials and fabrication methods as collaborators, architects can discover new aesthetics and solutions that would remain invisible in a purely digital design approach.

Ultimately, the thesis is motivated by the need to understand how fabrication-informed approaches can be operationalised within architectural offices, particularly in Portugal, so that computational design is more consistently connected to making, construction logics, and professional practice conditions (European Commission, n.d.).

Research Questions, Hypothesis and Objectives

Despite advances in computational design and digital fabrication, systematic integration of fabrication-informed workflows into everyday architectural office practice remains limited. This points to a research gap in understanding the organisational, cultural, economic, and knowledge-based conditions that enable fabrication knowledge to become routine rather than exceptional within professional workflows.

In this thesis, digital adoption refers to the extent to which architectural offices embed digital tools within their process-based workflows, rather than merely acquiring software or equipment. Although Building Information Modelling (BIM) remains central to debates on digitalisation, particularly with regard to coordination and efficiency (Martin, Watson, & Brooks, 2025), comparatively less attention has been directed toward how digital fabrication knowledge is embedded in everyday architectural work, especially as a driver of early-stage decision-making (Brozovsky, Labonnote, & Vigren, 2024). This imbalance suggests that fabrication-centric approaches are often perceived as exceptional, risky, or difficult to operationalise within conventional office structures and project cycles.

Current professional discourse still frequently frames digital fabrication in terms of downstream technical efficiencies, "streamlining" and "optimisation", which can obscure its broader architectural implications for tectonic thinking, design judgement, and material innovation (Picon, 2010). Tectonic theory, as articulated by Frampton (1995), reminds us that architecture ultimately materialises through construction, and that making is inseparable from the discipline's conceptual foundations. From this perspective, digital fabrication is not only a production technique but a potential source of design intelligence that can inform form, detail, assembly logic, and collaboration.

Research Hypothesis

A central challenge for contemporary practice is how digital fabrication can be repositioned from a downstream production service to an integral component of architectural thinking, aligned with architecture's fundamental purpose: to build. As Cañizares and Cohen (2024) argue, the central challenge lies in strategically "homing the machine" within the architectural office so that processes of making are no longer isolated from design, but instead actively inform and shape it.

The thesis therefore hypothesizes that centring digital fabrication expertise within architectural office workflows can reduce the distance between research-driven prototypes and everyday practice by reconnecting design and tectonics within a continuous design-to-production process. Under this hypothesis, materialisation, tooling, and assembly considerations enter the design process earlier, enabling fabrication knowledge to inform form, detail, and decision-making rather than serving only as a means of execution.

This need is particularly pronounced in the Portuguese context, where architectural offices operate under conditions of limited industrial capacity, uneven access to fabrication infrastructure, and an ongoing national agenda of digital transition. Within such constraints, the strategic integration of digital fabrication knowledge becomes particularly relevant for understanding feasible pathways to adoption. At the same time, the research engages with a broader international shift away from linear, segmented project delivery models toward more integrated forms of design–build thinking, in which material, technical, and constructive logics are brought upstream into the creative process (Gamal et al., 2024; Hauschild & Karzel, 2011; Hensel & Nilsson, 2016; Marble, 2012).

Against this backdrop, the central hypothesis of the thesis is that the early integration of digital fabrication expertise into architectural office workflows can reshape design processes and support more innovative and constructively coherent architectural outcomes. When fabrication knowledge and material constraints are addressed from the outset, rather than as late-stage technical requirements, the design process becomes more iterative, informed, and responsive to real-world conditions.

This hypothesis builds on evidence from other design and manufacturing disciplines, where the close coupling of design and making has been shown to reduce errors, minimise waste, and foster innovation. However, within architectural practice, there remains limited empirical understanding of how such integration can be effectively operationalised, as well as of the organisational, cultural, and technical challenges it entails. The hypothesis therefore requires systematic investigation within the specific context of professional architectural offices, where aesthetic, functional, and cultural ambitions intersect with material, technological, and production realities.

Research Questions

To investigate this hypothesis, the study poses three key research questions:

1. How can fabrication-informed methodologies be systematically embedded within the early stages of architectural design workflows, ensuring a coherent design-to-production continuum? This question directs the research toward identifying the practical strategies, workflow transformations, and organisational conditions required for fabrication knowledge to meaningfully inform design from the outset. It shifts the inquiry from simply asking what should change to examining how such integration can be operationalised in real practice - through adjustments to design workflows, new modes of collaboration, redefined team roles, and the coordinated use of digital tools that link early design decisions to downstream production.

2. In what ways can material constraints, tooling logics, and production methods operate as human–machine co-generative design drivers rather than downstream technical considerations? This question shifts the focus toward understanding how fabrication intelligence - embedded in materials, tools, and production processes - can actively shape architectural form, logic, and collaboration from the outset. It invites an examination of the qualitative transformations that occur when these factors inform design early on: how design intent evolves through continuous feedback with fabrication constraints; how the boundaries between designers, fabricators, and machines become blurred; and how new forms of human–machine co-creativity emerge. Such an inquiry also raises questions of authorship and agency - how architects negotiate creative control when materials and machines participate in design - and points toward new organisational typologies, such as research-integrated or fabrication-driven practices that leverage these generative models.
3. How can these insights be translated into a practical, operational framework that enables architectural offices to integrate digital fabrication knowledge into everyday practice? This question focuses on synthesis and implementation, directing the research toward developing a usable methodology that architectural offices can adopt within real project workflows. The aim is to move from conceptual understanding to an actionable framework - one that outlines processes, decision points, organisational adjustments, and strategic steps that support routine, fabrication-informed practice. While the question acknowledges the importance of local conditions in Portugal - such as cultural norms, market structure, and office scale - the intention is to create a flexible framework with broader applicability, contributing to international discussions on adaptive, digitally enabled, and sustainable architectural practice.

Research Objectives

To answer these questions, the thesis pursues the following objectives:

1. Objective 1: Integrate fabrication into early-stage design-to-production workflows. Investigate how fabrication-informed methodologies can be systematically embedded within the conceptual and schematic design stages of architectural projects. This objective involves identifying the process transformations, digital tools and design techniques that enable material and construction knowledge to shape design decisions from the outset rather than at the end. By doing so, the research aims to demonstrate that considering *how a project will be made* early in the process can expand architectural creativity rather than constrain it.
2. Objective 2: Develop a framework that positions digital fabrication as an intrinsic, human-centred component of design-to-production workflows within architectural practice. This

framework is intended to bridge design strategy, computational methods and architectural pedagogy - recognising that education and upskilling form part of the long-term transition toward fabrication-aware practice. It will take the form of a structured methodology or set of adaptable guidelines for architectural offices, synthesising theoretical insights and practical evidence into a coherent approach that enables projects to progress seamlessly from concept to fabrication-informed design and, ultimately, to digital production.

3. Objective 3: Contextual evaluation of the framework within Portuguese and international practice. Assess the implications of the proposed framework within the Portuguese context of digital transition, while situating the findings within a broader international discourse on adaptive and sustainable architectural practice. This objective involves illustrating the framework through case studies and interviews conducted in Portugal, capturing the current state of digital fabrication adoption locally, and reflecting on how these insights compare with global trends. It includes identifying context-specific challenges, such as market scale, access to fabrication facilities, or gaps in architectural education, and ensuring that the proposed strategies remain flexible enough to accommodate such variations. At the same time, the research aims to highlight the global relevance of the findings, contributing to wider discussions on how architectural practice can evolve in response to rapid technological change.

By meeting these objectives, the research aims not only to validate the central hypothesis but also to generate actionable knowledge for architecture practitioners. In summary, the thesis bridges theoretical inquiry with practice-oriented outcomes by demonstrating how fabrication knowledge can operate as early-stage design intelligence and by proposing a framework and implementation roadmap suitable for architectural office workflows.

Research Methodology

This PhD adopts a qualitative, mixed-methods research methodology designed to investigate how digital fabrication knowledge can be meaningfully integrated into architectural office workflows. Rather than evaluating technologies in isolation, the methodology focuses on practice-based processes, organisational structures, and human–machine interactions, aligning with the research's central aim of repositioning digital fabrication as an early-stage design driver within professional practice.

The methodological framework is structured as a three-stage research process that progressively links theory, empirical investigation, and framework development. This structure allows the research

to move from conceptual understanding to grounded analysis and, finally, to prescriptive outcomes that are applicable within real architectural offices.

Stage 1: Theoretical and Conceptual Foundation

The first stage consists of a critical literature review establishing the theoretical foundations of the research. This review examines key discourses related to the digital turn in architecture, digital tectonics, computational design, and fabrication-informed workflows. Particular attention is given to literature addressing the evolving relationship between design, materiality, and production, as well as recent debates on human–machine collaboration within architectural practice.

Rather than treating digital fabrication as a purely technical innovation, the review frames it as a cultural and organisational shift within architectural practice, one that reconfigures authorship, expertise, and workflows. This theoretical grounding informs the formulation of analytical criteria used in later stages of the research and situates the study within broader discussions on architectural practice transformation.

Stage 2: Empirical Investigation through Case Studies and Interviews

The second stage comprises an empirical investigation based on qualitative case studies and structured interviews, focusing primarily on architectural offices operating in Portugal and supplemented by international reference cases drawn from the literature. A case study approach was selected due to its suitability for capturing the complexity, variability, and contextual specificity of architectural workflows (Flyvbjerg, 2006).

Portuguese architectural offices were selected to represent a range of practice profiles, including offices actively experimenting with digital fabrication, those in transitional phases, and more conventional practices. This diversity enables a comparative understanding of how digital fabrication knowledge is adopted, resisted, or adapted across different organisational contexts. Structured interviews were conducted with architects and key practitioners, addressing topics such as design workflows, use of computational tools, experience with fabrication processes, perceived barriers to adoption, and future strategic aspirations.

All interviews with Portuguese practitioners were conducted in Portuguese and subsequently translated into English by the author, with the assistance of AI-based translation tools. These translations were carefully reviewed and edited to ensure accuracy, contextual fidelity, and conceptual clarity.

Interview data were analysed using thematic analysis, allowing recurring patterns, challenges, and enabling factors to be systematically identified. To support comparative analysis, each office was assessed along two analytical dimensions defined specifically for this research: digital maturity (the

extent to which computational design and fabrication workflows are embedded in practice) and research engagement (the degree of continuous learning, experimentation, and collaboration with research institutions or industry partners).

Stage 3: Framework Development and Synthesis

The third stage synthesises theoretical insights and empirical findings into the development of an original analytical and prescriptive framework: the Strategic Framework for Digital Architectural Practice (SFDAP). The SFDAP functions both as an interpretative model, used to classify and compare architectural offices, and as a practical tool to support strategic decision-making within practice.

By mapping case study offices along the axes of digital maturity and research engagement, the framework identifies typologies of practice and reveals patterns in how digital fabrication knowledge is operationalised. This synthesis enables the research to move beyond descriptive analysis and toward the formulation of actionable strategies for integrating fabrication-informed workflows into everyday practice.

The final phase of the research adopts a prescriptive orientation, translating analytical findings into practical guidelines organised as a roadmap for implementation. These guidelines address workflow reconfiguration, skill development, collaboration models, and organisational change, ensuring that recommendations remain grounded in the realities of professional practice rather than idealized technological scenarios.

By combining theoretical inquiry, qualitative empirical research, and framework-based synthesis, the methodology ensures that the research is theoretically rigorous, empirically grounded, and professionally relevant. Importantly, the methodology aligns with a human-centred perspective on digital transformation, foregrounding how architects work with machines rather than how machines replace architectural labour.

This approach allows the thesis to bridge the gap between academic research and professional application, positioning digital fabrication not as a downstream technical tool but as an integrated component of architectural thinking, collaboration, and making.

Research Scope

The scope of this thesis is carefully delimited to ensure depth within a manageable range. Geographically, the primary focus is on architectural practice in Portugal during the present era of digital transformation (roughly the late 2010s through the mid-2020s). This focus was chosen because Portugal represents a context where the opportunities and challenges of digital fabrication are pronounced: there is growing interest (as for the emergence of fab labs and research initiatives)

(Baptista, Paio, & Silva, 2013) but also identifiable gaps in uptake among everyday practitioners. By centring on one national context, the study can account for specific cultural, educational, and economic factors that influence practice, such as the size of typical offices, availability of fabrication facilities, and local construction culture. That said, the research is not intended to be only local. International trends are examined for context and comparison, and many findings are extrapolated to have relevance beyond Portugal. The inclusion of international case studies and literature ensures that the thesis speaks to global practice even as it grounds itself in local realities.

Topically, the thesis emphasizes design processes and organisational practices in architectural offices, rather than the details of engineering or software development. It looks at how architects work and how they can work differently with digital fabrication, rather than providing technical development of new fabrication machines or algorithms. For instance, discussions of computational tools are framed in terms of their impact on design workflow and design possibilities, not as an engineering achievement by itself.

The scope includes intersections with architectural education (since training and skill development are part of enabling practice change) and with project delivery methods (as much as they create a conducive environment for fabrication integration). However, it does not delve into unrelated construction industry aspects such as general contracting practices, building regulations (except where they specifically relate to digital fabrication), or the economics of fabrication hardware. Importantly, the research does not aim to cover every aspect of digital technology in architectural office practices. For example, while Building Information Modelling (BIM) and parametric design are discussed, they are contextualized around digital fabrication, the thesis is not a general study of BIM in practice. Similarly, emerging technologies like AR/VR or blockchain are touched upon only where they interface with the digital fabrication workflow. This selective focus ensures a coherent narrative centred on the core inquiry: integrating design workflows design-to-production, into practice.

By maintaining these scope boundaries, the thesis can provide a focused inquiry into how digital fabrication can be woven into architectural practice offices, both in theory and within the particular cultural/economic context of Portugal. This focus allows for actionable insights specific enough to be meaningful, while still engaging with the larger conversation about the future of architectural practice in the digital age.

Research Contributions

This research aims to make several key contributions to architectural knowledge and practice:

- **Theoretical Framework for Integration:** On a theoretical level, the thesis proposes a new framework for digital fabrication integration in architectural office practice. This framework

enriches the ongoing discourse on computational design and tectonics by linking these often abstract or academic ideas directly to practice-oriented workflows. In other words, it bridges the gap between the theory of "digital making" and the practical reality of designing buildings. By articulating principles and steps for embedding fabrication in design, it provides a conceptual model that other researchers and practitioners can further critique, test, and refine. This is especially significant as the field struggles with what the next "digital turn" means for architects – the framework intends to offer one concrete vision of that future.

- **Diagnostic Tool (SFDAP):** The thesis introduces a diagnostic tool for practice: the Strategic Framework for Digital Architectural Practice (SFDAP). This tool classifies architectural offices by their level of digital maturity and research engagement. By doing so, it enables practitioners and stakeholders to benchmark their progress in digital transformation. For example, an office might use the SFDAP criteria to identify itself as an "Innovator" or an "Emerging" practice in terms of fabrication integration, which can be valuable for strategic planning. The very act of defining such typologies is a contribution, as it sheds light on patterns of adoption and innovation across the industry. It helps answer questions like: What distinguishes a pioneer office from a late adopter in this area? What common challenges do "Emerging" offices face that prevent them from advancing? The diagnostic framework thus serves both as an analytical lens (for researchers to discuss practice) and as a practical checklist (for offices to self-assess and plan improvement).
- **Empirical Insights on Portugal:** Empirically, the thesis provides much-needed insights into the state of digital fabrication adoption in Portugal. This is a contribution to the architectural literature because, to date, relatively little has been published about how contemporary Portuguese offices are engaging with these technologies. The research documents current practices, success stories, and pain points in a specific national context, effectively filling a gap in the global narrative. By publishing these findings, the thesis ensures that Portugal's experience becomes part of the record. This way, future researchers, policy-makers, or office leaders can draw on this to understand regional dynamics of innovation. It also allows for comparative analyses with other contexts: for instance, contrasting Portugal's adoption trajectory with that of other countries can reveal how factors like public funding, education systems, or industry structure influence digital fabrication uptake.
- **Practical Guidelines for Practitioners:** On a pragmatic level, the thesis offers a set of strategic guidelines for architects and offices seeking to implement or expand digital fabrication in their practice. These guidelines, grounded in the theoretical framework and empirical evidence, bridge the "knowing–doing gap", helping translate the concept of integrated digital fabrication into concrete actions. They also include considerations beyond technology, such as fostering

a culture of innovation, encouraging interdisciplinary collaboration, and addressing the social and ethical dimensions of digital practice, ensuring that adoption of automation does not marginalize workers, but instead augments the creative roles of the humans involved. By providing these recommendations, the thesis acts as a resource for professionals, especially those in small to mid-sized offices who may not have the benefit of in-house research teams.

- **Positioning Fabrication as Design Driver:** Finally, a subtler but important contribution is the reframing of how we think about the role of fabrication in design. The thesis, through its hypothesis and findings, contributes to an evolving narrative in architecture that treats fabrication and materiality as sources of design intelligence rather than post-design concerns. In articulating this vision with contemporary evidence and terminology, the thesis adds to the intellectual momentum that is re-integrating the acts of designing and making in the digital era.

The contributions of the thesis are multi-layered: a new framework and vocabulary for integrating digital fabrication, a practical tool for assessment, a set of empirical case studies enriching the literature (particularly in a Portuguese context), and actionable guidance for practice. Together, these contributions advance both understanding and capability, helping to strategically position digital fabrication as a driver of workflow and tectonic innovation in architectural practice while fostering a collaborative, human–machine augmented mode of practice aligned with the principles of Industry 5.0.

Structure of the Thesis

This dissertation is organised into three main parts, reflecting the progression from theory to analysis to application:

- **Part I – Theoretical Background** (Chapters 1–3): This part establishes the intellectual and historical context for the research. Chapter 1 discusses architectural practice in the digital turn, examining how the advent of computation and digital tools has reshaped design thinking, aesthetics, and the architect's role. It traces the evolution from the early days of CAD to current explorations in AI-driven design, framing why the integration of fabrication is the next logical (and necessary) step in this evolution. Chapter 2 focuses on digital design methodologies, including design-to-fabrication workflows and emerging technologies. Here, key concepts such as file-to-factory processes, parametric design, simulation, and robotic construction are reviewed. This chapter also introduces ideas like material and fabrication intelligence, highlighting that digital fabrication is not just about making things faster, but about designing

things differently. Chapter 3 turns to the state of digital fabrication in architectural practice in Portugal. It provides an overview of the local landscape: identifying pioneering initiatives (such as fab labs, academic programmes, or notable experimental projects), as well as common challenges faced by Portuguese offices. Overall, Part I builds the case that the "digital turn" in architecture, while rich in new tools and theories, has yet to fully permeate everyday practice, thereby justifying the need for the present research.

- **Part II – Analysing Digitalisation of Architectural Practice** (Chapters 4–5): This is the core analytical section of the thesis. Chapter 4 presents the findings from the case studies and interviews, developing what could be called a taxonomy of practice. It introduces the Strategic Framework for Digital Architectural Practice (SFDAP) in detail, defining its criteria and categories. The chapter analyses both international and Portuguese cases through this lens, yielding insights into patterns of digital fabrication adoption. It also compares the Portuguese cases to international benchmarks, identifying which challenges are universal and which are context-specific. Chapter 5 then builds upon these insights to propose a process-based integration framework for digital fabrication. This framework maps out how fabrication-aware practices can be embedded across all project phases, from conceptual design and design development, through detailing and fabrication planning, to construction. It uses both the theoretical insights of Part I and the empirical data of Chapter 4 to illustrate what an ideal integrated workflow might look like. The chapter uses diagrams to visualize new workflow configurations, and present short illustrative scenarios or prototypes. By the end of Part II, the reader is presented with a framework that addresses the research questions, supported by real-world data and analysis.
- **Part III – Guidelines for Implementing Digital Fabrication in Portuguese Architectural Practice** (Chapter 6): The final part of the thesis is forward-looking and practical. Chapter 6 translates the research findings into actionable guidelines and strategies for implementation. Recognizing that each office and context will be different, the guidelines are presented not as one-size-fits-all prescriptions, but as a flexible toolkit. They cover multiple dimensions: Organisational (how to foster a culture of innovation, how to manage the change process, leadership and team roles for digital initiatives), Technical (recommendations on selecting fabrication technologies), and Educational (suggestions for training staff, hiring strategies, or collaborations with universities and fab labs to build knowledge). The chapter also addresses potential pitfalls and success factors, essentially acting as a "how-to" chapter for digital fabrication adoption. For instance, it includes a guideline that early integration efforts should start on smaller projects or internal R&D experiments to build confidence before tackling large commissions, or advice on calculating and communicating the return on investment of new

digital workflows to clients and stakeholders. The chapter underscores the broader implications of embracing these changes – arguing that doing so not only improves efficiency or spectacle in design, but also aligns architecture with a more sustainable and innovative trajectory for the construction industry at large.

The Conclusion section that summarizes the key findings, reflects on the implications for both practice and education, and suggests paths for future research.

Overall, the structured progression from context, to analysis, to application in the thesis ensures a cohesive narrative. The reader is first approached why the research matters, then shown what the current state and proposed solution are, and finally instructed in how these insights can be applied. This structure underlines the strategic positioning of digital fabrication as an early-stage design driver and a catalyst for human–machine collaboration in transforming architectural practice.

PART I – THEORETICAL BACKGROUND

The field of architectural practice is undergoing a profound transformation driven by the digital turn, which has reshaped design methodologies, tectonic articulation, and fabrication processes. Over the past decades, architecture has transitioned from traditional, manual design and construction techniques toward computationally-driven workflows that integrate design intelligence, material computation, and robotic fabrication. This transformation is fuelled by advancements in computational design, digital fabrication, and emerging technologies, which together redefine the role of the architect, the design process, and the act of making (Carpo, 2023; Picon, 2021).

To establish the theoretical foundation of this research, we examine three key domains: Digital Turn in Architecture, Digital Tectonics, and Digital Fabrication. The interplay between these fields is fundamental to understanding how computational tools influence architectural thinking and how fabrication constraints reciprocally inform design decisions (Oxman, 2017). By situating digital tectonics within architectural theory and material computation, this section critically evaluates the theoretical shifts, new design paradigms, and fabrication methodologies that shape contemporary architecture practice. As architecture increasingly relies on computational approaches, it becomes imperative to analyse how these methodologies influence architectural practice design workflows, collaborative processes in offices, and material engagement.

Yet a crucial question remains: How can these digital innovations move beyond isolated labs and avant-garde offices into mainstream architectural practice offices? As Canizares and Cohen (2024) observe, much of the discourse around digital fabrication still centres on technical efficiencies – 'buzzwords like streamlining and optimisation' – focusing on tools rather than values, which creates a friction with the conceptual nature of architecture and makes it 'difficult to locate digital fabrication's home' within the discipline. This thesis responds by locating that 'home' squarely in the architectural office. In other words, the following chapters examine the digital turn not as a theoretical abstraction, but as a transformative force in the day-to-day practice of architects.

CHAPTER 1

Architectural Practice in the Digital Turn

The digital turn in architecture refers to the paradigm shift brought about by the integration of digital technologies into architectural design and construction since the late 20th century (Carpo, 2013; Carpo, 2017). It encompasses the move from hand-drafting and analogue processes to computer-aided design (CAD), computational form-finding, building information modelling (BIM), and digitally driven fabrication (CAM). In essence, the digital turn marks a transition in architectural practice where computational logic, data, and algorithmic processes became central to how architects conceive and realise buildings. Architectural design practice processes have expanded in scope beyond representation-based documentation to include analysis, simulation and digital fabrication. This allow architects to better understand and manage how their virtual ideas are realised, and to innovate or challenge traditional construction methods (Burry, 2016). Thus, this shift has reshaped nearly every aspect of practice - from the way architects generate forms to how buildings are fabricated offsite or on site. Crucially, the digital turn is not just about adopting new tools; it represents a broader cultural change in architecture's methods and mindset (Carpo, 2025). Early on, for instance, digitally conceived designs often favoured seamless, curvilinear forms (the hallmark "blobs" of 1990s digital architecture), which stood in provocative contrast to traditional tectonic aesthetics that celebrate modularity and joints (Carpo, 2025). This evolution has been so significant that scholars like Carpo describe it in historical terms – he characterizes the late-20th-century advent of computation as the first digital turn and the contemporary data-driven, AI-infused era as a second digital turn in architecture's technological evolution (Yuan, 2025; Carpo, 2025). In framing this chapter, the thesis is that the digital turn has fundamentally reshaped architectural practice – from theory and aesthetics to the very methods of making. The digital turn in architecture also represents a fundamental transformation in architectural theory, design methodologies, and construction processes. Over the past few decades, architecture has moved from traditional manual workflows to computationally driven processes, integrating digital intelligence, material computation, and robotic fabrication (Hensel & Nilsson, 2016; Marbel, 2012; Hauschild & Karzel, 2012; Carpo, 2011; Picon, 2010). This shift has not only redefined how architects design and build but has also altered the very nature of architectural practice, introducing new paradigms of methodologies, collaboration, and production (Gramazio, Kohler & Langenberg, 2017; Oxman, 2017).

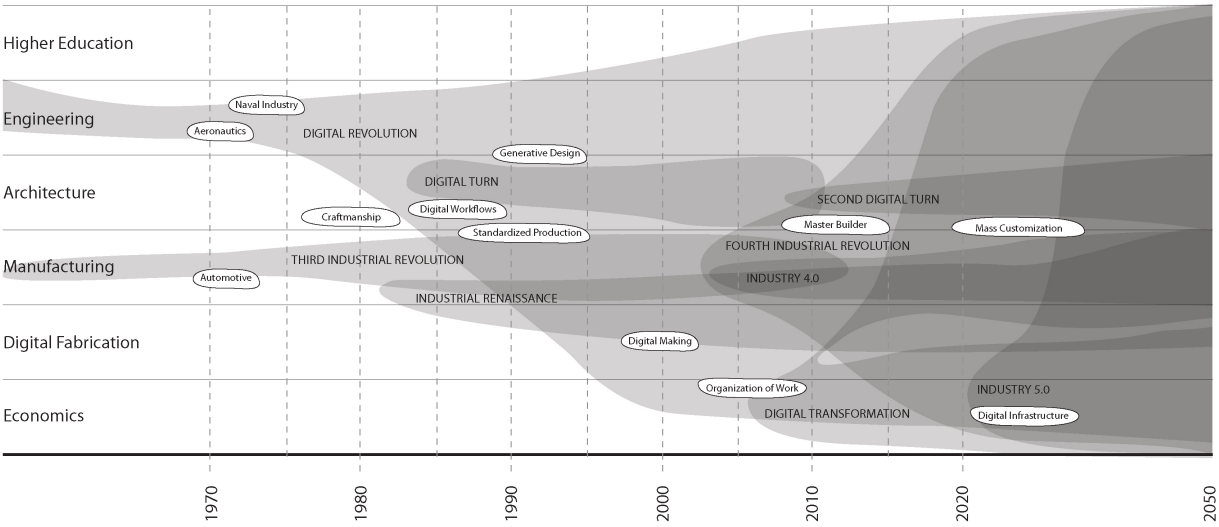


Figure 1.1: Graphic representation of the development of the digital infrastructure connecting architecture with related sectors, adapted from Codarin (2021). The diagram has been extended to include the emergence of Industry 5.0 (European Commission, 2021).

The visual overview in Figure 1.1 depicts the evolution of digital infrastructures that interconnect architecture, manufacturing, and related disciplines, tracing their development from the early Digital Revolution through the automation-driven paradigm of Industry 4.0 and into the emerging discourse of Industry 5.0). In this reading, Industry 5.0 does not replace Industry 4.0, but rather reframes it by reintroducing human agency, sustainability, and resilience as central values within highly automated and data-intensive production systems (Breque, De Nul, & Petridis, 2021).

Within the manufacturing stream of the diagram, the architecture branch highlights successive "digital turns" and the digital fabrication revolution, illustrating how computational design and automated production have progressively bridged the traditional divide between design and construction. By integrating these trajectories, the diagram supports the thesis argument that a shared digital ecosystem creates conditions for increased levels of customisation and performance, while foregrounding the role of architects in mediating between computational systems, material processes, and human judgement in contemporary design-to-production workflows.

Digitalisation in architecture extends beyond the mere adoption of computer-aided design (CAD) to integrate advanced computational tools such as parametric design, generative algorithms, artificial intelligence (AI), and digital fabrication techniques (Lloret-Fritsch et al, 2024; Carpenter et al, 2023; Vrachliotis, 2022; Kolarevic, 2003; Carpo, 2017; Picon, 2010). These innovations have blurred the boundaries between design and production, enabling architects to engage in processes that are simultaneously conceptual, performative, and material-driven (Oxman & Oxman, 2014; Gramazio & Kohler, 2008). As a result, the profession has witnessed a transition toward data-driven, performance-

oriented, and fabrication-informed design methodologies that challenge conventional architectural workflows (Burry et al., 2020; Menges & Sheil, 2015).

The digital turn means more than just the adoption of digital tools; it represents a paradigm shift in architectural thinking. Traditionally, architectural design was guided by static representation techniques, with drawings being the primary means of communication between the architect, engineer, and builder. The introduction of computational methodologies has enabled a more fluid, iterative, and data-informed approach to design, where form, material, and structure are conceived simultaneously rather than sequentially (Picon, 2010). This transition has brought about an unprecedented level of adaptability in architectural practice, allowing for complex geometries, real-time environmental simulations, and mass customisation in architectural design.

One of the most defining characteristics of this transformation is the emergence of algorithmic and parametric design as a relational and performance-driven paradigm, where architectural form results from encoded dependencies between geometric, material, environmental, and structural parameters rather than predefined shapes. In contrast to conventional drafting methods rooted in static representation, parametric systems enable continuous variation and feedback, allowing design solutions to be iteratively refined in response to changing inputs across the design process (Kolarevic, 2003; Nagy, Mandour, & Abd-Elsabour Ahmed, 2023). This shift from representation to simulation marks a crucial departure from modernist architectural methodologies, where form was often determined a priori, independent of performance criteria. As a result, contemporary projects increasingly exhibit a synthesis of computational logic, material behaviour, and digital fabrication constraints, demonstrating how digital tools have evolved from mere representational devices to generative instruments that shape the very logic of architectural production.

At the same time, the integration of digital fabrication technologies - including robotic assembly, CNC milling, and additive manufacturing (3D printing) - has redefined the relationship between design and construction. Traditionally, the design process culminated in a set of static drawings that were then interpreted and executed manually. In contrast, the digital turn allows for direct data translation from digital models to material fabrication, minimizing human error, reducing material waste, and improving efficiencies in construction (Gamal, Nashaat, Shahda, & Nosier, 2024; Gramazio & Kohler, 2014). This approach has introduced new possibilities for customisation, enabling architects to design and fabricate highly specific components that respond directly to performance criteria (Sousa, 2017). Furthermore, it has fostered a new form of digital craftsmanship, where material behaviour and fabrication constraints inform the generative design process itself.

The digitalisation of architecture has also introduced new methodological frameworks that redefine how architects conceive, develop, and execute designs. The rise of parametric and algorithmic design has led to the adoption of computationally defined relationships that allow for self-adaptive

geometries, enabling mass customisation and optimisation (Schumacher, 2009). These methodologies have significantly impacted contemporary architectural projects, moving beyond the standardised, modular logic of modernism toward more fluid, performative, and context-responsive solutions. By leveraging computational power to analyse structural, environmental, and material performance in real time, architects can create more resilient and adaptive built environments that respond dynamically to changing conditions.

Building Information Modelling (BIM) has further transformed architectural workflows, facilitating integrated, multidisciplinary collaboration. Unlike traditional two-dimensional design documentation, BIM provides a data-rich, parametric representation of buildings, incorporating real-time information on material properties, cost analysis, structural performance, and construction logistics (Garber, 2014). The extensive adoption of BIM has streamlined project coordination, by reducing errors and enhancing efficiency in large-scale architectural projects. When integrated with digital fabrication workflows, BIM allows for automation in construction processes, enabling prefabrication, robotic assembly, and modular construction techniques (Kolarevic & Klinger, 2008). This transformation reinforces how the digital turn has fundamentally shifted the role of the architect from a form-giver to a computational strategist, emphasizing the synthesis of data, simulation, and material production.

The introduction of artificial intelligence in architecture has further reshaped design thinking, introducing machine-learning-based design generation where computational models analyse large datasets to optimise spatial performance, energy efficiency, and structural feasibility (Leach, 2017). AI-assisted design tools demonstrate how algorithmic intelligence is becoming an integral part of architectural decision-making, allowing architects to automate design iterations, enhance predictive modelling, and explore previously unattainable design solutions. This computational approach aligns with the emergence of responsive and performative architecture, where building systems dynamically adapt to environmental changes and user behaviour. AI-driven urban planning and architectural design highlight how digitalisation is influencing the broader scale of cities, optimising zoning regulations, transportation networks, and energy grids through data-informed strategies (Carpo, 2017).

The digital turn has not only transformed design methodologies but has also reconfigured construction processes through model-based integration of design and fabrication, where BIM-centred workflows, DfMA principles, and AI-supported decision-making enable robotic fabrication, automated assembly, and mass-customised prefabrication to be coordinated from early design stages (Han et al., 2025). The development of large-scale 3D printing technologies has enabled the fabrication of entire building components with minimal material waste. Robotic construction has enhanced precision, speed, and safety, allowing for non-standard, geometrically complex assemblies that would be difficult to achieve through traditional methods (Gramazio & Kohler, 2008; Oxman & Oxman, 2014). The incorporation of smart materials - such as self-healing concrete, phase-change materials, and

responsive facades - demonstrates how material intelligence is increasingly integrated into digital design workflows, leading to buildings that dynamically interact with their environments (Glynn & Shafiei, 2009; Hensel, 2013; Sousa, Henriques, Xavier, 2019).

The transformation brought by the digital turn extends beyond the design and construction processes, restructuring the architectural office itself. Traditional professional hierarchies are being replaced by more interdisciplinary models, where architects work alongside computational designers, software developers, robotic specialists, and material scientists. The role of the architect has evolved beyond conventional design tasks to include expertise in data analysis, programming, and digital fabrication. Cloud-based design platforms and remote collaboration tools have globalized architectural practice, allowing offices to operate across multiple geographies in real-time. New economic models have emerged, where architectural offices offer customised, parametric design solutions and on-demand fabrication services, challenging the conventional fee-for-service model (Carpo, 2017).

The digital turn in architecture represents a fundamental shift in design thinking, construction processes, and professional practice. By integrating computational methodologies, algorithmic intelligence, and digital fabrication, architects are redefining traditional workflows and exploring new paradigms of authorship, collaboration, and production. As digital tools continue to evolve, their impact on sustainability, material innovation, and responsive environments will further shape the future of architectural practice. This transformation underscores the need for architects to continuously adapt to emerging technologies, ensuring that architecture remains at the forefront of digital innovation while retaining its critical and theoretical foundations.

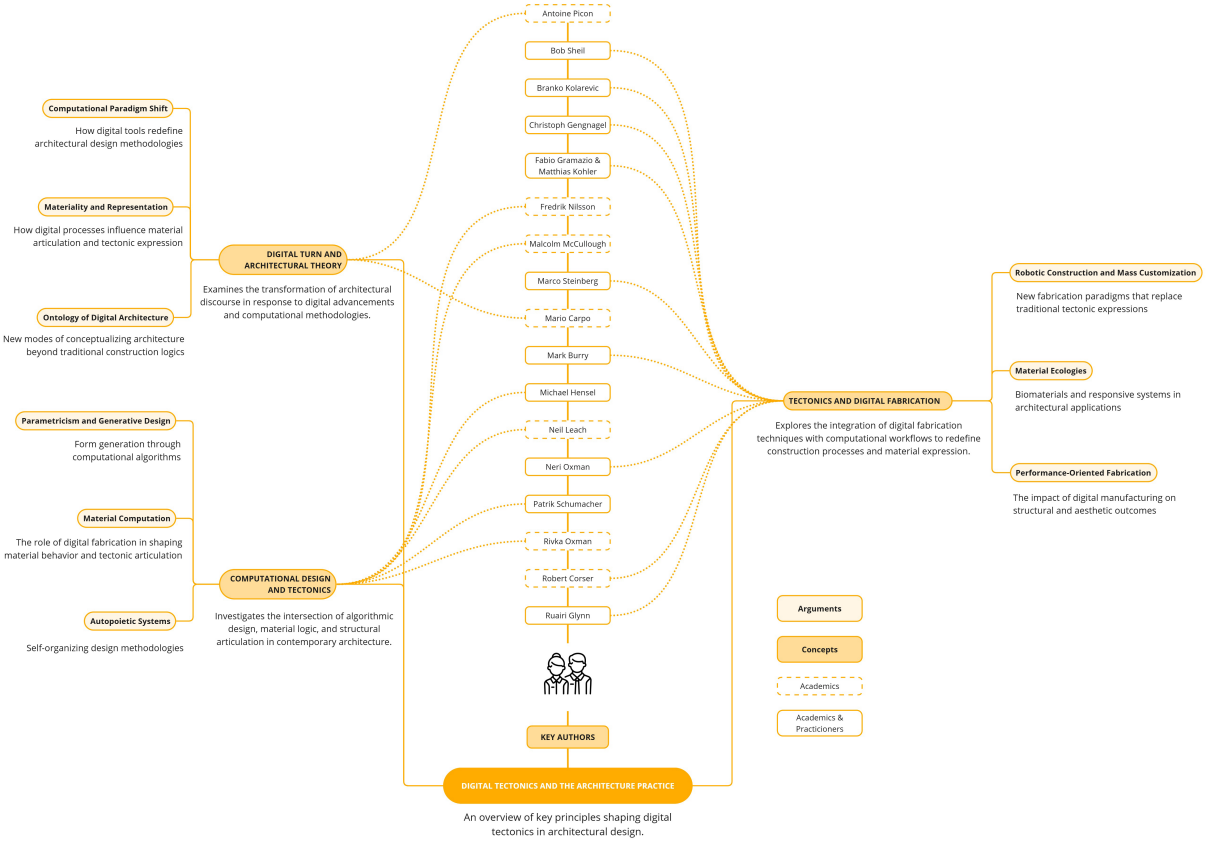


Figure 1.2: Mind Map on the Conceptual Landscape of Digital Tectonics in Architectural Theory and Practice. Enlarged version available in Annex L, Figure L.1.

Figure 1.2 visualizes the conceptual structure established in Section 1.1, mapping digital tectonics as a continuous framework that links architectural theory, computational design methodologies, and digital fabrication practices. Rather than presenting discrete categories, the diagram articulates digital tectonics as a progressive continuum in which theoretical shifts introduced by the digital turn are operationalised through computation and materialized through fabrication.

At the centre of the diagram is a shared intellectual framework informed by key theorists and practitioner–researchers, including Mario Carpo, Antoine Picon, Neil Leach, Patrik Schumacher, Rivka Oxman, and Fabio Gramazio and Matthias Kohler, among others. Their work establishes the theoretical, methodological, and material foundations from which the three domains emerge. The diagram therefore functions not only as a thematic overview, but as an analytical structure that clarifies how architectural discourse, computational processes, and fabrication technologies converge within digital tectonics. These three domains structure the remainder of this chapter and correspond directly to the analytical framework developed in the mind map.

Digital Turn and Architectural Theory

The first domain, Digital Turn and Architectural Theory, examines how architectural discourse has been transformed in response to digital technologies and computational methodologies. This domain addresses the conceptual shift from static representation toward generative, systemic, and information-driven modes of thinking, as articulated by authors such as Mario Carpo and Antoine Picon.

The subsection Computational Paradigm Shift describes how digital tools redefine architectural design methodologies by introducing algorithmic thinking, parametric variation, and iterative design processes. Architecture is no longer conceived as a fixed formal outcome, but as a set of rules and relationships capable of continuous adaptation.

Materiality and Representation focuses on how digital processes reshape the relationship between form, material articulation, and tectonic expression. Rather than abstracting materiality, digital representation enables new forms of precision, simulation, and material awareness, prompting a rethinking of how materials are conceived and communicated in design.

Ontology of Digital Architecture addresses deeper conceptual implications, proposing new modes of architectural thinking that extend beyond traditional construction logics. In this view, architecture is understood as an informational, relational, and process-driven system, laying the theoretical groundwork for later integration with computation and fabrication.

Computational Design and Tectonics

Building on this theoretical foundation, the second domain, Computational Design and Tectonics, investigates how architectural ideas are operationalised through algorithmic design, material logic, and structural articulation. Drawing on the work of Fredrik Nilsson, Malcolm McCullough, Michael Hensel, Neil Leach, Patrik Schumacher, and Rivka Oxman, this domain focuses on the methodological dimension of digital tectonics.

Parametricism and Generative Design explores form generation through computational algorithms, where design emerges from parameter-driven systems rather than predefined geometries. Tectonic articulation becomes a consequence of relational rules and data-driven variation.

Material Computation examines the role of computation in shaping material behaviour and tectonic articulation. Here, digital fabrication knowledge begins to inform design decisions, as material performance, structural behaviour, and fabrication constraints are embedded within computational models.

Autopoietic Systems describe self-organising design methodologies in which architectural systems evolve through feedback loops between geometry, material, and performance. This approach

reinforces the idea of tectonics as an emergent property of computational processes rather than a purely representational or stylistic concern.

Tectonics and Digital Fabrication

The third domain, Tectonics and Digital Fabrication, addresses the material realisation of digital tectonic thinking through the integration of digital fabrication techniques within computational workflows. Informed by the work of Ruairi Glynn, Robert Corser, Neri Oxman, Mark Burry, Marco Steinberg, Fabio Gramazio and Matthias Kohler, Christoph Gengnagel, Branko Kolarevic, and Bob Sheil, this domain focuses on how making re-enters architectural design as an active and generative process.

Robotic Construction and Mass Customisation examines new fabrication paradigms enabled by robotics, CNC machining, and additive manufacturing, which challenge traditional tectonic expressions. Projects such as those developed by Gramazio and Kohler demonstrate how robotic fabrication allows building components to be produced directly from design data, enabling mass customisation while maintaining precision and material intelligence.

Material Ecologies expands this perspective by framing materials, fabrication processes, and environmental performance as interconnected systems. This subsection addresses biomaterials, responsive systems, and material agency, highlighting how digital fabrication supports more adaptive and sustainable architectural practices.

Performance-Oriented Fabrication focuses on the impact of digital manufacturing on structural, environmental, and aesthetic outcomes. Here, fabrication constraints and performance criteria actively inform design decisions, positioning fabrication not as a downstream technical phase, but as a driver of tectonic innovation.

Taken together, the three domains illustrated in Figure 1.2 demonstrate that digital tectonics operates as a continuous design-to-production framework, linking architectural theory, computational methodologies, and fabrication practices. The diagram clarifies how theoretical discourse informs computational design strategies, which in turn enable fabrication-driven tectonic innovation.

This structure provides the conceptual basis for the present research, which positions itself within the Tectonics and Digital Fabrication domain while building upon the theoretical and computational foundations established in the preceding sections. By explicitly mapping these relationships, the diagram supports a critical reflection on how digital fabrication can be integrated earlier and more systematically into architectural practice, reinforcing tectonics as a central component of digital architectural thinking rather than a secondary technical concern.

1.1. Digital Tectonics and the Architecture Practice

The concept of digital tectonics, as discussed by Leach et al. (2004), emphasizes the integration of form, material, and fabrication in the digital age. It has long been central to architectural discourse, evolving from its classical roots in craftsmanship and structural expression to a digitally driven paradigm that integrates computational design and digital fabrication.

In this thesis, digital tectonics is understood as the point of convergence between the theoretical shift introduced by the digital turn and the material realities of construction enabled by digital fabrication. As established in the earlier discussion of the digital turn, the transition from representational to computational design fundamentally altered how architecture is conceived, shifting emphasis from static form to process, logic, and performance. Tectonics and digital fabrication therefore do not constitute a separate or subsequent phase, but rather represent the material continuation of this conceptual transformation. Digital tectonics emerges when computational design logics are translated directly into fabrication strategies, allowing structural articulation, material behaviour, and construction processes to be conceived as an integrated system rather than as sequential stages.

Historically, tectonics referred to the articulation of form, structure, and material, emphasizing the relationship between construction techniques and architectural expression. The origins of tectonic theory can be traced back to 19th-century architectural discourse, with figures such as Karl Bötticher and Gottfried Semper emphasizing the intrinsic relationship between material, form, and structure. Bötticher conceptualized tectonics as a duality between Kunstform (artistic form) and Werkform (structural form), where ornamentation was directly informed by structural logic (Frampton, 1996). Semper, in contrast, proposed the Four Elements of Architecture, categorizing tectonic expression into stereotomic and tectonic systems – one derived from heavy, mass-based construction, such as masonry, and the other from light, framework-based construction, such as timber structures (Semper, 1851).

In the 20th century, Kenneth Frampton redefined tectonics as the "poetics of construction," a critique against the postmodern detachment of architecture from material and structure. He argued for a renewed emphasis on craft, structural legibility, and material expression, rejecting the decorative superficiality of postmodernism. Frampton's view of tectonics celebrates the "poetic" interplay of load and support, the expression of joinery, and the craft of making - think of a timber beam clearly resting on a column with an artful join that reveals how it's held together (Carpo, 2025). In this classical view, the joint or connection is celebrated as much as the overall form; architecture's beauty lies in revealing how parts come together. In the mid-twentieth century, design theorist David Pye similarly considered the relationship between craft and production, defining the distinction between "workmanship of risk"

and “workmanship of certainty.” The former celebrates the artisan’s skill and the inherent variability in hand craftsmanship, while the latter relies on predetermined processes (often mechanized) that guarantee a fixed outcome. Pye’s framework, developed in the context of traditional woodworking, presaged concerns about automation in architecture by asking how much spontaneity and human touch should be preserved as building techniques become more mechanized. This notion of tectonics reinforced the expressive capacity of construction, situating materiality and assembly at the core of architectural meaning (Frampton, 1995; Picon, 2010).

The digital turn in architecture brought with it a reinterpretation of tectonics. Early digital avant-garde architects often pursued seamless, curvilinear forms with hidden connections - an aesthetic made possible by technologies like CNC fabrication and fiberglass shells - which some critics saw as a denial of tectonic legibility (Carpo, 2025). This sparked a kind of “culture war” in the 1990s: adopting digital tools meant embracing smooth, continuous surfaces, whereas defending traditional tectonics meant emphasizing assembled parts and joints as an ideological stance (Carpo, 2025). However, as digital practice matured, architects began to seek a new tectonic expression through digital means. The concept of digital tectonics emerged, suggesting that computational design and fabrication can have their own intrinsic structural and expressive logic (Carpo, 2025).

With the advent of computational tools and digital fabrication technologies, digital tectonics has redefined the interaction between design processes, material constraints, and construction methodologies (Frampton, 1995; Kolarevic, 2003; Oxman, 2012). The transition from traditional to digital tectonics marks a significant paradigm shift in architecture, moving beyond the static principles of material assembly towards dynamic, algorithmic, and fabrication-informed processes. This transformation enables architects to conceive of structures that are not merely designed but computationally generated and directly fabricated through digital means. Scholars such as Rafael Puig and Underléa Miotto Bruscato (2020) highlight how the era of digital tectonics has expanded the possibilities of material articulation and construction, dissolving the traditional boundaries between design conception and material execution (Puig & Bruscato, 2020).

Digital tectonics does not merely digitize traditional construction methods but reconfigures the design-to-fabrication continuum, allowing for unprecedented levels of precision, complexity, and material efficiency (Oxman, 2017). It integrates parametric design, generative algorithms, and robotic fabrication into the architectural workflow, creating new aesthetic and structural possibilities (Kolarevic, 2003). Mario Carpo (2017) describes this transformation as the "second digital turn," a shift from representational digital tools such as CAD to generative, algorithmic design systems including BIM, parametric modelling, and AI-driven design. This new mode of production enables mass customisation, where each architectural component can be uniquely optimised for structural performance and material efficiency. According to Carpo, the move from standardisation to

customisation marks a fundamental break from modernist paradigms, allowing for a new form of architectural expressivity (Carpo, 2011).

Rivka Oxman (2017) expands on this idea, arguing that digital tectonics transforms material logic itself, where form is no longer dictated by external structural constraints but rather emerges from computational and material synergies. Her research on material-based computational design demonstrates how architects can embed material intelligence into digital processes, enabling forms that are not only computationally efficient but also materially performative. One key idea in this realm is "digital materiality," introduced by Gramazio and Kohler (2008). Digital materiality refers to the synthesis between computational design and the behaviour of physical matter, a process in which digital instructions are tightly coupled to material properties and fabrication processes. In traditional construction, drawings and plans are abstract until material is cut and assembled, but in digital fabrication the line between design and making blurs: data and material are interwoven, and the algorithm becomes an extension of the craftsman's hand. For example, in robotic fabrication of a timber structure, the wood's grain and flexibility - once considered constraints - can become parameters in the algorithm. Designers can script how a robot should respond to the wood's natural behaviour in real time, effectively letting material feedback shape the form. A striking illustration was the ICD/ITKE Research Pavilion, where digitally cut wood panels were programmed to bend into curved shapes by virtue of their own fibre tension, merging computational design with the material's innate tendencies. Such projects exemplify digital tectonics: the final form is not just digitally conceived but materially computed through feedback loops between bits and atoms.

The integration of robotic fabrication, 3D printing, and CNC milling has fundamentally altered the relationship between design and materialization. Fabio Gramazio and Matthias Kohler (2014) highlight how robotic fabrication introduces a new tectonic language, where construction is no longer constrained by manual craftsmanship but instead informed by data-driven material manipulation. Their research in robotic masonry and adaptive fabrication exemplifies how digital tectonics enables performative material assemblies that respond dynamically to environmental and structural parameters (Gramazio & Kohler, 2014). Branko Kolarevic (2003) categorizes digital fabrication methods into subtractive, additive, formative, and robotic systems, each offering unique possibilities for architectural production. These fabrication strategies allow for high-precision, non-standardised components, enabling customisation at an architectural scale. This shift disrupts industrial-era paradigms of mass production, replacing them with mass customisation, where each building component is optimised through digital design-to-fabrication workflows (Kolarevic, 2003).

Building on these fabrication logics, contemporary digital tectonics is increasingly understood as a pathway to sustainability. Additive Manufacturing (AM) and other digitally controlled processes enable architects to precisely calibrate material distribution to performance demands, minimizing

waste through near-net-shape deposition, toolpath optimisation, and part consolidation (Danish AM Hub, 2024). Parametric, fabrication-aware models link geometry to material provenance and lifecycle data, making it possible to design for disassembly (DfD), repair, and remanufacture from the outset (Brandão, 2022). In practice, digital tectonic strategies integrate bio-based binders and fibbers, recycled aggregates and polymer feedstocks, and hybrid or graded composites, while encoding reversible joints and standardised interfaces to extend component lifespans. Coupled with sensing and robotic execution, components can be re-fabricated, reconditioned, or reprinted in situ, strengthening circular economy flows at the scale of parts, assemblies, and buildings. In this way, the computational precision that expands formal and structural expression simultaneously underwrites resource stewardship - aligning design intent, fabrication data, and material cycles within a coherent, fabrication-informed ecology. Despite the opportunities of digital tectonics, several critical debates persist. Scholars such as Neil Leach (2017) argue that digital tectonics risks losing its connection to material authenticity, as digital processes often favour abstract, algorithmic complexity over constructional logic. The question of digital craftsmanship remains central - how does one reconcile the precision of robotic fabrication with the embodied knowledge of traditional craftsmanship? Moreover, Antoine Picon (2013) critiques the potential homogenization of digital tectonics, where parametric processes lead to overly deterministic, repetitive formal expressions. He warns against algorithmic redundancy, emphasizing the need for a critical approach that balances computational efficiency with tectonic richness.

Indeed, the embrace of digital tectonics has provoked varied reactions within architectural culture. Not all practitioners have welcomed the digital turn uncritically; there is a noted resistance among some architects and builders who fear that an overreliance on computation may undermine core architectural values. Critics argue that parametricism's focus on formal complexity often overlooks social and cultural context, yielding visually striking designs that risk detachment from local needs and meanings. Such scepticism is partly a defence of traditional craftsmanship and intuitive design wisdom, wary that the culture of architecture could become dominated by technical virtuosity at the expense of human-centric concerns. Ethically, questions arise about accountability and authorship when algorithms generate significant portions of a design - if a project's form is largely the product of a script or AI, who bears creative responsibility for its success or failure? Some within the profession caution that this trend might deskill the architect, reducing the role to that of a process manager rather than a master builder. There are also practical and economic worries: a digital divide could emerge in practice, whereby offices and professionals who cannot (or choose not to) adapt to rapid technological change may become marginalized.

Proponents of digital innovation counter that these tools are ultimately extensions of age-old architectural goals - to improve how we visualize, make, and experience buildings - and that architects

can harness them without surrendering their critical agency. They emphasize the importance of education and critical engagement to ensure that technology serves as a means to enrich design, not an end in itself. Many theorists now argue that computation enables a new kind of tectonic expression - one where form, structure, and materiality are integrated from the start by digital means. This reconfiguration of the design–material relationship has even revived some old values in new guise: architects now talk about crafting with code and robots, and making the data or fabrication process legible as part of the architectural experience (for instance, exposing CNC toolpath marks as surface texture, much like chiselling marks in stone). In this way, the digital turn doesn't abandon tectonic principles but reinterprets them through the lens of technology. It challenges architects to think of construction and design as a continuous digital continuum, where the separation between drawing and building breaks down. This ongoing cultural debate highlights that the "digital turn" is not only a technical revolution but also a professional and ethical one. It challenges architects to integrate new tools thoughtfully, maintaining a balance between innovation and the enduring values of context, craftsmanship, and social responsibility in architecture.

1.2. Digital Turn and Architectural Theory

Over the past two decades, numerous theorists have attempted to articulate what the digital turn means for architecture. Early pioneers in digital theory – Branko Kolarevic, Rivka Oxman, Antoine Picon, Mario Carpo, among others – laid the groundwork by analysing how computation would transform design thinking. For instance, Kolarevic (2003) highlighted the rise of CAD/CAM and parametric modelling, predicting a revolution in how architects generate and fabricate forms. Oxman (2017) similarly discussed the shift from geometry-driven design to process-driven design, where algorithms enable unprecedented formal complexity and integration of performance criteria. In Digital Culture in Architecture, Picon (2010) examined how the influx of digital tools was not just a technical shift but a cultural one – altering architects' sensibilities, aesthetics, and even the way they conceive of creativity. These works helped define the first digital turn, when architects moved from analogue to digital processes, and struggled with its implications for authorship, form, and construction.

Cache's theory of computational form anticipates much of contemporary digital tectonics: in Earth Moves he describes parametric "second-generation" design systems that compute unique variations of geometry, producing what he terms 'subjectiles' (surface-derived objects) and 'objectiles' (volume-derived objects) (Cache, 1995). In this view, every component becomes a programmatically generated instance rather than a fixed type, so that material form emerges from parametric logic. Similarly, Lynn's foundational essay on Architectural Curvilinearity frames architecture in topological terms: geometry is conceived as pliant, folded surfaces that "infold" contextual forces into form (Lynn, 1993). Lynn

argues that bending, twisting and folding are not mere formal effects but result from "an intensive curvilinear logic" that integrates cultural and environmental influences within continuous surfaces (Lynn, 1993). These ideas, of architecture as an evolving, algorithmic construct, were recognised early on; the CCA's Archaeology of the Digital notes that Cache's "Non-standard Digital Folding" and Lynn's "Going Primitive" lectures were seen as conceptually anchoring the dialogue around digital form-making (Lynn, 2013). Together, Cache and Lynn's work underscores how digital tools enabled a shift toward process-driven tectonics: objects and assemblies are no longer pre-given types but computationally generated variations, laying an epistemological foundation for today's generative, fabrication-aware design methodologies.

Building on these foundations, Mario Carpo famously introduced the term "the second digital turn" to describe more recent developments (Carpo, 2025). In Carpo's analysis, if the first digital turn was about the proliferation of tools like Rhino, Maya, or 3D printing (essentially explicit computational control), the second digital turn is about the age of big data and artificial intelligence – when design tools start to learn from data patterns rather than follow rules explicitly set by designers (Yuan, 2025). Carpo's latest writings (2023, 2025) position AI as the newest chapter in architecture's ongoing technological evolution, extending the narrative of digital architecture into our current decade. Crucially, Carpo notes a key distinction: unlike the parametric software of the 2000s, which operated on predefined algorithms and rules, today's generative AI systems derive their "knowledge" from vast datasets of existing designs and images (Yuan, 2025). As he succinctly puts it, systems like DALL·E or Midjourney do not truly design in the human sense; rather, they perform an "automated imitation of visual commonplaces," reproducing the statistical average of their crowd-sourced training inputs (Yuan, 2025). In other words, generative AI feeds on precedent. This insight underscores how the digital turn is evolving: from architects coding rules into software (as in parametric design) to architects curating data and guiding AI, which introduces a different mode of authorship. Carpo even provocatively suggests that "there is no creation without imitation," arguing that AI's remixing of precedents simply makes explicit a truth that all design draws on prior knowledge (Yuan, 2025). This perspective helps us contextualize the digital turn not as a finished event but an ongoing story – one that has now arrived at the era of AI-assisted design.

Alongside enthusiastic narratives of progress, critical voices have asked whether the digital turn truly represents a disruptive paradigm shift or rather an incremental evolution. Marcos, Fernández-Álvarez, and Pak (2024) offer one such critique. They investigate whether decades of digital innovation in architecture qualify as a "disruptive innovation comparable to modernism's transformative impact," or if the changes are more superficial. By synthesizing insights across the field, Marcos et al. (2024) chart how computation has undeniably transformed the "triad" of structure, form, and materiality in architectural practice over the years. For example, digital tools have enabled lighter structures through

optimisation, more fluid forms through parametric design, and novel material assemblies via robotic fabrication. Yet, these authors caution that technology alone does not guarantee architectural progress. They call for integrating humanistic meaning into digital design, urging architects not to lose sight of cultural and social values amid the pursuit of technical sophistication. In their view, the digital turn should not be regarded as a neutral or purely technical shift – it demands a critical engagement to ensure that computational methods serve deeper architectural intentions. This critical lens enriches our understanding of the digital turn by reminding us that true innovation in architecture is not measured only by new tools, but by how those tools enable better buildings and experiences.

This transformation is deeply rooted in theoretical explorations that examine the cultural, epistemological, and material implications of digital architecture. The reconfiguration of tectonics within the digital turn has been a subject of analytical exploration, particularly in understanding how computational logic reshapes architectural expression. Antoine Picon emphasizes how the shift from manual craftsmanship to algorithmic design challenges conventional notions of tectonic clarity. He critiques the tendency of parametricism to generate formally complex yet structurally ambiguous configurations, highlighting the risks of a digital fabrication process that prioritizes efficiency over material expressivity. Similarly, Mario Carpo frames this shift within the context of what he calls the "Second Digital Turn", where architecture moves from mass production to mass customisation. His research examines how non-standard design methodologies, facilitated by algorithmic processes, redefine fabrication strategies and material logic. Carpo also warns against an over-reliance on computational automation, where formal exploration risks neglecting constructional integrity and the tectonic legibility of built structures.

In his more recent work, Mario Carpo (2017) characterizes the contemporary moment as a true “second digital turn,” driven by the unprecedented power of computation and information technology. He argues that today’s digital tools have become “tools for thinking” rather than merely tools for making – enabling designers to harness big data, simulation, and optimisation in ways that fundamentally change architectural practice. In practical terms, this means that design is increasingly informed by algorithms that can predict and generate solutions beyond the direct capacity of the human mind, for example using machine learning to evolve forms or solve engineering problems (Carpo, 2017). Parallel to Carpo’s thesis, a post-digital discourse has emerged, suggesting that the field has entered a new phase following the initial digital revolution. The post-digital perspective contends that digital technology is now a ubiquitous and integral part of practice rather than a novelty; it recognises our current moment to be markedly different from the early days of CAD and computational experimentation. Whereas the first digital turn (in the late 20th century) introduced computing into a predominantly analogue profession, the post-digital condition assumes continuous connectivity and computation as a given. Architects today operate in an environment where advanced tools are

omnipresent and accessible, from parametric software to AI-driven design assistants, and this pervasiveness calls for critical reflection. The post-digital argument thus reframes digital architecture not as a niche avant-garde experiment but as the new normal – a cultural habitat in which architects must interrogate how technology alters their thinking, workflow, and authorship. This expanded theoretical horizon, encompassing Carpo's Second Digital Turn and post-digital critiques, highlights that contemporary architectural theory is engaging not just with the adoption of new tools, but with their epistemological implications: how they change the way architects conceptualize problems and solutions, and how the identity of the architect is evolving in response.

The literature of the 2020s has started to grapple with how emergent technologies like Generative AI and advanced robotics fit into (or extend) the narrative of the digital turn. A theme in these discussions is co-authorship between human and machine. Increasingly, designers experiment with generative AI image models or algorithms that can produce design options, effectively making the AI a "co-designer." This development has practical and philosophical implications. On the one hand, it promises to augment the architect's creativity – AI can quickly generate iterations or unexpected ideas, expanding the solution space. On the other hand, it raises questions about authorship and originality (if AI recombines existing precedents, who is the author of the result?). Patrik Schumacher (2024) enters this debate from the angle of architectural aesthetics and authorship. He observes that in contemporary practice – especially one now tinkering with AI – the timeless concept of beauty has been sidelined or treated as irrelevant, seen as too subjective in our hyper-rational, tech-driven design culture. Schumacher argues vehemently against this exclusion, calling it a grave mistake to treat aesthetic judgment as mere "irrationality." Instead, he contends that beauty and aesthetic intuition remain essential, even (or especially) in the age of AI (Yuan, 2025). As algorithms churn out countless forms, Schumacher reminds us that architects still need an "experiential and ethical compass" to discern what is genuinely architecture (and worth building) versus a meaningless output. In his words, generative tools may offer boundless novelty, but architects must ensure that what gets built is not only innovative and efficient, but also meaningful and oriented toward human well-being (Yuan, 2025).

By reasserting the indispensability of beauty and human-centric values, Schumacher provides a timely counterpoint to tech optimism, ensuring that the second digital turn does not eclipse architecture's cultural and experiential dimensions. Meanwhile, Carpo (2025) and others encourage a balanced approach. Rather than viewing AI as an autonomous genius or fearing it as a threat, Carpo suggests seeking a critical middle ground: architects should carefully decide which aspects of design to delegate to machines and which to retain under human control (Yuan, 2025). This echoes a broader notion of "co-agency" in design processes – where human designers and AI systems collaborate, each contributing what they do best. For example, an AI might rapidly generate façade patterns based on data, while the architect evaluates them against contextual, functional, and aesthetic criteria that

require human judgment. Rather than a wholesale automation, the vision is a co-pilot model: the AI as a capable assistant constrained by the architect's intent (Yuan, 2025). Such frameworks ensure that as we embrace the latest digital tools, we don't lose the authorial intentionality and critical oversight that define good architectural practice. Indeed, many voices now stress integration over abdication – using AI and computation to enhance creativity and efficiency, but always guided by an architect's curatorial eye and ethical considerations.

As digital tectonics continues to evolve, its theoretical framework remains shaped by a critical balance between formal innovation, material performance, and tectonic articulation. The interplay between computation and craft, as examined by these theorists, ensures that architecture remains not just a product of digital processes, but a synthesis of technological precision and expressive construction, reinforcing its role as both an art and a science.

1.3. Computational Design and Tectonics

The emergence of digital tectonics as a fundamental shift in architectural theory and practice has been driven by several key theorists who have critically examined the interplay between digital technologies, material articulation, and computational design. This discourse has evolved as a response to both the possibilities and challenges introduced by computational tools, generative algorithms, and digital fabrication techniques. By integrating these elements into architectural workflows, contemporary theorists have redefined the role of tectonics within digital environments, bridging the gap between traditional construction methodologies and computationally driven paradigms. Rather than constituting a unified theory, digital tectonics has been shaped through intersecting lines of inquiry developed by architectural theorists and practitioner-researchers. These contributions articulate how computation reshapes architectural thinking (Carpo, Picon), how material intelligence and fabrication feedback inform form generation (Oxman, Gramazio & Kohler), and how authorship, performance, and automation challenge traditional disciplinary boundaries (Leach, Schumacher). Together, these positions establish the conceptual and methodological conditions from which the three branches of the mind map emerge: computational design logics, material-performative systems, and fabrication-driven tectonic articulation.

The evolution of computational design has profoundly influenced digital tectonics by reframing architecture as an emergent outcome of algorithmic processes. Parametricism, as articulated by Patrik Schumacher, situates computation as a driver of spatial and tectonic coherence, though critics highlight risks of formal excess detached from constructional logic.

Rivka Oxman's work on material computation shifts tectonic reasoning toward material behaviour, where form emerges from computational–material feedback rather than abstract

geometry. Neil Leach extends this discourse by examining the epistemological consequences of AI and machine learning, emphasizing performance over representation.

These developments also provoke questions of authorship and creativity. Carpo argues that the Alberti model of sole authorship has been replaced by distributed agency between humans and machines. While algorithmic tools expand the design solution space, concerns persist regarding homogenization, responsibility, and loss of intuition. The emerging consensus frames architects as orchestrators of computational processes, curating and guiding machine intelligence rather than relinquishing authorship.

1.4. Tectonics and Digital Fabrication

The contributions of Fabio Gramazio and Matthias Kohler to the discourse on digital tectonics are particularly relevant in the field of robotic fabrication. Their research at ETH Zürich's Gramazio Kohler Research focuses on the intersection of computational design and robotic construction, demonstrating how digital tectonics can materialize through automation. Their experiments with robotic bricklaying, adaptive timber assemblies, and large-scale additive manufacturing illustrate how digital tools can directly inform fabrication processes, creating an integration between design and construction (Gramazio & Kohler, 2014). Their work highlights the potential of robotic fabrication to enhance the precision and adaptability of architectural elements, challenging traditional notions of tectonic craftsmanship.

Contemporary research is also exploring how robotic fabrication can incorporate human skill in tandem with automation, rather than replacing it. For instance, Gramazio and Kohler's team has demonstrated how human craftsmanship might interface with robotic precision in an augmented bricklaying project. In this case study, a complex brick facade for a winery in Greece was constructed by masons working in concert with a robotic system: the human builders laid bricks guided by an augmented reality interface, while a robotic arm ensured each unit's placement conformed to the digital design geometry (Mitterberger et al., 2020; Gramazio Kohler Research, n.d.). This human–machine collaboration allowed the project to achieve a level of complexity and customisation that neither the mason nor the robot could have accomplished alone. The masons contributed their tacit knowledge of material and skilled handling, and the robot provided accuracy and repeatability, embodying the concept of digital craftsmanship. Such examples illustrate that digital tectonics need not eliminate the role of the craftsman; instead, it can create new synergies where craft is enhanced by computation. The architect's role in these scenarios often extends to designing the process and tools for collaboration - effectively choreographing how human and machine work together. The result is a richer tectonic outcome, one that leverages algorithmic exactitude without forfeiting the variability

and intuition of human labour. This line of inquiry reinforces the idea that the future of digital fabrication can balance efficiency with expression, merging the age-old pride of workmanship with the opportunities of advanced technology.

Other theorists have also contributed significantly to the field of digital tectonics. Bob Sheil's investigations into experimental making and non-standard construction processes explore the performative and expressive potential of robotic fabrication (Sheil, 2012; Burry et al., 2020). Ruairi Glynn's research into interactive and kinetic architectures examines how computationally driven systems can create dynamic, responsive environments (Glynn, 2014). Marco Steinberg and Christoph Gengnagel have explored the implications of computational construction and structural optimisation, respectively, advancing the role of digital technologies in engineering-informed design strategies (Steinberg, 2015; Gengnagel, 2016). Robert Corser's work on material systems in robotic fabrication, Branko Kolarevic's research on digital manufacturing, and Mark Burry's explorations into digital heritage preservation further enrich the theoretical landscape of digital tectonics (Corser, 2012; Kolarevic, 2003; Burry, 2016). Collectively, these theorists have shaped contemporary understandings of digital tectonics, each contributing unique perspectives on the integration of computation, materiality, and fabrication. Their work emphasizes the need to critically engage with digital tools, ensuring that technological advancements serve not only as instruments of formal exploration but also as catalysts for a deeper, more meaningful architectural expression. As digital tectonics continues to evolve, ongoing research must address the challenges of algorithmic standardisation, material intelligence, and constructional integrity, ensuring that architecture remains both innovative and structurally articulated in the digital age.

1.4.1. Robotics Construction and Mass Customisation

This branch represents the structural and organisational dimension of digital tectonics, where automation and variation redefine how tectonic systems are assembled and coordinated. The Robotic Construction and Mass Customisation branch captures a defining tectonic consequence of digital production: the capacity to fabricate non-standard parts reliably, and to assemble them through programmable sequences. Here, mass customisation is not simply formal variation; it is a tectonic model in which joints, tolerances, and component differentiation become manageable through data-driven workflows. This logic aligns with Carpo's account of the "second digital turn," where non-standard variation becomes feasible at scale because digital models can drive fabrication directly, reducing dependence on repetitive standard types (Carpo, 2017).

From a tectonic perspective, robotics and automated assembly shift attention toward process design: how components are oriented, picked, placed, fastened, or bonded; how fabrication constraints shape geometry; and how assembly logic becomes a generator of form. In this context,

robotic systems do not merely execute a completed design; they actively influence the design's constructability and articulation. The tectonic "detail" is no longer drawn only as representation; it is also encoded as instruction, tested through prototyping, and refined through machine capabilities. This reframes the relationship between craft and automation: rather than eliminating craft, robotic production can relocate craft into the design of sequences, toolpaths, and interfaces, where human judgement guides the use of machine precision.

The branch also foregrounds the organisational implications of mass customisation. If every component can be different, workflows must support variation without losing coordination. Digital tectonics therefore intersects with project delivery and collaboration: architects increasingly coordinate with engineers, fabricators, and machine operators, integrating fabrication planning earlier to ensure that geometric ambition aligns with material behaviour and production constraints. In this sense, robotic construction becomes a tectonic driver because it forces architecture to treat making not as a final stage but as a continuous constraint and opportunity shaping design decisions from the outset.

1.4.2. Material Ecologies

This branch shifts tectonic discourse from assembly alone to material behaviour and environmental interaction, framing digital tectonics as an ecological and performative system. The Material Ecologies branch shifts the discussion from machines to matter, arguing that digital tectonics is equally defined by how computation engages material behaviour, environmental responsiveness, and lifecycle thinking. This branch builds directly on Oxman's proposition that material intelligence can be embedded into design processes, allowing form to emerge from computational–material synergies rather than from abstract geometry alone (Oxman, 2017). Under this lens, "ecology" does not refer only to sustainability as a moral imperative; it refers to systems in which material properties, structural behaviour, and environmental conditions are treated as active participants in tectonic articulation.

Material ecologies therefore expand tectonic reasoning in two directions. First, they broaden what counts as tectonic "expression": instead of celebrating the joint solely as a visible articulation of assembly, tectonic meaning can be expressed through responsiveness, adaptation, and performance, how a material reacts to humidity, temperature, load, or time. Second, they reframe design as the orchestration of behaviours across scales, from material microstructure to building assemblies. Digital workflows enable this by linking simulation, parametric control, and fabrication constraints, so that the same model can coordinate geometry, material distribution, and production logic.

This branch also connects digital tectonics to contemporary sustainability agendas by emphasizing how digitally controlled fabrication can support material efficiency, circularity, and lower-impact systems. When design models encode provenance, disassembly logic, or repair strategies, tectonics

becomes aligned with resource stewardship rather than solely with expressive assembly (Brandão, 2022; Danish AM Hub, 2024). Yet the branch remains critical: ecological claims must be evaluated against real production conditions, supply chains, and construction practices. A material ecology approach therefore strengthens tectonic thinking precisely because it demands accountability, linking formal ambition to material consequence.

1.4.3. Performed-Oriented Fabrication

This branch positions fabrication as an evaluative and generative feedback loop, where tectonic decisions are continuously informed by measurable performance outcomes. The Performance-Oriented Fabrication branch positions fabrication as a feedback mechanism through which architectural performance is tested, measured, and refined. Rather than treating making as execution, this branch emphasises the loop between modelling, prototyping, and production constraints, where performance criteria (structural, environmental, or experiential) directly shape fabrication strategy, and fabrication outcomes inform design revision. This logic is central to digital tectonics because it ties tectonic articulation to verifiable behaviour: details, assemblies, and material distributions are iterated not only for appearance but for performance.

Performance-oriented fabrication extends the idea of computation as "tools for thinking" into the realm of construction: the fabrication process becomes a site where design assumptions are validated against physical reality. Toolpaths, machine tolerances, curing times, bending limits, or assembly sequencing are not external constraints added later; they become design parameters that restructure form and detail. This resonates with critiques of purely formal parametricism: tectonic richness is strengthened when computation remains accountable to constructional logic and material behaviour (Picon, 2013; Leach, 2017). It also addresses the craft debate: performance feedback does not eliminate judgement; it intensifies the need for judgement, because interpreting performance results and balancing competing criteria remains a human responsibility.

In practice, performance-oriented fabrication encourages workflows that combine simulation with prototyping, and prototyping with iterative redesign. It fosters a tectonic culture where the "detail" is not finalized only in drawings, but through successive cycles of modelling, making, and evaluation. As such, this branch provides a key bridge to later discussions of fabrication integration in professional practice: it shows why digital fabrication belongs upstream in design, not merely as production capacity, but as a mechanism of architectural intelligence.

In closing this chapter, it's clear that the digital turn has been a multifaceted revolution, one that started with computers entering the drafting room and has led, several decades later, to algorithms and AI co-creating alongside architects. This journey has dramatically expanded architecture's toolkit:

parametric modelling, simulation, robotic fabrication, and now machine learning are part of the architect's lexicon. But as the updated perspectives in this chapter show, each new wave of technology invites us to revisit fundamental questions. What does it mean to design when part of the "intelligence" resides in our tools? How do we retain authorship, craftsmanship, and meaning in a process suffused with computation? The "digital turn" is not merely a story of increasing automation or efficiency; it is about redefining the role of the architect and the potential of architecture itself. Embracing generative AI, for example, could herald unprecedented creativity and personalization in design, yet it also challenges architects to guide these tools with wisdom, ensuring that projects remain grounded in human needs and ethical considerations (Yuan, 2025). In practice, the architect of the digital era must be both a technologist and a humanist: fluent in algorithms and fabrication protocols, yet equally concerned with beauty, context, and social purpose. The following chapters will continue to explore how this balance plays out in architectural practice, but the foundation laid here (a deepened understanding of the digital turn) will inform that exploration. As we move forward, one thing is certain: the dialogue between tradition and innovation, between the physical and the digital, will continue to shape the trajectory of architecture in the years to come. However, despite these profound shifts in theory and capability, robotic fabrication's integration into routine practice remains limited. This gap between what is possible in theory and what is realised in practice forms the central problem this thesis addresses.

CHAPTER 2

Digital Design and Fabrication Methodologies in Architectural Practice

The digitalisation of architectural practice has fundamentally transformed how architecture is conceived, developed, and materialised. While early digital tools primarily served representational purposes, supporting drafting, visualisation, and documentation, contemporary computational approaches extend far beyond representation. Today, digital design operates as a generative, analytical, and materially informed methodology that actively shapes architectural decision-making from concept to construction. This transformation constitutes an epistemological shift in architectural practice, redefining how knowledge is produced, evaluated, and applied through design.

This chapter examines the evolution of digital design methodologies and their impact on architectural practice, with particular attention to the growing integration of digital fabrication. Parametric and algorithmic design, performance-driven modelling, interaction design, and integrative design-research practices have progressively shifted architecture from static, linear workflows toward dynamic, iterative, and feedback-driven processes. In these workflows, computation mediates not only form generation but also material behaviour, fabrication constraints, and environmental performance, enabling design to operate as a continuous negotiation between intent, data, and making (Carpo, 2017; Oxman, 2017).

Rather than treating digital fabrication as a downstream technical phase, contemporary architectural practice increasingly incorporates fabrication logic at the earliest stages of design. Computation thus operates as an integrated design-and-fabrication methodology, reconfiguring traditional distinctions between drawing and building, theory and practice, and design and construction. Digital tools no longer merely describe architecture; they actively participate in its production, transforming architectural knowledge into executable information.

The chapter is structured around two complementary perspectives. Section 2.1 conceptualizes digital fabrication as a design strategy, examining its role in shaping architectural thinking, authorship, material intelligence, and innovation within practice. Section 2.2 then analyses digital fabrication as a workflow, focusing on the operational structures, technologies, and collaborative processes through which digital design is translated into built form. Together, these sections frame digital fabrication not as a discrete technological add-on, but as a central methodological shift redefining architectural practice in the digital age.

By framing digital fabrication as both a conceptual strategy and an operational methodology, this chapter establishes the theoretical basis for the analytical and empirical investigation that follows, informing the development of the Strategic Framework for Digital Architectural Practice (SFDAP) and its application to contemporary architectural offices.

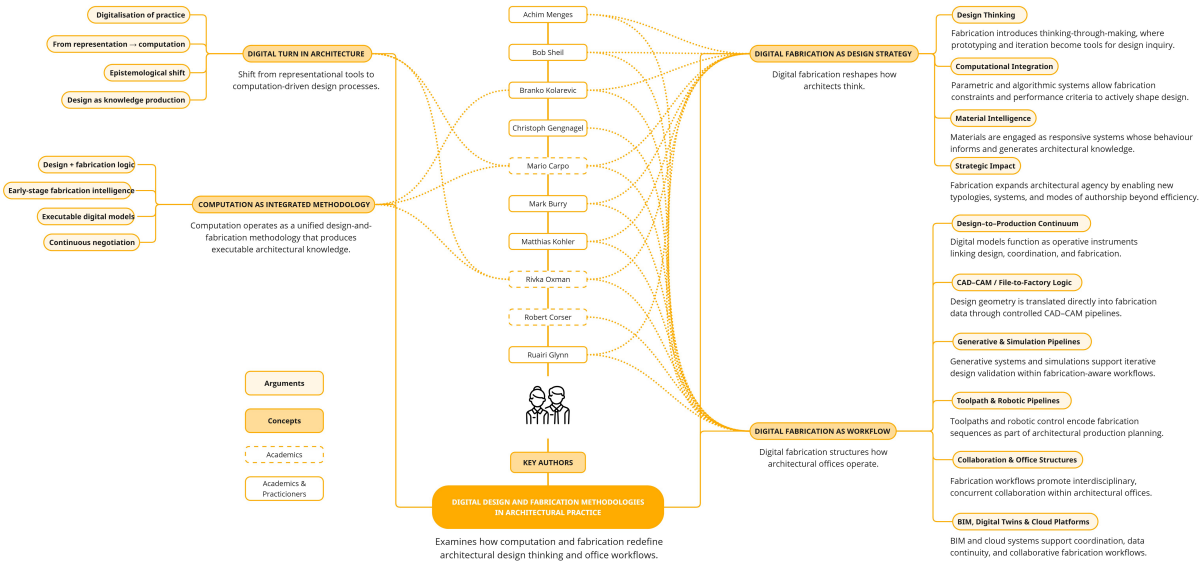


Figure 2.1: Mind Map on Digital Design and Fabrication Methodologies in Architectural Practice, outlining digital fabrication as both a design strategy and an operational workflow shaping contemporary architectural practice. Enlarged version available in Annex L, Figure L.2.

The organisation of the mind map (Figure 2.1) reflects a deliberate effort to structure digital fabrication as a dual methodological condition within contemporary architectural practice, articulated through two complementary strands: digital fabrication as a design strategy and digital fabrication as an operational workflow. This structure acknowledges the broader digital turn in architecture as an epistemological shift, in which computation moves beyond representation to become a medium for producing architectural knowledge. By grounding the map in foundational theoretical contributions, such as those of Carpo and Oxman, while simultaneously drawing on research-through-design and practice-based authors, the chapter positions digital fabrication as both a conceptual framework and a professional reality. The strategic strand foregrounds how fabrication reshapes architectural thinking through processes of thinking-through-making, material intelligence, and expanded design agency, while the workflow strand translates these conceptual shifts into the concrete organisational, technological, and collaborative structures of architectural offices. The pairing of these strands is intentional: it resists a purely theoretical reading of digital fabrication, as well as a purely technical one, and instead frames fabrication as a connective methodology linking design cognition, computational systems, and production processes. In this sense, the mind map operates not merely

as a synthesis of existing discourse, but as a structuring device that situates this research at the intersection of theory and practice, providing the conceptual and operational grounding for the development of the Strategic Framework for Digital Architectural Practice (SFDAP) and the empirical analysis that follows.

2.1. Digital Fabrication as a Design Strategy

Digital fabrication has emerged as a transformative design strategy within contemporary architectural practice, redefining the relationship between conception, materialisation, and construction. Unlike conventional workflows, where design development and fabrication are sequential and largely disconnected, digital fabrication enables architects to integrate material logic, production constraints, and assembly intelligence directly into the design process. This integration allows digital models to function not merely as representations, but as operative instruments capable of generating, testing, and materialising architectural ideas.

Importantly, this section approaches digital fabrication not as an experimental or purely academic pursuit, but as it is increasingly implemented within architectural offices. In practice, fabrication-driven strategies are being adopted as part of everyday design workflows, influencing how projects are conceptualized, iterated, and delivered. As such, digital fabrication operates as a strategic framework that reshapes architectural thinking, rather than simply as a set of advanced construction techniques.

2.1.1. Digital Fabrication and Design Thinking

Introducing fabrication considerations at the early stages of design fundamentally alters architectural thinking. When architects work fluidly between digital models and physical prototypes, design becomes an iterative process of exploration grounded in material feedback. This mode of practice aligns with what Glynn and Sheil (2011) describe as "making as a form of inquiry," in which fabrication is not a final step but a means of generating knowledge throughout the design process. Prototyping, testing, and even failure become productive moments that inform subsequent design decisions.

This approach fosters a culture of experimentation within architectural offices. Rather than committing to a single solution early on, architects can explore multiple design variants in parallel, rapidly fabricating and evaluating alternatives. As Burry (2011) argues, this iterative mindset requires architects to embrace complexity, uncertainty, and non-linearity as integral to creative practice. Digital fabrication supports this shift by lowering the cost, both temporal and economic, of testing ideas, thereby encouraging conceptual risk-taking and speculative design.

In offices equipped with in-house fabrication facilities, such as fab labs or maker spaces, this strategic integration becomes even more pronounced. Architects gain direct agency over

materialization processes, enabling them to prototype ideas at multiple scales and to refine designs through continuous feedback between digital and physical environments. This proximity between design and making embeds fabrication intelligence within the architectural project from its inception.

2.1.2. Integration with Computational Design

Digital fabrication as a design strategy is inseparable from computational design methodologies. Parametric and algorithmic tools allow architects to encode design intent, material behaviour, and fabrication constraints within adaptable systems rather than fixed geometries. In this context, form is no longer predetermined; it emerges through the interaction of parameters, rules, and performance criteria.

Kolarevic (2003) describes this condition as a "digital praxis" in which design, analysis, and production converge. Fabrication parameters, such as machine tolerances, material limits, and assembly logic, become active drivers of design rather than downstream constraints. As a result, architectural form and fabrication processes co-evolve, producing solutions that are both formally expressive and materially viable.

This integration also transforms collaboration within architectural offices. Computational designers, engineers, and fabrication specialists increasingly work alongside architects from the earliest project phases, contributing expertise that informs both conceptual and technical decisions. Shared digital environments, parametric models, BIM platforms, and simulation tools facilitate this interdisciplinary exchange, reinforcing digital fabrication's role as a strategic organiser of design workflows rather than a specialised technical service.

2.1.3. Material Intelligence and Design Knowledge

A key contribution of digital fabrication as a design strategy lies in its capacity to enhance material intelligence. Rather than selecting materials from predefined catalogues, architects can engage with materials as responsive systems whose properties, such as strength, flexibility, porosity, or thermal performance, are actively explored and manipulated through design.

Digital fabrication enables architects to engage with material behaviour as a design variable rather than a fixed constraint. Through iterative feedback between design intent and material response, architectural knowledge emerges from direct engagement with making, reinforcing fabrication as a source of design intelligence rather than a purely technical operation.

2.1.4. From Efficiency to Innovation

While digital fabrication undeniably improves efficiency and precision, its strategic significance extends beyond optimisation. By integrating making into the design process, architects are encouraged to

rethink conventional typologies, construction logics, and aesthetic norms. Digital fabrication enables the exploration of novel structural systems, bespoke components, and non-standard assemblies that would be impractical or prohibitively expensive using traditional methods.

While digital fabrication improves precision and coordination, its strategic significance lies in how it reshapes architectural thinking. By embedding making within the design process, fabrication-informed practice encourages architects to reconsider conventional design logics and professional roles. Fabrication thus functions as a strategic driver that extends architectural agency into materialization, without reducing design to technological determinism.

Digital fabrication functions as a design strategy that reshapes architectural practice at a fundamental level. It transforms how architects think, how they engage with materials, and how they collaborate within interdisciplinary teams. By embedding fabrication intelligence into the design process, architectural offices cultivate a mode of practice that is iterative, experimental, and materially grounded. Digital fabrication thus operates not only as a means of making architecture, but as a strategic mechanism for expanding architectural design intelligence by reconnecting conception, materiality, and construction.

2.2. Digital Fabrication workflows in Architectural Practice

While digital fabrication operates as a strategic framework shaping architectural thinking (as discussed in Section 2.1), it also manifests concretely through specific workflows that structure how architectural offices design, coordinate, and produce buildings. These workflows redefine the operational relationship between digital models, fabrication technologies, and construction processes, enabling a continuous flow of information from design conception to material execution.

In contemporary practice, digital fabrication workflows are commonly described as a design-to-production continuum, in which digital models integrate design intent, simulation data, and fabrication logic within a single computational environment (Gramazio & Kohler, 2008; Menges & Sheil, 2015). Rather than relying on linear sequences of drawings and specifications, architectural offices increasingly employ data-rich models that directly inform manufacturing and assembly processes. This shift alters not only how buildings are produced, but also how architectural teams collaborate and make decisions.

In practice, office-based digital fabrication workflows typically combine three interconnected layers: (1) CAD–CAM translation, where design models generate fabrication-ready data; (2) generative and simulation tools, which support iterative design development and performance checking within the same model environment; and (3) toolpath and robotic control, where fabrication sequences and

constraints are encoded as part of production planning. These layers are not universally adopted at the same intensity across firms, but they provide a useful structure for describing how information moves from design intent to fabrication output within contemporary offices.

2.2.1. Digital Design–to–Production Continuum

At the core of contemporary fabrication workflows lies the transformation of the digital model into an operative instrument. Parametric and BIM-based environments enable architects to embed geometric constraints, material parameters, and production requirements within a shared model, allowing design changes to propagate across multiple levels of detail. In this context, the model functions simultaneously as a design tool, a coordination platform, and a source of fabrication data.

Kolarevic (2003) describes this convergence as a "digital praxis" in which design, analysis, and fabrication are connected through computational processes rather than manual translation. Operationally, this means that model structure, naming conventions, parameter logic, tolerances, and component hierarchies are no longer neutral representational choices: they directly affect how fabrication information is extracted, checked, and communicated.

Within office practice, this continuum typically involves structured model handoffs and verification stages, such as: model rationalization (aligning geometry with fabrication constraints), model-to-data extraction (identifying what information is needed for production), prototype or sample validation (testing details at 1:1 or sub-scale), and coordination reviews with specialist partners. These steps allow fabrication considerations to be addressed systematically, rather than appearing late as corrections to finished design drawings.

2.2.2. CAD–CAM Integration and File-to-Factory Logic

A central component of digital fabrication workflows is the integration of Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). CAD–CAM workflows allow geometries developed in digital environments to be translated into fabrication data that can be interpreted by CNC equipment and manufacturing systems. In practical terms, CAD–CAM integration is enabled through a chain of model preparation, geometry rationalisation, tool-specific file formats, nesting or material layout, and machine instructions generated through CAM software.

Within architectural offices, CAD–CAM workflows support mass customisation: differentiated components can be produced efficiently when variation is controlled through parametric rules and fabrication constraints. Kolarevic (2003) and Carpo (2011) describe how this changes production logic by shifting away from repetition toward project-specific differentiation. Operationally, this requires offices to manage version control (to avoid fabrication from outdated models), maintain traceability

between model elements and fabricated parts (IDs, tags, schedules), and define quality assurance steps (checking tolerances, assembly interfaces, and machining allowances).

Practice examples such as Mark Burry's contribution to the Sagrada Família illustrate how parametric modelling and digital fabrication can be used to manage complex geometry while maintaining constructability and precision (Burry & Burry, 2006). In workflow terms, the relevance of such projects lies less in their singularity and more in what they exemplify operationally: the need for careful data organisation, consistent model logic, and robust translation pipelines from design geometry to production information.

2.2.3. Generative Design and Simulation in Workflow Pipelines

In many offices, fabrication workflows are supported by generative systems and simulation tools that inform design decisions before production data is generated. Generative methods, parametric definitions, rule-based systems, or algorithmic scripts, help manage variation and automate the generation of component families. Simulation tools, structural, environmental, material behaviour, or performance analyses, support iterative checking of feasibility and performance, reducing the risk of late-stage redesign.

Operationally, the value of these tools depends on how they are integrated into coordination processes. Rather than being isolated "analysis packages," simulations often function as verification layers within the workflow: they test whether the parametric system remains within tolerances, whether fabrication constraints are respected, and whether assembly logic remains coherent as design changes. This requires clear protocols for inputs and outputs: what data is extracted from the model for simulation, how simulation results are reintegrated into the model, and how decisions are documented for the wider team.

This workflow integration typically demands collaboration between computational designers, engineers, and fabrication specialists. The operational shift is not simply the presence of simulation, but the establishment of repeatable feedback loops where analysis results trigger explicit model updates and coordination decisions.

2.2.4. Toolpath Programming and Robotic Fabrication Pipelines

Beyond CAD–CAM translation, advanced digital fabrication workflows involve direct engagement with toolpath programming and robotic control. In these workflows, fabrication is not treated as a black box that passively receives geometry; instead, production planning is coordinated with design intent. Toolpaths, describing machine movement sequences, tool orientation, cutting or deposition strategies, and operational parameters, become a critical interface between design information and material execution.

Within architectural offices, toolpath and robotic pipelines typically involve specialist roles and tightly defined procedures. Computational designers or fabrication specialists may generate and test toolpaths, simulate machine motions to detect collisions or inefficiencies, and coordinate with manufacturers to ensure that production constraints are met. This often includes developing process-specific prototypes, mock-ups, or sample runs to validate the feasibility of machining or assembly sequences.

The operational implication is that workflow responsibility expands: the office must manage not only geometry and documentation, but also machine-specific constraints, tolerances, production sequences, and verification steps. In practice, this requires clear division of responsibilities (who owns the parametric definition, who validates the CAM output, who signs off on fabrication data), as well as procedures for change control when design updates occur late in the process.

2.2.5. Interdisciplinary Collaboration and Office Structures

Digital fabrication workflows reshape patterns of collaboration within architectural offices by promoting concurrent and interdisciplinary modes of working. Engineers, computational designers, facade consultants, manufacturers, and fabrication partners are often involved from earlier phases to reduce risk and maintain data continuity. This does not necessarily eliminate drawings or traditional coordination, but it changes what is considered authoritative: information is increasingly coordinated through shared digital environments and structured model data.

Many offices formalize this collaboration through internal specialist teams, fabrication leads, or computational design units. Others rely on external partners while maintaining strong internal competence in model organisation and data preparation. In both cases, operational effectiveness depends on communication protocols, shared file structures, versioning systems, and agreed responsibilities for model validation and production sign-off.

Where offices maintain in-house fabrication facilities, such as CNC routers, laser cutters, 3D printers, or robotic cells, these resources often support iterative prototyping and quality validation rather than full production. In operational terms, in-house facilities can shorten feedback cycles by enabling rapid testing of details, tolerances, and assembly logic, while final production may still be delivered by industrial partners.

2.2.6. BIM, Digital Twins, and Cloud-Based Platforms

Beyond fabrication-specific tools, BIM platforms, digital twins, and cloud-based collaboration systems increasingly function as workflow infrastructure for digital fabrication. BIM often acts as the coordination backbone for geometry, schedules, and multidisciplinary information, while parametric models may generate fabrication-specific outputs or component variation logic. In many offices, the

fabrication workflow relies on maintaining consistency between these environments: parametric definitions drive component differentiation, BIM structures manage coordination and documentation, and cloud platforms support collaboration, traceability, and review cycles.

Digital twins can extend this continuity across construction and operation by linking model information to real-world construction sequencing, site verification, or lifecycle performance tracking. Operationally, the relevance of digital twins in fabrication workflows lies in their capacity to maintain data continuity and to support validation: what is designed, what is fabricated, what is installed, and what is measured can be aligned within a shared information system.

Cloud-based platforms strengthen office-scale implementation by supporting distributed collaboration and robust version control. They enable teams and partners to access coordinated models, track changes, manage approvals, and document decisions. This becomes particularly important in fabrication-enabled projects, where small changes in geometry or parameters can have significant downstream consequences for production and assembly.

2.2.7. Operational Implications for Office Practice

The adoption of digital fabrication workflows has significant implications for how offices organise expertise, responsibilities, and project delivery. Operationally, these workflows can support faster iteration, improved precision, and clearer coordination between design intent and production requirements. However, they also require organisational adaptation: investment in skills, software interoperability, data management protocols, and collaborative structures.

Offices implementing fabrication workflows typically develop internal standards for model structuring, naming conventions, parameter logic, and fabrication data extraction. They also require clear training pathways and role definitions, particularly where toolpath programming or robotic pipelines are involved. More broadly, fabrication-enabled practice tends to increase interdisciplinary dependency: architectural teams must coordinate continuously with engineering and manufacturing knowledge, not as late-stage support, but as embedded workflow input.

Digital fabrication workflows redefine how architectural offices operate by establishing continuous links between design modelling, coordination, and production planning. Through file-to-factory logic, CAD–CAM integration, parametric systems, toolpath and robotic pipelines, and interdisciplinary collaboration, fabrication becomes an operational methodology embedded within office practice. The increasing use of BIM, digital twins, and cloud platforms further supports workflow continuity and office-scale implementation. Together, these operational structures explain how computational design is translated into fabrication-ready information and built outcomes within contemporary architectural practice.

CHAPTER 3

Digital Transformation in Architectural Practice in Portugal

Digital transformation in architecture represents more than just the adoption of new software or tools; it marks a fundamental shift in how architects conceive projects and build. As the RIBA report (2018) explains, digital transformation is "not just the adoption of a set of technologies. Rather, it is a fundamental shift in culture, supported and facilitated by technology". This means that the entire design workflow – from concept to construction – is being reconceived. Collaboration is more integrated, data drives decision-making, and new, hybrid processes link computation to construction. In other words, the digital era is reshaping architectural work as a cultural and procedural transformation.

In Portugal, the digital transformation is challenging architectural practice by exposing the gap between traditional modes of working and the demands of a technology-driven environment. While leading architecture offices and research centres have embraced Building Information Modelling (BIM), computational design, and digital fabrication, the majority of small and medium-sized practices still operate within conventional methods, often constrained by limited resources and institutional inertia. This uneven adoption reflects structural issues in the profession, such as the predominance of small offices, fragmented collaboration with the construction sector, and a regulatory framework that has been slow to adapt to new digital standards. Nevertheless, a growing network of universities, professional bodies, and innovative offices is pushing forward experimentation with parametric design, robotic fabrication, and immersive technologies, suggesting that the Portuguese architectural landscape is entering a transitional phase where digital culture and craftsmanship may coexist and potentially redefine practice.

Thus, it is important to better understand the practices already implemented in order to propose and promote capacity-building initiatives, update regulatory frameworks, and strengthen cross-sector collaboration, ensuring that digital transformation not only modernizes design processes but also contributes to more sustainable, inclusive, and resilient architectural practices in Portugal.

To support the analysis in this chapter, primary data was collected through semi-structured interviews with Portuguese architectural offices. In total, 17 architectural offices were approached for the study, selected according to a set of predefined criteria aimed at ensuring relevance to the research focus on digital fabrication and computational design in professional practice. These criteria included: (i) demonstrable engagement with digital design and fabrication technologies within the office (such as parametric modelling, BIM-to-fabrication workflows, CNC or robotic fabrication); (ii) evidence of implemented projects or ongoing research integrating digital processes beyond representational use;

(iii) office scale, organisational structure, and years of practice, to capture a range of professional contexts; and (iv) geographical representation within the Portuguese architectural landscape.

Of the 17 offices contacted, 9 agreed to participate, providing a robust qualitative sample for in-depth inquiry. Interviews were conducted through a combination of online video calls and in-person meetings at the offices, allowing for both logistical flexibility and direct observation of workplace environments, including design workflows and, where applicable, in-house fabrication facilities. The insights gathered from these interviews constitute a central empirical foundation for the chapter, grounding the theoretical discussion in first-hand accounts of how Portuguese architectural practices are adopting, adapting, and negotiating digital transformation within their everyday professional operations.

3.1. Portuguese Context: Adoption and Challenges

The Portuguese architectural ecosystem is shaped by unique cultural, economic, regulatory, and educational conditions that influence how digital transformation unfolds. The sector is largely composed of small offices (often micro-companies) operating on tight budgets, which constrains their ability to invest in costly new tools or training. Culturally, the profession prides itself on a strong craft heritage and design tradition; some practitioners remain sceptical of high-tech approaches, even deliberately avoiding a "technological" image in favour of familiar manual methods. On the policy side, government initiatives have lagged behind those of other countries – unlike contexts such as France, where the state has mandated BIM adoption and funded widespread training, Portugal's authorities have provided little direct support or incentives for digital practices. Finally, educational factors play a significant role: until recently, many architecture curriculum in Portuguese universities offered minimal exposure to BIM or digital fabrication, leaving graduates underprepared (indeed, some tenured faculty insisted on 2D drafting well into the 21st century, meaning many students graduated "without even knowing what BIM is!" as one interviewee lamented). These intertwined factors – limited resources, a cautious professional culture, sparse top-down support, and outdated curricula – form the backdrop against which Portuguese architects are navigating digital transformation in practice.

In Portugal, digital fabrication emerged first in academic and research settings rather than in everyday architectural design practice. Lisbon's ISCTE – Instituto Universitário de Lisboa hosts since around 2011 the Vitruvius FabLab, a digital-fabrication workshop equipped with multiple 3D printers, a laser cutter and a CNC milling machine that supports student and research projects (ISCTE – Instituto Universitário de Lisboa, n.d.). Porto's Faculty of Architecture launched a Digital Fabrication Lab (DFL) in 2013 "dedicated to research on digital design and fabrication technologies" (Centre for Studies in Architecture and Urbanism, n.d.). These specialised labs illustrate that resources do exist in Portugal,

but mostly within universities. It should be noted, however, that some industry and private-sector initiatives existed early on. For example, EDP (Portugal's energy utility) established a FabLab in 2008, and Porto's OPO'Lab began in 2010, showing that digital fabrication was already emerging outside academia. These examples suggest that academic labs were not the sole originators of fabrication technology in Portugal. In contrast, most architecture offices have only experimented with CNC milling or 3D printing on a very limited scale. A number of pioneering offices began using simple rapid-prototyping (e.g. 3D-printed models) in the 2010s, but they typically relied on external service bureaus or academic machines. In practice, Portuguese architects often report limited in-house fabrication tools altogether, and must coordinate with outside labs. This pattern mirrors global trends: Duarte (2013: page 31) emphasizes that digital fabrication enables "fast and automated production of physical objects" from digital models, but notes that its adoption often begins in research contexts before spreading to practice. In other words, Portugal saw digital fabrication enter the curriculum and research agendas (through labs like DFL and Vitruvius FabLab) long before it became commonplace in offices.

Despite these efforts, infrastructure limitations remain a major barrier for Portuguese offices. Interviewees repeatedly expressed frustration over the absence of equipment and software. Such reports contrast sharply with the well-resourced academic labs. In industry terms, this means many Portuguese offices cannot in-house any physical fabrication and rely on third-party providers. One practitioner summarized the broader digital transition challenge within offices - where fabrication and BIM maturity are tightly coupled: "when I returned to Portugal in 2017, I realised that it was still starting here, with some delay. But I don't think it's for lack of will - I think the problem is lack of means. The transition to a tool like Revit requires more than buying software: it requires preparation, training, process systematization, financial investment - and all that is difficult for a micro-company like ours. Our willingness to migrate to Revit took time to materialize precisely due to lack of resources." (Annex B - Atelier Peninsular).

Internationally, infrastructure deficits are recognised as an obstacle in small architecture offices. The RIBA survey (2018), notes that leading practices invest in robust "back-of-house" digital setups - dedicated teams, software, and hardware - to support BIM and design tasks. In Portugal, by contrast, most offices are small and cannot easily justify such investments. The result is that Portuguese architects spend extra time coordinating with external workshops or academic facilities. This uneven infrastructure translates into slower learning. Limited in-house fabrication infrastructure forces Portuguese offices to rely on others, adding cost and complexity, whereas larger international offices often build these capabilities internally (RIBA 2019).

Closely related is the skills gap in Portuguese architectural practice. Even when hardware is available, few offices have staff with the necessary training. In our interviews it emerged that most

architects learned digital fabrication informally - through short workshops or on-the-job trial-and-error - rather than through formal education. This reflects international findings: the RIBA report (2018) found that "lack of digital skills" was the third-biggest challenge for offices, cited by 48% of UK respondents. Similarly, Silva and Paio (2024) report that Portuguese offices call for "educational reforms" to build relevant competencies. As one interviewee stressed, the gap begins at the university level and carries into practice: "We are way behind in architectural education in Portugal compared to the rest of Europe because we refuse to evolve. Tenured professors still say everything should be in 2D – it's surreal in this day and age. Many students graduate without even knowing what BIM is! … We don't invest in what we should – which is, ultimately, innovation." (Annex E - Konceptness)

In Portugal, the absence of systematic training in CAD/CAM or CNC programming means offices often must hire specialists or send staff on short courses. The net effect is that even motivated architectural offices find it hard to staff their digital workflows. In this respect, Portugal's situation mirrors the UK: RIBA (2018) emphasizes that investment in skills is "core to digital transformation," and that many offices struggle with under-trained staff. Portuguese architects experience this more intensively given smaller office teams and less access to continuous professional development.

A deeper cultural and institutional resistance also constrains adoption. Digital fabrication represents a significant shift from traditional design methods, and interviewees observed a conservative mindset among some peers and clients. These comments align with RIBA's finding that digital transformation is fundamentally "a shift in culture". In the UK report (2018), 56% of respondents recognise better outcomes from digital methods, but many offices still lack "willingness to change" and strong leadership to drive it. Portuguese offices report the same inertia. Silva and Paio (2024) highlight "resistance to change" as a persistent challenge in Portugal. One interviewee pointed to habitual practices that blunt the benefits of new tools: "not everyone uses the tools with awareness of what they're doing. They adapt old ways of working to contemporary instruments – drawing as if they were still at a drafting table… There are still offices where you feel resistance to digital methods, perhaps out of a certain modesty or a desire to seem 'non-technological'." (Annex A - 18–25 Research Studio). In practice, this means that without an internal driver inside the office or demand from clients, digital fabrication remains sidelined. In short, the international literature stresses that digital adoption requires a supportive culture and clear incentives (RIBA, 2018); Portuguese architects report that these are often absent, making digital fabrication seem optional or experimental rather than mainstream.

Finally, financial and resource constraints play a critical role. High equipment and training costs were cited by every interviewee. As Silva and Paio (2024) note, Portuguese practices face "high costs" as a major obstacle. During the interviews, participants remarked that even mid-range 3D printers or CNC routers represent investments equivalent to multiple years of office rent. This aligns with international findings: the RIBA report (2018) identifies cost as "the most significant barrier," especially

the difficulty “finding funds to invest in new technology and to up-skill staff”. The financial burden is compounded by limited public support for non-tech-classified offices: “here in Portugal, everything came out of our pocket. It is very difficult to access grants or support because many programs are aimed at technology-based companies. Architecture offices are often marginalized, as if they were not ‘digital’ companies.” (Annex B - Atelier Peninsular).

In practice, most Portuguese offices are small-to-medium businesses with tight budgets. There is little client pressure (and therefore fee increase) to cover costs, so any major purchase is hard to recover. The interviews revealed that many architectural offices leave equipment acquisition until late in a project. In effect, financial caution reinforces the other challenges: offices delay adopting new methods because they cannot realistically pay for machines, software licenses, or specialised personnel upfront.

In comparison with international trends, Portuguese architecture offices face similar core issues - notably skill shortages, cultural inertia, and high costs - but with accentuated local factors. RIBA’s UK data (RICA, 2018) confirm that many architects worldwide struggle to build digital capabilities. Likewise, Silva and Paio (2024) found that Portuguese offices share these concerns (noting “resistance to change” and “high costs” explicitly). Where Portugal differs is scale: with fewer large offices and less external demand, Portuguese practices have even more limited infrastructure and budgets than their international peers. Consequently, challenges like acquiring CNC equipment or finding skilled operators pose greater difficulties. Nonetheless, the broad pattern is consistent: as RIBA observes, transformational tools alone cannot succeed without addressing culture, leadership, and training. Our interviews reinforce this: despite enthusiasm for innovation, Portuguese architects consistently point out that technology won’t help if people aren’t ready or able to use it.

The historical adoption of digital fabrication in Portugal has been gradual and mostly confined to research settings; the key barriers identified (limited infrastructure, skill gaps, conservative mindsets, and cost) echo global studies but are magnified by local constraints (Silva, 2024). Addressing these issues - for example through targeted education and supportive policies - will be necessary if Portuguese offices are to catch up with international digital practice.

From a theoretical standpoint, the trajectory of digital fabrication uptake in Portugal can be understood through innovation adoption models. Rogers’ Diffusion of Innovations theory emphasizes that an innovation’s rate of adoption depends on how potential users perceive certain attributes – notably its relative advantage, compatibility with existing practices, complexity, trialability, and observability (Newcastle University, n.d.). Innovations that demonstrate clear benefits, fit well with current values/workflows, can be tried on a small scale, and have visible successful outcomes tend to spread more rapidly, whereas high perceived complexity slows adoption (Newcastle University, n.d.).

In the Portuguese context, many of these factors have so far hampered diffusion: if digital fabrication is not clearly seen as advantageous over traditional methods, or if it is difficult for small offices to experiment with due to cost and scale, adoption naturally lags. Likewise, the Technology Acceptance Model (TAM) from information systems research highlights perceived usefulness and ease of use as key determinants of whether individuals embrace a new technology. In Portugal's architectural offices, these perceptions have been tempered by practical constraints – TAM assumes that once a person intends to use a technology, they are free to do so, yet in reality external barriers like budget limitations and organisational inertia can intervene. Indeed, as critics of TAM note, focusing only on usefulness and ease of use can overlook factors such as cost and structural imperatives that significantly affect adoption decisions. This theoretical lens helps explain why many Portuguese architects could be categorized as late adopters: the innovation must not only prove its value and usability but also overcome systemic constraints in order to diffuse within this social system.

3.1.1. Fabrication Laboratories and Innovation Hubs in Portugal

The following Fabrication Laboratories and maker hubs, though based in academic or community settings, are examined here for their influence on professional practice. They often serve as extensions of an architect's toolkit in Portugal, providing fabrication resources to offices that lack in-house facilities. By reviewing these labs, we highlight how innovations developed in academic contexts can spill into everyday office use – a critical link given this thesis's focus on digital fabrication in architectural offices.

Fab Labs (fabrication laboratories) emerged in the early 2000s with MIT's Centre for Bits & Atoms as community workshops offering access to advanced digital fabrication tools (laser cutters, CNC mills, 3D printers) (Winn, 2023; Fab Foundation, n.d.). The Fab Lab network has since grown into a global community: "more than 2,500 centres across 125 countries," each providing public access to sophisticated making equipment and training. Fab Labs explicitly aim to "democratize access to the tools for technical invention" (Fab Foundation, n.d.), turning "almost anything" into a possibility for anyone anywhere. In Portugal this model has been adopted by both public and private institutions. The first Portuguese Fab Lab, OPO'Lab in Porto (founded 2010), describes itself as a "multidisciplinary centre and the first FabLab in Portugal for architecture, engineering, design, promoting research, education and cultural activities" (OPO'Lab, n.d.). Other initiatives that followed include FabLab Lisboa (a public digital fabrication hub in Lisbon) and corporate labs like FabLab EDP (established to foster innovation within the energy group) (FabLabs.io, n.d.). Together with university labs (e.g. Vitruvius at ISCTE-IUL and the FAUP Digital Fabrication Lab), these form a national network that mirrors the global Fab Lab vision: open-access workshops that foster local entrepreneurship and maker-driven innovation (OPO'Lab, n.d.; FabLabs.io, n.d.).

At the policy and incentives level, interviewees contrasted Portugal's limited support with other European contexts in which the state actively steers digital transition: "I worked in an office in France where the State already required the transition to BIM for public works… the State funded training for the entire team in ARCHICAD. There's a different dynamic – a different understanding of its importance. They understand that it's essential for competitiveness, not only in the country but also abroad. Here in Portugal, we do what we can with the resources we have, patching things together, but ideally, we would have real support." (Annex B - Atelier Peninsular). Echoing this, offices emphasized the need for predictable, long-horizon incentives to de-risk adoption: "we never had any kind of support for this kind of implementation – we thought we would, but we didn't. I think if companies were rewarded – if the government reduced taxes, or there was some certification marking companies as innovative in this area (with some return on investment) – it would be a great asset. If it's going to be mandatory, then maybe 10 years earlier we should start giving companies the conditions to adapt. But for us, it's always been our own investment." (Annex E - Konceptness).

Fab Labs have become increasingly integrated into architectural education and practice. Architecture schools worldwide are building Fab Labs "to provide their students with the skills to support new learning processes, scientific innovation and development linked to architectural practice and the building industry" (Paio et al., 2012). In Portugal, Fab Labs serve to democratize access to digital fabrication: small offices, students, and community groups can prototype complex designs without the need for industrial-scale facilities. These labs foster experimentation by allowing designers to iterate rapidly. Importantly, they bridge academia and practice. Fab Labs acts as an interdisciplinary hub where research, education and professional fabrication converge. This mirrors international Fab Lab models (like MIT's CBA labs or European fab networks) in adopting open, cross-disciplinary research agendas (Winn, 2023; Fab Foundation, n.d.), while also reflecting Portuguese priorities (for instance, a focus on cork as a sustainable material).

Yet interviewees cautioned that labs alone are insufficient without a broader network of collaborators across the project lifecycle: "we came back to Portugal enthusiastic and ready to move forward… but then we were missing the partners. There was no one doing structures, HVAC, etc. That ecosystem – as it's now called – really has to exist. Everyone should be making this journey, at their own scale, in their own way. But honestly, I don't know if that's happening." (Annex G - Saraiva + Associados).

Vitruvius FabLab (ISCTE-IUL)

Vitruvius FabLab was launched at ISCTE–IUL (Lisbon) around 2012 as part of an initiative to integrate digital fabrication into Portugal's architecture education (Paio et al., 2012). The lab was established after a 2011 symposium on digital fabrication and, as Paio et al. explain, "the main points were the

creation of the Vitruvius FabLab–IUL laboratory and the definition of appropriate new lines of research in digital fabrication". In other words, Vitruvius was explicitly set up to develop research, teaching, and innovation around CAD/CAM and physical prototyping. Its mission statement describes it as "a space for knowledge-sharing, manufacturing and innovation" aimed at exploring CAD/CAM modelling for architectural models, modular building systems, and participatory design processes to solve real local problems (ISCTE – Instituto Universitário de Lisboa, n.d.).

Vitruvius FabLab is equipped with the key digital fabrication tools (CNC milling machines, laser cutters, 3D printers, collaborative robotic arm, etc.), providing students and practitioners hands-on access to fabrication technology. The lab also hosts public events (summer schools, exhibitions) to connect with broader communities (ISCTE – Instituto Universitário de Lisboa, n.d.).

Vitruvius's impact on education and practice has been significant. Academics report that it makes fabrication "hands-on" rather than abstract: Paio et al. (2012) note that students' interest is easy to capture when they see the "visually impressive" outcomes of digital fabrication. Vitruvius also fosters industry links: the lab has established partnerships with offices and with ISCTE's sociological and computing researchers to develop new materials and building systems (Paio et al., 2012; ISCTE – Instituto Universitário de Lisboa, n.d.). Vitruvius FabLab exemplifies how an academic Fab Lab can enrich curricula and spin out innovations, in line with the global Fab Lab vision of distributed R&D.

DFL - Digital Fabrication Lab (FAUP, Porto)

The Digital Fabrication Lab (DFL) at the Faculty of Architecture, University of Porto (FAUP) was formally established in 2013 as a research group of CEAU/FAUP dedicated to advanced digital design and manufacturing in architecture (Digital Fabrication Laboratory, n.d.). As the lab's webpage explains, DFL was founded to "investigate the use of advanced digital technologies in the field of architectural design and construction". Its mission is to "revolutionize" architecture by integrating robotics, computation and new materials into design and building. Among its stated achievements, DFL notes that it was "the first research group in Portugal investigating robotic fabrication in architecture" (Digital Fabrication Laboratory, n.d.) and a "leading research group investigating the use of cork in architecture", highlighting both its pioneering role and its material innovations. The lab's multidisciplinary team (faculty, postdocs, students) works on projects ranging from digital fabrication research to industry collaborations.

Equipped with industrial multi-axis arms, a prototype cable-driven builder ("SPIDERobot"), custom CNC tables, 3D printers and large-format display equipment, DFL can fabricate sizable architectural components. For example, DFL developed the CorkCrete Arch: a full-scale parametric vault made from 3D-printed glass-fibre-reinforced concrete panels embedded with cork (Sousa, Martins, & de Azambuja Varela, 2016). This project - coordinated by DFL director J. P. Sousa – demonstrates DFL's

emphasis on robotic fabrication and sustainable materials (cork being a regionally important biomaterial). As one presentation notes, CorkCrete used a "single parametric design environment and robotically-fabricated formwork" to produce a hybrid cork-concrete arch (Sousa, Martins, & de Azambuja Varela, 2016).

DFL also cultivates industry partnerships. For instance, it worked with Mota-Engil (a Portuguese construction office) to develop a 3D-printed modular facade system, and it collaborates on EU projects involving automated construction. Interviewed researchers emphasized DFL's role in "bringing the factory into the architecture school", noting that working with real contractors and materials helps students understand constructability early on. With its academic-industry network and cutting-edge equipment, DFL has helped transform FAUP into a hub of "non-standard construction" experimentation - a clear example of digital transformation in practice.

Overall, both Vitruvius FabLab and the FAUP DFL reflect and extend international Fab Lab trends. Like MIT's CBA labs or Europe's school and municipal fab spaces, they provide open workshops for innovation and learning (Winn, 2023; Fab Foundation, n.d.). Their impact is comparable to these global models: they democratize technology (making tools accessible to all, not just industry), promote interdisciplinary design thinking, and accelerate the adoption of computational methods in architecture. At the same time, they adapt the Fab Lab concept to Portugal's context - emphasizing local materials (cork) and community-oriented projects. Portuguese Fab Labs serve as critical nodes in the digital transformation of architecture: by fostering experimentation, education and practice simultaneously, they help move the profession toward more inclusive, technology-driven modes of design and construction.

Lab2PT (EAAD, Guimarães)

The University of Minho has become a regional leader in digital fabrication research. At its School of Architecture, initiatives like the ACTech Hub, the ARENA – Advanced Design & Technology Lab, the Advanced Ceramics R&D Lab, and the Construction and Technology Laboratory explore the integration of digital manufacturing techniques into building components, including research on ceramic elements, robotic fabrication, and 3D concrete printing. These efforts demonstrate that beyond Lisbon and Porto, academic hubs in Minho are also actively bridging architecture and advanced fabrication, spreading a culture of innovation across Portugal.

The Lab2PT – Landscape, Heritage and Territory Laboratory at the School of Architecture, Art and Design of the University of Minho (EAAD-UMinho) has consolidated itself as a significant national hub for research at the intersection of architecture, design, technology and material experimentation. Operating across the campuses of Guimarães and Braga, the laboratory brings together researchers from architecture, urbanism, design, archaeology, geography and the social sciences, fostering a

distinctly transdisciplinary approach. Its mission emphasizes the integration of critical, historical and technical perspectives, offering a fertile environment for the development of advanced design and construction methodologies.

Within this ecosystem, the University of Minho hosts a strong infrastructure dedicated to digital fabrication and construction innovation, including laboratories for prototyping, CNC manufacturing, 3D printing, ceramics, mould-making, and robotic manufacturing. Among these, the Advanced Ceramics R&D Lab (ACLab) and the ARENA – Advanced Design & Technology Lab stand out for their focus on material research and digital/robotic workflows. These facilities enable experimentation with additive manufacturing, automated assembly processes, and digitally driven construction systems, positioning the school as a regional reference in advanced fabrication.

Research developed through ACTech Hub and the Lab2PT has explored the potential of 3D-printed ceramic components, robotic material manipulation, and the integration of computational design with construction technologies. Although many of these outputs remain at the scale of prototypes or experimental components, they reflect a commitment to bridging design and production in ways that respond to contemporary demands for sustainability, material efficiency and technical innovation. The emphasis on ceramics—an important material in Portuguese craft and construction traditions—also demonstrates how digital processes can revitalize established industries through new forms, techniques and applications.

Together, these initiatives illustrate that innovation in architecture and digital fabrication in Portugal is not confined to the metropolitan centres of Lisbon and Porto. The University of Minho plays a key role in decentralizing technological research capacity, fostering local–regional networks, and contributing to a broader national culture of experimentation. Its work is particularly relevant for emerging agendas in distributed manufacturing, circular construction, community-oriented design, and the development of new material systems, offering valuable insights for future collaborations between academia, industry and public institutions.

Other Maker Spaces in Portugal

Portugal's maker ecosystem extends far beyond the FabLabs of ISCTE (Vitruvius) or FAUP (DFL). Major cities like Porto and Lisbon now host multiple FabLabs and maker hubs that cater to architects, designers, entrepreneurs and creative communities alike. These projects highlight the broad reach of makerspaces in Portugal. Here, "makerspace" refers to a shared workshop aligned with the global Maker movement, equipped with tools like 3D printers and CNC machines (akin to a FabLab) and intended for open-ended prototyping. Even small towns have DIY fabrication workshops and "repair cafés" (supported by EU Erasmus projects) that engage citizens in design and sustainability. In all cases, the emphasis is on accessibility and collaboration: workshops are often open to any creative (student,

artist, entrepreneur or hobbyist) and frequently partner with local governments, schools or universities to run training and joint projects. By equipping users with digital tools and fostering peer learning, these spaces have enabled concrete architecture and spatial innovations. For instance, community workshops have prototyped furniture, public-art installations and emergency shelters, blending craftsmanship with digital fabrication. Portugal's network of maker and fab spaces is actively expanding the opportunities for architects and makers to prototype, learn and collaborate, thus invigorating both the profession and the wider creative community (OPO'Lab Porto, 2023).

Notable examples include Fab Lab Lisboa and Fab Lab Benfica in Lisbon, which are part of MIT's global Fab Lab network and provide community access to laser cutters, 3D printers, and CNC machines. Additionally, independent maker spaces in cities like Braga and Coimbra have emerged, offering workshops that familiarize students and professionals with digital fabrication tools. These spaces collectively help diffuse fabrication knowledge beyond academic institutions into the broader design community.

3.1.2. Modes of Adoption of Digital Fabrication in Portuguese Architectural Practice

The adoption of digital fabrication within Portuguese architectural practice has intensified over the last decade, driven largely by experimental and research-oriented collaborations between academic institutions and industry partners. In this chapter, "adoption of digital fabrication" is understood not merely as the possession of advanced manufacturing equipment, but as the degree to which digital design-to-production workflows are structurally embedded in architectural practice. This includes both in-house capacities, such as 3D printing, CNC milling, or robotic fabrication, and sustained collaborations with external fabrication laboratories and industrial partners.

Importantly, adoption does not presuppose ownership of machinery. Architectural practices may meaningfully integrate digital fabrication by routinely outsourcing prototyping, testing, or full-scale production to specialised facilities, provided that fabrication constraints and possibilities are incorporated upstream in the design process. In this sense, digital fabrication operates as a design strategy and organisational practice, rather than solely as a technical resource.

As noted by Neves, Beirão, and Rocha (2017: page 137), "the use of digital fabrication tools in Portuguese architecture is a very recent approach," one that initially emerged within academic and experimental settings and has only more recently begun to influence professional practice. This transition from academia to practice is reflected in a series of pioneering projects, research prototypes, and design–build workshops in which parametric design, computational control, and digital manufacturing were central to both the conceptualisation and realisation of architectural outcomes.

The following case studies exemplify this evolution, illustrating different modes of adoption, scales of intervention, and forms of collaboration through which digital fabrication has contributed to the transformation of architectural practice in Portugal.

A Living System - Discursive Wall (Iscte, Lisbon)

One of the earliest and most illustrative examples of the adoption of digital fabrication within the Portuguese architectural context is A Living System – Discursive Wall, developed at ISCTE-IUL in Lisbon in 2012. Conceived as an experimental, full-scale interactive installation, the project emerged from an international workshop that brought together academia, digital fabrication laboratories, and industry partners, namely VitruviusFabLab–ISCTE, Rhino3DPortugal (Digitalab), and FabLab EDP (Silva e Paio, 2013).



Figure 3.1: Living System – Discursive Wall workshop prototype (2012). Interactive wall component developed during the A Living System workshop at Vitruvius FabLab, ISCTE-IUL (Source: Vitruvius FabLab ISCTE-IUL, 2012).

The project was explicitly structured around the integration of computational design, digital fabrication, and physical computing as a continuous design-to-production workflow. Rather than treating fabrication as a post-design phase, digital fabrication was embedded as a design strategy, shaping both formal generation and material articulation. The Discursive Wall (Figure 3.1) was developed through three interdependent phases: parametric pattern generation, digital fabrication,

and advanced interaction, forming a coherent digital process that linked abstract computational logic with physical performance. At the design level, parametric patterns were generated using Rhino and Grasshopper, drawing on generative systems such as Voronoi diagrams, circle packing, metaballs, and pixel-based mappings. These computational geometries were not merely representational but directly informed fabrication constraints and assembly logics. The transition from digital model to material artefact was achieved through CNC milling, using cork as the primary material. The wall consisted of 135 individually fabricated cork modules (33 × 33 cm), mounted onto a Valchromat structural grid, resulting in a 5 × 3 m responsive surface. Crucially, the project extended beyond digital fabrication into interactive architectural behaviour. Using Arduino microcontrollers and the Firefly plug-in for Grasshopper, the wall incorporated real-time sensing, computation, and actuation. Infrared sensors detected user proximity and movement, translating analogue input into digital data that dynamically controlled servo motors embedded behind each module. This enabled the surface to deform and react in real time, transforming the wall into a responsive architectural system rather than a static installation (Baptista, Paio, & Silva, 2013). From a methodological perspective, A Living System – Discursive Wall exemplifies an early Portuguese adoption of a closed-loop digital fabrication workflow, where feedback between sensing, computation, and material performance informed iterative design decisions. The project aligns with international theoretical frameworks on interactive architecture and ubiquitous computing, explicitly referencing concepts such as Tangible Bits (Ishii) and Ubiquitous Computing (Weiser), while simultaneously grounding these ideas in a locally situated architectural experiment

Importantly, this case also highlights a specific mode of adoption prevalent in Portugal during the early 2010s: fabrication through institutional collaboration rather than in-house production. While the architectural practice did not operate its own fabrication infrastructure, access to CNC machinery and electronic prototyping was enabled through FabLab partnerships and academic laboratories. This model of adoption, outsourcing fabrication while retaining design authorship and computational control, foreshadows patterns later observed in professional Portuguese offices engaging with digital fabrication.

A Living System – Discursive Wall represents a foundational case in the Portuguese context, demonstrating how digital fabrication entered architectural practice initially through experimental, research-driven environments. It illustrates a transition from digital tools as representational devices to digital fabrication as an operative and performative design methodology, anticipating later professional applications of parametric design, CNC fabrication, and interactive systems within architectural practice in Portugal.

CorkCrete Arch (FAUP, Porto)

A 1:1 prototype developed by the Digital Fabrication Lab (DFL) at FAUP in partnership with Mota-Engil and Amorim Cork (2016). This project used a KUKA robot to fabricate an arched vault of glass-fibre reinforced concrete structure with a covering of insulation cork. The goal was "to use robotic fabrication technologies in the production of a novel building system" (Neves, Beirão, & Rocha, 2019). By parametrically controlling both concrete and cork materials, the team achieved a highly prefab, easily assembled arch. (Professor José Pedro Sousa of DFL coordinated the project.) The CorkCrete Arch exemplifies how academic research units apply digital workflows and CNC milling to real materials, creating new construction methods and form-finding opportunities (Neves, Beirão, & Rocha, 2019).

The CorkCrete Arch project (Figure 3.2) is a full-scale experimental vault developed at FAUP's Digital Fabrication Lab, combining robotically-milled cork formwork with 3D-printed concrete panels. This project demonstrated how parametric design and custom fabrication techniques can produce new hybrid material systems suited to local materials (cork) and sustainable construction.



Figure 3.2: CorkCrete Arch at FAUP (Source: Sousa, J. P., 2017).

Lisbon Oceanarium Extension (Campos Costa Arquitectos)

Completed in 2013, this extension to the Lisbon Oceanarium features an innovative ceramic-tile facade. Pedro Campos Costa's office designed a cubical volume clad in 5,000 ceramic tiles reminiscent of marine scales that also serve as sunshades. Campos Costa described how they worked with Cumella Ceramics (Spain) to produce the custom tiles. The original design envisioned fully self-supporting interlocking tiles, but "due budget restrictions and for safety reasons" the solution became a thin tile cladding on a steel frame (Neves, Beirão, & Rocha, 2019). At the time of fabrication (2013) Cumella lacked advanced CNC capabilities, so the office hand-prototyped the shapes and relied on partner workshops for production. This case shows both the opportunities (parametric tile design, new materials) and limitations (cost, fabrication capacity, regulatory safety) of early digital approaches in

practice. Campos Costa's facade (Figure 3.3) required close architect-industry coordination, reflecting a shift towards more customised workflows.

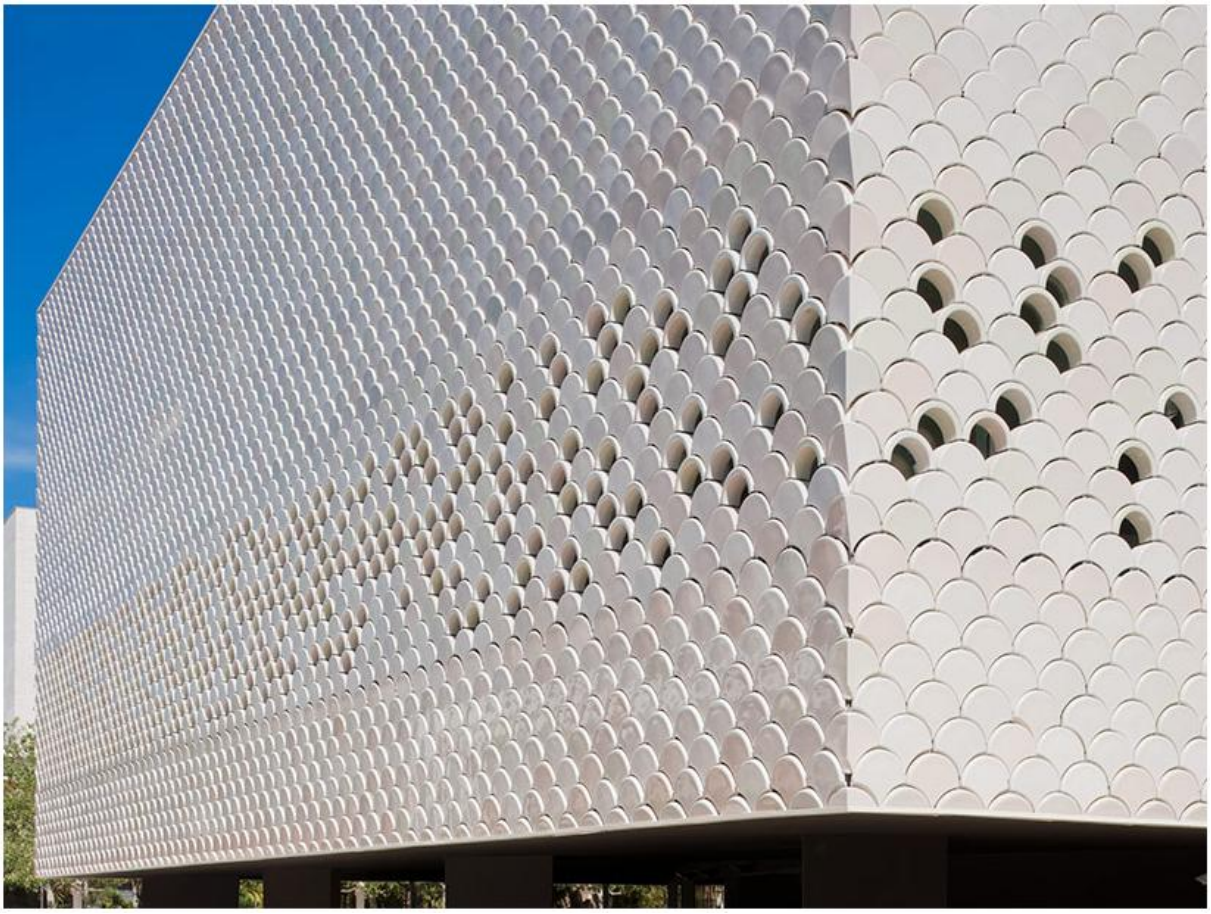


Figure 3.3: Lisbon Oceanarium Extension Façade (Source: Hudson, D., 2013).

CEAAD Cork Pavilions (FAUP/ISCTE)

The Advanced Digital Architecture program (CEAAD) - a collaboration between FAUP and ISCTE's Vitruvius FabLab - has resulted in several built exhibits. For example, the Amorim Cork Isolamentos pavilion at Concreta 2013 was entirely digitally designed and fabricated by Pedro Varela, Maria João de Oliveira and Emmanuel Novo under professors Alexandra Paio and José Pedro Sousa supervision (de Azambuja Varela, de Oliveira, & Novo, 2013). This cork pavilion (Figure 3.4) featured complex curved cork-board surfaces generated parametrically. A follow-up project (Concreta 2015 "Cork Shell Pavilion") by CEAAD participants Filipe Brandão and João Sousa also explored cork through custom digital models (Brandão & Sousa, 2015). Both projects established "a unique University–Industry relationship" (with Amorim Cork) and were constructed at ISCTE's Vitruvius FabLab (de Azambuja Varela, de Oliveira, & Novo, 2013). In these pedagogical design-build efforts, architects-in-training

learned fabrication by digitally modelling natural materials and using CNC-cutting, demonstrating the educational impact of digital workflows.



Figure 3.4: CEAAD Cork Pavilions (Source: ArchDaily, 2013).

Design-Build Workshops (Évora 2020–2022)

Beyond formal education, intensive summer schools have mixed digital techniques with traditional craftsmanship. The "Craftsmanship meets Digital Fabrication" programs (Évora 2020, 2022) by Passa Ao Futuro brought architecture and design students together with local artisans over two weeks (Passa ao Futuro, 2020). Teams used digital tools (Grasshopper modelling, environmental simulation) and CNC fabrication alongside woven plant materials and basketry, to design and build retractable shading structures on site (Passa ao Futuro, 2020). These hands-on events explicitly "strengthen the tradition of building and craftsmanship enhanced with the use of digital tools". They exemplify how workshops can teach digital-material workflows: participants design in software, rapidly prototype with 3D-printed or milled components, and then integrate them with analogue construction.

Collectively, these cases illustrate a shift in practice and culture. Projects like CorkCrete and the Oceanarium extension show how parametric design and CNC fabrication enable new forms and customised assemblies, potentially improving material efficiency and architectural expressiveness. The academic-collaborative pavilions demonstrate digital craftsmanship as a mode of architectural research and industrial engagement (de Azambuja Varela, de Oliveira, & Novo, 2013). Interviews with

Portuguese practitioners reinforce that curiosity and academic exposure drove initial adoption of these tools, and that industry partnerships are "essential" for realizing custom designs (Neves, Beirão, & Rocha, 2019). As a result, architects are evolving toward a networked workflow from concept to construction: ideas are tested as digital prototypes, then refined with manufacturers, effectively "democratizing" fabrication through shared CNC platforms.

At the same time, limitations remain clear. Scale is a challenge - fully digital construction of an entire building is not yet feasible with current resources (Neves, Beirão, & Rocha, 2019). Architects cite cost, regulatory barriers and risk as barriers: one notes that laws and insurance were not originally written for digitally-fabricated elements. Smaller offices may struggle to invest in robotic equipment, and many projects still rely on manual or semi-digital processes. Cultural factors also play a role; Portuguese construction traditionally favours off-the-shelf solutions, so digital customisation requires mindset change. Finally, digital workflows demand new skills, so educational initiatives are critical to overcome knowledge gaps.

Nonetheless, these case studies highlight the significant potential of digital fabrication in shaping the future of Portuguese architecture. They suggest a trajectory toward more sustainable and expressive design - where local materials like cork are crafted into intricate geometries with minimal waste, and where customised components such as tiles, panels, and moulds can be produced efficiently and affordably. Through close collaboration, interdisciplinary teams are able to move between digital design and physical production, enabling iterative and responsive workflows. As Neves, Beirão, and Rocha (2019) observe, the architectural process in Portugal is progressively shifting "from a traditional process to a network of information from idea to construction." While still emerging, digital fabrication is cultivating a culture of innovation and experimentation, expanding design possibilities. To fully realise these benefits, however, continued investment in technological infrastructure, education, and regulatory adaptation will be essential.

Collectively, these cases (spanning academic prototypes and commercial projects) illustrate how Portugal's digital fabrication efforts are moving from the lab to the office. Early academic experiments like the CorkCrete Arch and CEAAD pavilions provided a testing ground, while projects such as the Lisbon Oceanarium extension by a private office demonstrate digital fabrication's entry into mainstream practice. This trajectory confirms the thesis's focus: translating fabrication innovation into the day-to-day operations of architecture offices.

These projects illustrate the potential of digital fabrication to reshape architecture – from novel structural systems to unique aesthetic expressions. Yet, they also underscore a critical observation: such initiatives in Portugal largely occur in research or special projects, not as part of mainstream practice. This observation reinforces the thesis's central question: how can the innovations seen in experimental cases become integrated into everyday architectural practice?

3.2. Portugal in Internacional Context: Digital Fabrication Adoption in Comparative Perspective

Digital fabrication has become an important component of architecture education and practice worldwide (El Khateeb, Abdulghany, & Youssry, 2022). However, the pace and form of adoption vary by country. In Portugal, digital fabrication in architecture has grown from isolated academic initiatives to broader public labs only in the last decade (Neves, Beirão, & Rocha, 2019; Paio & Brimet, 2013). In contrast, countries like Spain, the UK, Germany, and the US have longer and more coordinated histories of Digital Fabrication integration. Leading architecture institutions in Spain and the US pioneered advanced fabrication research (like MIT's Centre for Bits and Atoms, UC Berkeley's work on printing materials (ETH Zurich/Swiss Federal Institute of Technology, 2017). Governments also play a role: the UK's Digital Built Britain strategy (2015) explicitly supports BIM and digital processes in construction (RIBA, 2018), and Germany's national Industry 4.0 agenda has funded large R&D efforts in construction robotics and 3D printing. Spain benefits from European and regional innovation programs that encourage maker culture and university–industry collaboration (Interreg Europe Policy Learning Platform, 2022). Portugal's policy support has been more modest: a 2012 FabLab initiative (COMPETE program) marked the first national push for digital fabrication access (Neves, Beirão, & Rocha, 2019), and city-level projects fill much of the gap.

Interviewees underscored this comparative lag, especially around BIM maturity and digital practice: "other countries have been doing this for over 10 years – in Canada, in Finland, in the Nordic countries. We are the last country in Europe to seriously implement BIM… we're very, very behind. Our construction sector is underdeveloped compared to Europe, America, and Canada. When a foreign client (e.g. from the UK) arrives here, they're shocked to see we still show 2D plans. There's still a huge cultural shift to be made. Outside Portugal, BIM is already part of daily life, while here we're still taking our first steps." (Annex E - Konceptness). "Portugal was slower to embrace these tools. In many offices abroad (especially in Northern Europe), BIM and other digital technologies have been the standard for years, while here there's still reluctance and only now it's starting to become widespread." (Annex F - Rebelo de Andrade).

Policy and Institutional Support

In the UK, government and professional organisations actively promote digitisation in architecture. The 2018 RIBA survey highlights the UK's Digital Built Britain agenda, which mandates BIM on public projects and encourages digital collaboration. This top-down push has positioned the UK as a world leader in design digitisation, with architects "unique[ly] placed" to meet urbanisation and sustainability

challenges through technology (RIBA, 2018). Germany similarly backs digital fabrication through research funding and industry programs. Spain leverages EU structural and innovation funds: Interreg projects have seeded FabLabs (e.g. Food FabLab in Portugal's TagusValley for agri-food innovation and university FabLab networks in Spain (Interreg Europe Policy Learning Platform, 2022). By contrast, Portuguese national policy has had limited focus on digital fabrication. Aside from the FabLab programme in 2012 (Neves, Beirão, & Rocha, 2019), most support comes from local initiatives (like Lisbon's FabLab is municipally funded) or EU projects (Interreg Europe Policy Learning Platform, 2022). These differences mean that, compared to its peers, Portugal relies more on bottom-up maker networks and smaller grants, whereas countries like the UK and Germany align digital fabrication with broader digital economy goals.

Adoption in Practice

In professional practice, the extent of digital fabrication uses mirrors policy and education. Spanish architects have embraced digital fabrication in specialty projects, aided by local maker communities. Early adoption was largely confined to universities, but as open-source tools became affordable, design offices began digital production on novel projects (Turan, 2013). In the UK, many offices are BIM-centric but are only gradually exploring fabrication at scale. RIBA reports (2018) note that UK practices are open to digital change, and specific demonstrators show benefits of digital fabrication, but mainstream construction still lags. In Germany, architects often work closely with engineers and manufacturers; state-of-the-art practices use large-format printing and robotics in prototypes, reflecting Germany's industrial push. In the US, adoption is driven largely by research labs and startups. Portuguese practice remains emerging: Neves et al. (2019) note that only a small "emerging group of Portuguese architects" uses Digital fabrication systematically. Many Portuguese offices are still discovering digital fabrication via academic labs or FabLabs rather than as standard workflow. Overall, while practitioners everywhere recognise digital tools, only countries with robust support see digital fabrication move from novelty to routine.

International partners also set higher expectations for BIM literacy and integrated delivery: "take Asia – over there, you simply don't hire anyone who doesn't know how to work in BIM… They're trained that way from the ground up (many come from British universities with more advanced education in this). We, in Portugal, are not there yet. The international offices we work with – many with well-established digital practices – have already achieved that marriage between manual conceptual work and digital work, which shows they are at a much more advanced stage than us here in Portugal. Unfortunately, there is still a great lack of digital literacy in the sector." (Annex G - Saraiva + Associados).

Integration in Education

All the compared countries increasingly incorporate digital fabrication into architectural curricula. International surveys find that digital fabrication content is "rapidly becoming an important part of architecture education worldwide" (El Khateeb, Abdulghany, & Youssry, 2022). In Portugal, the shift began in academia: Instituto Superior Técnico in Lisbon established a digital fabrication lab in 2007, and one of its students later founded OPO-Lab in Porto – the country's first maker-oriented architecture space(Neves, Beirão, & Rocha, 2019). Lisbon's FabLab EDP (2008) and Vitruvius FabLab (ISCTE, 2011) then opened to the public, followed by FabLab Lisboa (2013). Porto's Faculty of Architecture inaugurated a dedicated Digital Fabrication Laboratory (DFL) with a robotic arm in 2014, marking a leap in hands-on education (Neves, Beirão, & Rocha, 2019). By comparison, Spanish programs have long offered Fab Academy courses (for example at IAAC) and many universities maintain FabLabs. The UK's architecture schools (as The Bartlett, LSBU) and technical institutes teach digital design and prototyping, aligning with national tech initiatives (RIBA, 2018). Germany's universities have introduced entire degrees in digital construction, and ETH Zurich even offers a one-year MAS in Architecture & Digital Fabrication (as part of its NCCR Digital Fabrication) (RIBA, 2018). US schools (MIT, Harvard GSD, etc.) widely run fabrication offices and partner with makerspaces. Thus, while Portugal is catching up - recent graduates may still lack mandatory Digital fabrication training - its academic path now mirrors others' emphasis on "learn by doing" fabrication labs (Interreg Europe Policy Learning Platform, 2022).

Importantly, not all interviewees viewed the gap as permanent; several saw evidence of convergence led by newer cohorts and impending policy shifts: "some Central and Northern European countries were a bit ahead of Portugal in integrating BIM into education and practice – I remember being impressed seeing students abroad using ArchiCAD back in 2006, while in Portugal most of us were still stuck in 2D. But Portugal isn't irretrievably behind. In recent years – especially with the younger generation – we've been catching up. Portugal wasn't a pioneer, but is now aligning with global trends… the gap is closing, and with upcoming government BIM mandates we'll likely converge further." (Annex I - TEKSTUDIO).

Infrastructure Availability

Physical infrastructure reflects these trends. Portugal today has a network of FabLabs (Lisbon, Porto, Évora, etc.) and university workshops, but far fewer than larger countries. Spain has dozens of FabLabs (e.g. Barcelona's FabLab, FAB Lab Madrid, Seville) and maker centres; Barcelona's city government even runs a Fab Lab network as public service (Barcelona City Council, n.d.). The UK has numerous fab facilities (in universities and city "makerspaces"), supported by initiatives like the High-Value Manufacturing Catapult's Digital Construction technologies. Germany's universities and research

centres offer cutting-edge labs (e.g. Stuttgart's ICD, TUM's lab) and private offices support advanced workshops. The US has an extensive fab network too: MIT-founded CBA's Fab Foundation affiliates, plus university and community labs coast-to-coast. In summary, Portugal's infrastructure is growing but still limited. Other countries show that broad access (especially via free, publicly-backed labs (Interreg Europe Policy Learning Platform, 2022) can greatly expand Digital fabrication use among students, startups, and artisans.

Best Practices and Lessons

Several international initiatives offer models for Portugal. One is the university–industry collaboration: Spain's Castilla y León region co-founded FabLabs at four public universities to translate research into commercial prototypes (Interreg Europe Policy Learning Platform, 2022). Portugal's universities could similarly partner with local offices via on-campus labs. Municipal leadership is also key: Lisbon's FabLab shows that city funding and open access can cultivate a maker ecosystem (Interreg Europe Policy Learning Platform, 2022). Other countries' programs (like the UK's focus on digital skills through RIBA or Germany's vocational integration of Digital fabrication (RIBA, 2018) suggest that linking FabLabs to formal education and professional training strengthens impact. In practice, Portuguese architects can learn from abroad by adopting collaborative workflows: for instance, UK and US offices increasingly embed fabrication teams in projects, and cross-disciplinary Swiss programs (NCCR Digital fabrication) integrate architecture and engineering (ETH Zurich, School for Continuing Education, n.d.). In policy, Portugal might emulate Germany's funded consortia approach (pooling universities, industry and government) to scale up Digital fabrication R&D. Overall, the comparative evidence suggests that Portugal's digital fabrication sector would benefit from increased strategic support - building on local FabLabs, embedding labs in curricula, and seeking international collaboration – following best practices demonstrated in neighbouring countries and allies (Interreg Europe Policy Learning Platform, 2022).

Portugal's digital fabrication in architecture shares the global trajectory of moving from cutting-edge research into wider practice, but it has evolved later and on a smaller scale than in Spain, the UK, Germany, or the US. Where those countries have national roadmaps, dedicated programs, and richer infrastructure, Portugal relies on incremental growth in academia and municipalities. By studying international surveys and case studies (El Khateeb, Abdulghany, & Youssry, 2022), Portuguese architects and policymakers can identify gaps - for example in policy incentives and educational integration - and adopt proven measures from abroad (as thematic FabLabs, public-sector funding). Integrating these lessons could help Portugal accelerate its digital transformation in architecture and align its practice more closely with international innovations.

While Portugal faces many of the same hurdles as other countries, certain challenges – and opportunities – stand out as unique to its context. One challenge is the small scale and late timing of

its adoption curve: with fewer resources and a delayed start, there is a risk of falling behind global standards unless efforts are intensified. At the same time, being a late adopter also confers a strategic advantage: Portuguese architects can leapfrog by learning from others' experiences and implementing best practices with the benefit of hindsight. Moreover, Portugal's rich architectural culture offers distinctive opportunities. Local research and projects often blend tradition with innovation in ways that could differentiate Portugal's approach to digital fabrication. For example, the Digital Fabrication Lab in Porto pioneered robotic construction using cork – a regionally abundant, sustainable material – in the "CorkCrete Arch", marrying advanced parametric methods with local craft and environmental sensibilities. Similarly, design-build workshops in Évora explicitly sought to "strengthen the tradition of building and craftsmanship" through the use of digital tools, demonstrating how indigenous building knowledge can be enhanced (rather than replaced) by technology. By leveraging such cultural strengths – an ingrained craftsmanship ethos, familiarity with materials like cork, and creative adaptability – Portugal can carve out a niche in digital fabrication that plays to its advantages. In essence, Portugal's digital transformation in architecture need not simply replicate foreign models; it has the potential to develop a distinctive hybrid model where global innovation is integrated with local context and identity. Realizing this potential will require strategic support, but it could position Portuguese architects to contribute unique solutions to the worldwide discourse on digital design.

3.3. Digital Fabrication and Professional Transformation in Portuguese Architecture

Digital fabrication in Portuguese architecture reveals a mixed picture of innovation emerging in the face of significant constraints. In brief, Portuguese architects have begun to experiment with CNC, 3D printing, and robotics in both design offices and academic workshops. However, adoption remains uneven. The research identified four inter-related challenges: infrastructure, skills, culture, and cost. These reflect international findings that digital fabrication faces low adoption in AEC due to economic, organisational, and technical barriers (Tan, Ng, & Hall, 2023). A survey found that 69% of architects cite cost as the primary obstacle to new technologies, noting that "cost of purchasing new software, [and] time and investment…to get staff up to speed" are major issues (RIBA, 2018). Nearly half of offices also report a lack of in-house digital skills. And crucially, many offices still lack the "right organisational culture" to pursue innovation (RIBA, 2018). Interviews (Annexes A to I) conducted with several Portuguese architecture offices in the context of this research support these claims, confirming that cost, limited technical training, and conservative workflows remain constant barriers in the national context. In other words, despite strategic discourse on Industry 4.0 and BIM, practical adoption in Portugal lags behind because small offices have tight margins and heavy workloads.

Despite these challenges, the research also highlighted enabling factors, especially the role of Fab Labs and collaborative spaces. Fab Labs in Portugal are becoming crucial innovation hubs. By offering public workshops equipped with CNC machines, 3D printers, laser cutters and other tools. In practice, these labs democratize access: local architects can prototype custom components without buying their own machinery. They also foster knowledge sharing by linking to the global Fab Lab network (Gershenfeld, 2005). This builds a pipeline of skilled graduates who understand the entire digital-design-to-fabrication process and can "plug into" international expertise and standards. In short, the Fab Lab ecosystem provides an educational bridge: it partially alleviates infrastructure gaps and can help develop the new technical skills Portuguese architects need.

The presented examples of digital fabrication within Portuguese architectural practice illustrate how these trends play out in real projects. In the academic field. Digital fabrication is reshaping workflows: architects are starting to design with fabrication constraints in mind, coordinating directly with fabricators or even fabricating parts themselves. It also highlights a learning curve: Portuguese practitioners must navigate trade-offs (e.g. material costs) and leverage networks (fabrication partners) to implement their designs.

On a broader scale, Portugal's experience mirrors international patterns. The main barriers identified - cost, skills, and regulation - are nearly identical to those reported in surveys from the UK, US, and Hong Kong (RIBA, 2018). Tan et al. (2023) categorize the obstacles to digital fabrication implementation into five areas: economic, organisational, personnel, technological, and regulatory. These categories correspond directly to the challenges identified in the Portuguese context, including financial constraints, cultural resistance, skill gaps, technological limitations, and policy shortcomings. Similarly, the RIBA survey (2018) highlights the importance of "having the right organisational culture," a point supported by Portuguese participants in the interviews (Annexes A to I) who emphasized the role of leadership and mindset in enabling change. This alignment suggests that strategies developed abroad - such as integrated workflows, subsidized training programmes, and international collaborations - could be effectively adapted to support Portugal's digital transition.

Consequently, digital fabrication is enabling new practices and knowledge in Portuguese architecture. Design processes are becoming more iterative and material-aware. Architects often prototype form with physical models early on and refine geometry together with fabrication planning. In this process, they learn to treat material properties and machine behaviour as design parameters (Hirsch et al., 2023). In architecture offices, integrating digital fabrication requires learning about supply chains and manufacturing constraints. Over time, this is creating a generation of hybrid professionals - part architect, part maker - who combine CAD/CAM skills with traditional design training. This shift toward a "computational craft" approach aligns with global pedagogical trends where architecture education includes robotics and digital prototyping.

The emergence of hybrid practitioner roles highlights an ongoing reconfiguration of architectural identity in Portugal. Among younger architects and those engaged in Fab Labs or experimental practices, there is a growing tendency to adopt expanded professional identities that encompass not only design authorship but also technological integration and fabrication. These practitioners operate across digital and physical domains, positioning themselves as "architect-makers" who actively shape production processes rather than delegating them. In contrast, a number of established professionals maintain a more traditional conception of architectural practice, selectively adopting digital tools while preserving established workflows and self-definitions. This divergence reflects a broader negotiation within the profession between expanded and delegated models of expertise. The way Portuguese architectural offices resolve this tension has significant implications for organisational structures, knowledge distribution, and the uptake of digital innovation. Where technological competencies are internalized, offices are more likely to develop integrated workflows that connect design intent with fabrication logic; where such competencies remain externalized, digital expertise risks becoming siloed, potentially slowing the diffusion of advanced practices. Recognizing this condition, some industry actors advocate mentorship and training models that frame technological engagement as an extension of architectural craft rather than a departure from it, supporting a gradual transformation of professional identity without undermining creative autonomy.

Nonetheless, key barriers remain. Without continued support, these obstacles could slow momentum. In Portugal this means addressing uneven regional access (most Fab Labs are in big cities).

Here an ethical and political concern comes into focus: unequal access to technology and training may lead to an architectural "digital divide" within Portugal. The benefits of digital transformation are not reaching all practitioners evenly. Advanced fabrication facilities and workshops are concentrated in Lisbon and Porto, giving offices in these hubs and those affiliated with universities a significant advantage, while professionals in smaller cities or rural areas are left with fewer opportunities to participate. Fab Labs aim to "democratize access to the tools for technical invention", yet in practice many architects on the periphery struggle to leverage these resources. Similarly, larger or better-funded offices can more easily invest in technology and staff training, whereas small offices with tight budgets risk falling further behind. This raises critical questions of equity and inclusion: Who truly stands to benefit from digital adoption in Portuguese architecture, and who might be left out? If digital fabrication and BIM become prerequisites for competitive projects, then practitioners without access to these tools or skills could see their work marginalized. There is also a generational dimension – younger architects exposed to digital methods may thrive, while older professionals who lack training might find their experience devalued or face pressures to retrain. In past technological shifts, we have seen "de-skilling, a rise in wealth inequality, ... and older generations being left behind" when change is not managed inclusively (Royal Institute of British Architects (RIBA, 2018). The Portuguese Order of

Architects and other institutions may need to address this explicitly, ensuring that support is channelled to those at risk of exclusion. Ethically, the profession has a responsibility to avoid a scenario in which digital transformation reinforces existing inequalities or creates new ones. Politically, this touches on regional policy and educational outreach – for instance, should there be incentives to establish Fab Labs or training centres in inland regions? Should public funding prioritize broad access over concentrating excellence in a few hubs? These questions do not have easy answers, but it is clear that a more inclusive approach to digital innovation is needed. As the RIBA has noted in the UK context, it is crucial to promote technology adoption "in ways that are trusted, responsible and inclusive" so that its benefits accrue to the profession and society as a whole, rather than exacerbating disparities (Royal Institute of British Architects [RIBA], 2018). In Portugal, recognizing the uneven landscape is the first step toward remedial measures, such as targeted grants, traveling workshops, or online knowledge platforms, that can help bridge the gap between pioneers and laggards, ensuring the digital future of architecture is one in which all practitioners have a stake. Additionally, clarifying building codes for new components and integrating fabrication thinking into client expectations remain priorities. Cost is unlikely to drop dramatically in the short term, so creative business models (shared workshops, fabrication-as-a-service) may be needed. At the same time, there is potential for growth. Portugal has strong research universities and a growing tech sector that can fuel innovation. European and national funds (e.g. Horizon Europe projects on digital construction, and the national Digital Transition plan) could be targeted to architectural applications.

The future directions suggested include:

Policy Support

Like Silva and Paio (2024) advocate, government agencies should include architecture in digital innovation plans. This could take the form of grants for offices to adopt fabrication equipment, tax incentives for R&D in construction technologies, or standards/regulations that encourage modular fabrication. A public strategy (similar to Germany's Industrie 4.0 roadmap) would demonstrate that digital building methods are a priority.

Education Reform

Architecture programs must embed digital fabrication more deeply. This means not only offering dedicated lab courses but integrating CNC/3D printing modules into core design offices. Establishing Fab Labs at academic institutions and strengthening ties with industry projects will ensure students graduate with relevant skills. Expanding these initiatives (and promoting them to practicing architects) will build a critical mass of makers.

Industry–Academia Partnerships

Formal collaborations between universities and offices can accelerate transfer of methods. Joint workshops, funded research consortia, or innovation hubs would help convert experimental knowledge into practice. Facilitating more of these collaborations - through internships, sponsored thesis projects, or collaborative R&D grants - could spread fabrication know-how.

Community Building

The Fab Lab network in Portugal should keep expanding. New maker spaces in secondary cities and outreach events would raise awareness and build a culture of tinkering. A stronger maker community helps normalize digital tools as everyday practice, reduces fear of technology, and can produce grassroots innovations.

These reflections show that digital transformation, and digital fabrication in particular, is slowly but progressively influencing Portuguese architecture, largely from the ground up. The reflective synthesis brought together in this chapter integrates the infrastructural, skill-based, cultural, and economic dimensions of this challenge, while also indicating how international experience and earlier themes developed in the thesis can inform potential responses. By addressing the identified barriers through coordinated policy measures, educational reform, and strengthened partnerships, Portugal can nurture an architectural sector in which custom fabrication, parametric design, and industrialized building processes converge. This trajectory aligns with the thesis's broader argument that digital transformation, while complex and uneven, ultimately opens new horizons for design innovation and efficiency in the built environment.

Above all, a central reflection emerging from the critical examination is that, while Portuguese universities and Fab Labs have played a pioneering role in introducing digital fabrication, the future of these methods depends on their normalisation within architectural offices. Policies, educational structures, and collaborative partnerships must therefore support architects incorporating digital fabrication into everyday professional workflows, effectively closing the gap between experimentation and building production.

In summary, although digital fabrication is progressively reshaping Portuguese architecture, its impact remains uneven and is still largely driven by academic and experimental contexts. Bridging the gap between experimentation and routine professional practice requires more than incremental or ad hoc adoption; it calls for a structured approach capable of aligning skills, infrastructure, organisational culture, and research engagement within architectural offices. This need provides the rationale for Chapter 4, which introduces a strategic framework designed to support the systematic integration of digital fabrication into everyday architectural practice.

PART II – ANALISING DIGITALISATION OF ARCHITECTURAL PRACTICE

CHAPTER 4

Framework for Digitalisation of Architectural Practice

Architectural practice today faces rapid technological change, prompting the need for strategic guidance on digital transformation. In response, this chapter proposes a Strategic Framework for Digitalisation of Architectural Practice (SFDAP) that assesses offices along two key dimensions – their level of Digital Maturity and their degree of Research Engagement. By mapping out an office's position in this two-dimensional space, the framework provides tailored insights: a high-maturity, high-engagement office will have very different needs than a low-maturity, low-engagement office, and SFDAP helps identify appropriate development pathways for each. In this way, the framework offers structured yet scalable guidance adaptable to different starting points on the digitalisation journey. While we use the concept of digital maturity (Deutsch, 2017) as a framework, the focus here is specifically on fabrication processes and tools. Thus, the integration model addresses how digital fabrication tools and material constraints are embedded into the design workflow, rather than addressing non-fabrication digital tools in general.

4.1. Towards a Strategic Framework for Digital Maturity in Architecture

Building on the empirical findings and critical synthesis presented in the previous chapters, this section introduces a strategic framework designed to support architectural practices in systematically navigating digital transformation, with particular emphasis on the integration of digital fabrication into everyday design workflows.

Methodologically, the development of SFDAP involved three main stages, ensuring both theoretical grounding and empirical validation. Parameter development entailed drawing on established literature to define clear indicators for each dimension. On the technology side, indicators such as BIM usage, computational design tools, and data management systems were informed by digital transformation models in design (Kolarevic, 2003; Walliss & Rahmann, 2016; Perera et al., 2022). On the knowledge side, factors like in-house research and design (R&D) projects, university collaborations, and evidence-based design practices drew from evidence-use theory in other fields (Nutley et al., 2007; Lomas, 2000). These literature-derived indicators established what aspects of practice to measure on each axis. Framework construction then organised these indicators into the SFDAP matrix, mapping out offices according to their scores on Digital Maturity and Research

Engagement (Nutley et al., 2007; Lomas, 2000; Suter et al., 2009; and McKinsey, 2020). This structure reveals both strengths and gaps in an office's approach – for example, distinguishing a "high-tech but low-research" practice from a "research-driven innovator." Empirical validation followed by applying the framework to a diverse sample of 47 architecture offices worldwide (see Annex J for the dataset). The sample was intentionally constructed to ensure diversity across several criteria, including geographical location, office size (ranging from small offices to large multidisciplinary practices), market orientation (local, national, and international), and degree of engagement with digital technologies and research activities. This purposeful sampling strategy enabled the framework to be tested across a wide spectrum of organisational contexts and levels of digital adoption, rather than being limited to highly specialised or technologically advanced offices.

Each office's profile on the matrix was analysed, and the initial theoretical parameters were iteratively refined based on observed patterns. This empirical stage ensured that the SFDAP categories and scales reflect real-world practice rather than only abstract theory, calibrating the framework against actual office behaviours and outcomes.

Throughout this process, SFDAP's development remained grounded in theory while continually refined by data. Initial categories and assumptions drawn from literature were tested against evidence from the 47 architectural offices, leading to adjustments where necessary. Measuring digital maturity provides a crucial "roadmap" for organisations to plan and improve their transformation efforts (Walliss & Rahmann, 2016; Staab, 2023, Burry, 2016). By combining scholarly models with empirical data from practice, this chapter bridges the conceptual discussions of earlier chapters with a concrete, evidence-based tool for architects.

Underpinning this research design is a clear epistemological position. The study adopts an interpretivist stance, recognizing that knowledge about digital practice in architecture is context-dependent and socially constructed through the experiences of practitioners. Rather than examining phenomena from a detached, purely positivist viewpoint, we (as researchers) engage with architects' subjective insights – through interviews, case studies, and observations – to construct an understanding of digital fabrication adoption. This aligns with the tradition of interpretive inquiry in architecture, wherein multiple realities and narratives are expected and valued (Groat & Wang, 2013). At the same time, the research is guided by a pragmatic concern for usefulness: the SFDAP framework is intended as a practical outcome that can inform decision-making. Thus, the epistemology could be described as interpretive-pragmatic. We acknowledge that any framework is a simplification of reality (constructed through our interpretation of data), yet we pursue it because it can provide actionable knowledge for architects. Reflexively, the researcher's role is recognised as an active instrument in this inquiry – from framing the questions to interpreting interview data – which necessitates transparency and critical self-awareness. By stating this epistemological stance, we make clear that the framework

is not an objective truth machine, but a product of qualitative synthesis aimed at insight and improvement. This positioning within a constructivist paradigm ensures that the nuances of practice (the "why" and "how" behind quantitative metrics) remain central to the framework's development, lending it relevance and credibility in the eyes of practitioners who navigate those nuanced realities daily.

It is important to acknowledge the limitations and potential biases inherent in the research design and implementation. First, the selection of case studies – both the 47 international offices and the focused Portuguese offices – was purposive, targeting known digitally active or innovative practices. This introduces a selection bias: the sample may over-represent forward-thinking offices while under-representing those that have struggled or lagged in digital adoption. As a result, the framework might skew toward highlighting success factors rather than the full spectrum of challenges. Second, data collection relied heavily on interviews and self-reported information (in addition to published sources). This raises issues of response bias and subjectivity – practitioners may have portrayed their use of technology in a favourable light, or the researcher's own enthusiasm for digital innovation might have subtly influenced interpretations. We attempted to mitigate this by triangulating interview data with external records and critical literature, but some bias inevitably remains. Third, the contextual scope is a limitation: a significant portion of the qualitative data comes from Portugal, a specific cultural and economic setting. While SFDAP was also applied to an international sample for breadth, the framework's categories (e.g. what counts as "high" research engagement) may reflect assumptions prevalent in Western or academically-linked practice environments. Different metrics or dimensions might emerge as more important in other contexts (for example, social impact or craft skill might be vital in locales where formal R&D is scarce). Additionally, the rapidly evolving nature of technology means any snapshot of practice can become dated; what is cutting-edge today (like AI-driven design assistance) could be commonplace tomorrow, potentially shifting the "maturity" scale over time. We recognise that the SFDAP model is a product of the late 2020s and may need future revision as the field progresses. Finally, there is an inherent interpretive bias in how we coded and scored offices on the two axes – another researcher might classify certain borderline cases differently. To be transparent, we have documented our coding criteria (Annex J) and provided rationales for each office's placement. Nonetheless, the framework's utility should be appraised with an understanding of these limitations: it is a guiding tool, not an absolute diagnostic, and it works best in concert with qualitative judgment about each unique practice.

Questions of validation and contestation naturally arise for a new framework like SFDAP. We have taken initial steps to validate the framework by applying it to a diverse set of offices and observing whether the two axes meaningfully distinguish different practice profiles (indeed, the clustering of offices into Pioneers, Innovators, etc., in our analysis suggests that the framework captures real

variations). However, further validation is both necessary and encouraged. One way to test SFDAP would be through longitudinal studies: for example, a set of offices could self-assess their SFDAP position, implement recommended strategies, and be re-assessed after a few years to see if the framework successfully predicts or guides improvement in digital integration. Another approach is to engage external experts or offices in using the framework as a diagnostic tool and gathering feedback – do practitioners find their categorisation accurate and the suggestions useful? Such field testing could either reinforce the framework's credibility or highlight areas for refinement. It is equally important to consider how the framework might be contested. Scholars or practitioners might argue that two axes are insufficient to capture something as complex as architectural practice. For instance, design quality or social value might be proposed as additional dimensions of "maturity" not accounted for in SFDAP. Others might question the weighting of factors: is BIM usage as important as we assumed, or should cultural factors weigh more? We welcome these critiques as part of the framework's evolution. SFDAP is intentionally a simplified model of reality – its strength is clarity, but that comes at the cost of abstraction. Therefore, we see the framework as a living construct: its validity will be proven not by being unchanging, but by its ability to be adapted, improved, or even challenged by new evidence. In academic terms, this is an open invitation for replication and falsification attempts. If future research finds a different typology that better explains digital adoption in architecture, then the SFDAP will have served as a stepping stone in that ongoing inquiry. In practice, if an office finds that their experience doesn't align with the framework's implications, that feedback is invaluable for adjusting the model. By outlining how SFDAP could be validated, tested, or contested, we underscore that the framework is meant to provoke discussion and continuous learning in the field – much like any design, it thrives on iteration.

Placing this work within broader architectural research paradigms, we find it at an intersection of several modes of inquiry. It is fundamentally a practice-based study: it draws empirical insight from real-world architectural practice (through interviews, case observations, etc.), rather than from laboratory experiments or purely theoretical constructs. In doing so, it aligns with the tradition of interpretive inquiry, as it seeks to understand and explain phenomena (digital fabrication usage) by interpreting contextual meanings and narratives provided by practitioners. This interpretive, case-focused approach is well-established in architecture and design research, where rich descriptions and qualitative understanding often yield the most relevant knowledge for practice (Groat & Wang, 2013). At the same time, the project has a strong element of design research — not in the sense of creating a building prototype, but in producing a framework intended to inform design practice. In research terminology, this could be seen as research for design: the outcome is a tool (SFDAP) to aid architects and offices in reflecting on and strategizing their digital transformation. By constructing this tool, the thesis engages in a form of design inquiry, analogous to how a research-through-design study might

produce a conceptual model or artifact as a vehicle for knowledge. This blend of interpretive and design research paradigms reflects a contemporary view of architectural research: scholarly investigation can both analyse practice (to generate theory) and propose interventions (to change practice). In sum, the methodology and framework development presented in Chapter 4 (Methodological Design and Framework Development) is situated within a pragmatic paradigm that values usefulness and context. It resonates with practice-based research approaches, where the credibility of findings is gauged by their grounding in actual practice and their utility to that practice. Yet it also contributes to academic discourse by formalizing a typology and inviting further scholarly examination. By straddling these paradigms, the research ensures that the SFDAP framework is not only theoretically sound and rigorously derived, but also impactful for those at the forefront of architectural innovation, thereby fulfilling the dual aims of interpretive understanding and practical guidance.

The sections that follow clarify how offices are assessed on the two key dimensions and how the SFDAP classification logic works, including the typology of practice profiles that emerges. In doing so, we illustrate how SFDAP can guide offices of varying profiles in planning their digitalisation strategies.

4.1.1. Definition of Key Parameters (Digital Maturity, Research Engagement, Office Size)

Before discussing the typology of architectural practices, it is essential to define the key parameters of the SFDAP framework. The classification is based on two primary axes – Digital Maturity (DM) and Research Engagement (RE) – supplemented by a contextual factor, office size, which can influence a practice's capacity for innovation. Below, each parameter is defined and situated in relevant literature to establish the conceptual basis for the framework.

In this thesis, Digital Maturity (DM) refers to the extent an office has integrated digital fabrication. We assess it on a 1–5 scale, where 1 indicates minimal digital use and 5 indicates fully integrated, advanced computational workflows across projects. Research Engagement (RE) denotes how actively an office pursues research and innovation, through in-house R&D, academic collaborations, or experimental projects. This too is rated 1–5, from no research activity to a high level of continuous innovation and knowledge development. Additionally, office size (small, medium, large) is noted, as scale can impact resources and adoption.

Digital Maturity

This refers to the extent to which an architectural office has integrated digital fabrication tools, processes, and mindsets into its practice. We adopt the notion of "digital maturity" to describe integration of digital tools as in Deutsch (2017). Framing our study this way helps reveal pathways by which offices can progress from basic to advanced fabrication capabilities. In industry and academia,

digital maturity is often described by staged models representing ascending levels of capability and integration. For example, Optimisely's Digital Experience Maturity Model outlines five progressive stages: Ad-hoc, Basic, Intermediate, Advanced, and Leading. Each stage corresponds to greater incorporation of digital technologies and stronger strategic alignment of digital initiatives. Similarly, construction industry frameworks use four to six maturity levels – ranging from nascent or ad-hoc at the low end up to truly innovative at the high end – to assess an office's digital readiness (Das et al., 2023; Jäkel et al., 2024). In our framework, we adopt a five-point scale for Digital Maturity roughly analogous to these models. A score of 1 (or 2) indicates very low or essentially non-existent digital integration; a 3 represents a moderate, intermediate level of engagement with digital tools; and a 5 denotes an office that is fully digitally integrated, where advanced technologies are used as a matter of routine. For instance, a DM = 5 practice would be leveraging BIM, parametric design, robotics, and AI regularly across projects, whereas a DM = 1 office might still rely largely on traditional CAD or even analogue methods. Notably, Perera et al. (2022) observe that digital transformation in design and construction has often been "chaotic and ad-hoc," underscoring the need for clear maturity stages to guide practice. At the upper end of our DM scale, offices demonstrate systematic digital strategies and deployment of cutting-edge tools, whereas at the lower end, digital adoption tends to be piecemeal or absent. In summary, the Digital Maturity parameter captures how far along the technological adoption curve a practice is – from rudimentary use of isolated digital tools to holistic, integrated digital operations.

Research Engagement

Research Engagement (RE) is defined as the degree to which an office actively engages with research and knowledge development in its work. This engagement ranges from passively using external research findings to actively co-producing new knowledge. Drawing on models of evidence use from other fields (Lomas, 2000; Nutley et al., 2007; Suter et al., 2009), we conceptualize research engagement as a spectrum rather than a binary trait. At the lower end (RE scores of 1–2), an office might be considered merely "research-aware" – keeping an eye on emerging technologies and ideas but not systematically consulting academic literature or investing in R&D. Such a practice might occasionally read industry reports or attend conferences, but research is not embedded in decision-making. In the mid-range (around RE = 3), offices become "research-informed," actively applying known research findings or best practices in their projects – for example, implementing insights from published BIM best-practice guides or sustainability research in design work. These practices use research knowledge instrumentally to improve outcomes, though they may not generate new research themselves. At the high end of the spectrum (RE scores of 4–5), offices can be termed "research-active" or "research-led." These organisations don't just consume knowledge; they help create it. For instance,

a research-active architecture office might collaborate with universities on developing new design methods, run an in-house R&D lab, or publish results of practice-based innovation experiments. In public policy terms, our notion of high research engagement parallels what Lomas (2000) calls a "linkage and exchange" model – a collaborative mode where practitioners and researchers engage in mutual learning and co-production of knowledge. Nutley et al. (2007) similarly argue that deep process engagement (i.e. being part of the research creation process) tends to yield more significant innovation than merely using research in a conceptual (inspirational) or instrumental (problem-solving) way. Reflecting these insights, we calibrate the RE scale such that a score of 5 corresponds to offices whose culture and structure strongly support ongoing R&D and experimentation, whereas lower values down to 1 indicate progressively less systematic research involvement (from occasional and incidental at best, down to effectively none). In essence, the Research Engagement parameter measures how deeply an office immerses itself in the knowledge cycle – whether it merely follows others' innovations or actively drives innovation in the field.

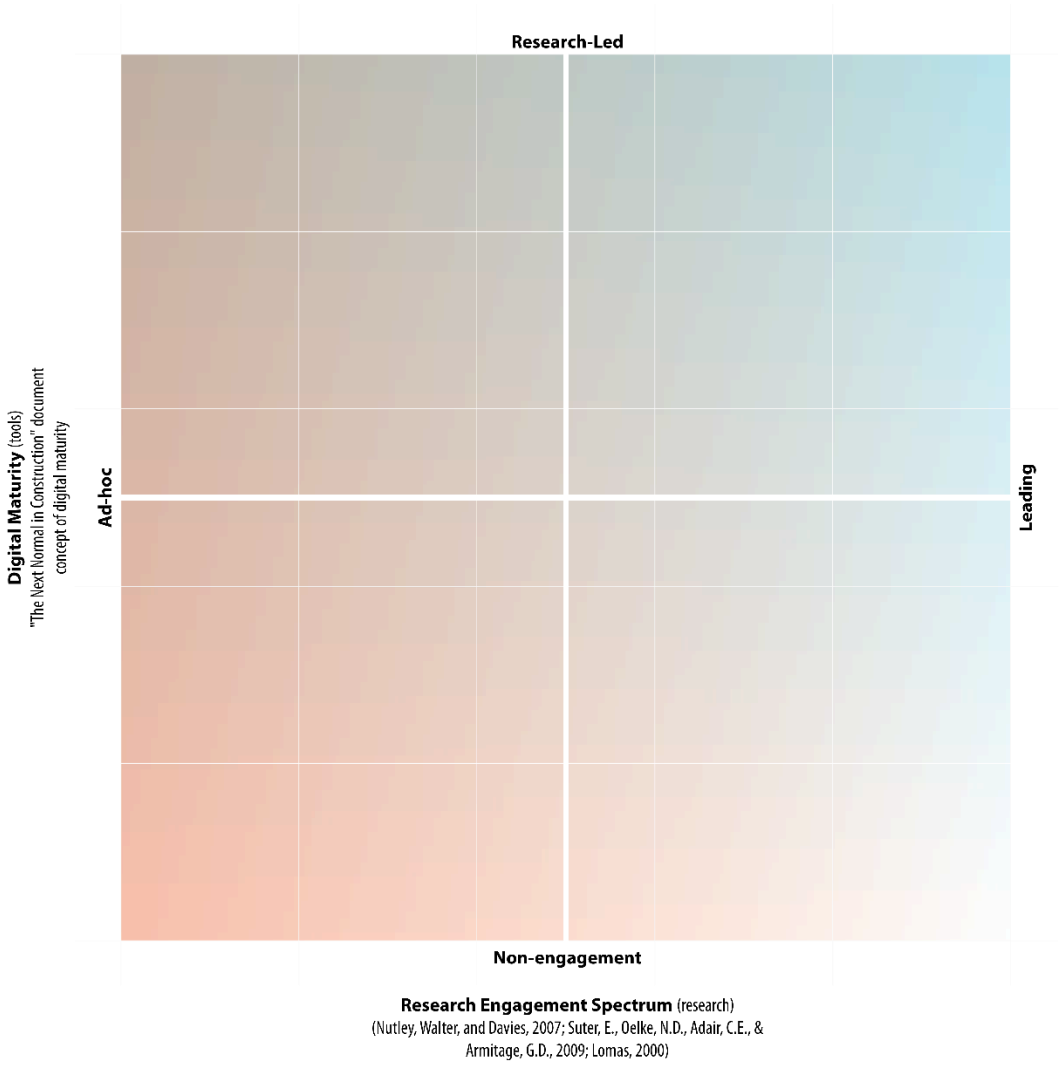


Figure 4.1: Strategic Framework for the Digitalisation of Architectural Practice (SFDAP): Digital Maturity vs. Research Engagement Matrix.

This matrix visualizes the SFDAP framework, plotting architectural offices across two key axes: Digital Maturity (extent of technology integration) and Research Engagement (degree of involvement with research activities). It provides a conceptual basis for categorizing offices as Digital Pioneers, Innovators, or Digitally Emerging, enabling structured assessment of their position in the digital transformation landscape. Based on sources: Nutley et al. (2007), Lomas (2000), Suter et al. (2009), and McKinsey (2020).

Office Size

Although not an axis in the two-dimensional matrix, office size is included in our framework as a contextual parameter because an organisation's scale often influences its capacity for digital adoption and research. We classify office size in three bands by number of staff: Small (fewer than 50 employees), Medium (50–300 employees), and Large (more than 300 employees). These thresholds align with common industry and EU definitions for enterprise size, although in architecture the vast majority of practices are small offices below 50 people. Office size is relevant because larger offices typically have more resources – financial, technical, and human – to invest in new technologies and in-house R&D. For example, global practices like Foster + Partners or Arup (both of which in our dataset score DM=5 and RE=5) are large offices that sustain dedicated R&D departments and can afford early adoption of cutting-edge tools. Smaller offices, in contrast, often operate with tighter budgets and leaner teams, which can constrain their ability to experiment. A 10-person office may have to rely on off-the-shelf software and occasional external consultants; such resource limitations are likely to be reflected in lower DM and RE scores (indeed, many small offices in our study scored toward the lower end on both axes). In short, while size itself does not determine innovation, it conditions what is feasible. Our framework takes size into account when interpreting an office's DM and RE: a small, high-scoring office might be "punching above its weight" through strategic focus, whereas a large, low-scoring office might indicate underutilised capacity. Notably, the typologies introduced below often correlate with size – Digital Pioneers tend to include several large offices, while Digitally Emerging practices are frequently small or mid-sized – but there are exceptions. Including office size as a parameter thus allows us to contextualise DM and RE scores in terms of an office's operational scale and resource environment.

4.1.2. Framework Classification: Typologies of Architectural Practice

By mapping out architectural practices on the two axes of Digital Maturity and Research Engagement, clear patterns emerge that group offices into distinctive typologies. Our analysis of numerous offices revealed that, despite continuous variation, organisations tend to cluster into three broad categories.

Based on the DM and RE parameters, offices can be categorized into three typologies: Digital Pioneers, Digital Innovators, and Digitally Emerging practices. Each typology represents a different profile in terms of technology adoption and research culture, with its own characteristics and examples:

Digital Pioneers (DM=5, RE=5)

These offices sit at the cutting edge of architectural practice. Digital Pioneers exhibit the highest level of maturity, meaning they have adopted advanced technologies as core components of their processes, and they actively engage in research as a fundamental part of operations. In practical terms, a Pioneer office routinely employs generative design algorithms, AI-driven tools, full BIM and digital twin workflows, and even robotic fabrication or custom software development. At the same time, it nurtures a research-oriented culture: Pioneer offices often have dedicated R&D teams or labs, formal partnerships with academic institutions, and a prolific output of publications or conference presentations showcasing their innovations. In theoretical terms, these offices exemplify the ideal of knowledge co-production – they do not merely apply existing research, but actively collaborate in creating new knowledge (Nutley et al., 2007; Lomas, 2000). Lomas's "linkage and exchange" model of research use, which emphasizes mutual learning between researchers and practitioners, is essentially realised in these settings. Pioneers help shape the very knowledge they later use in practice. They also tend to be leaders in the profession at large: Pioneer offices commonly spearhead industry forums, pilot experimental projects, and set benchmarks that others follow. For instance, in our dataset, Archi-Union (an innovative practice based in China) was recorded with DM=5 and RE=5, noted for pioneering work in robotic digital fabrication and material research. Likewise, global design leaders such as Arup, Snøhetta, Studio RAP, or Zaha Hadid Architects fit this profile: all invest heavily in internal research groups and use those findings to push the boundaries of architecture. Many Pioneers are medium-to-large in size and exemplify the "Leading" stage in general digital maturity models – in other words, they are the digital and knowledge leaders of the industry. A Digital Pioneer demonstrates how high technological integration coupled with a strong research engagement can yield a practice that continuously innovates and often defines new paradigms for others to emulate.

Digital Innovators (DM=4, RE=4)

The Innovator typology represents offices with a strong digital footprint and substantial engagement with research, though not quite at the extreme frontier of experimentation that defines the Pioneer group. These offices have typically integrated many advanced tools – for example, widespread use of BIM, parametric design and simulation in their workflows (indicating an "advanced" maturity level) – and they often experiment with emerging tools like computational analysis, VR/AR, or digital fabrication on select projects. Innovators make active use of research and new ideas, for instance by

applying state-of-the-art best practices from building science or collaborating on occasional research initiatives, but such activities tend to be project-driven rather than part of a pervasive R&D culture. This aligns with what Nutley et al. (2007) call instrumental use of evidence (directly applying research findings) and partial process use (engaging in research processes sporadically). In other words, Innovators move beyond a one-way "research uptake" model and foster some two-way exchanges between practice and research, yet they might still lean more on adapting existing innovations than on generating radically new ones. Our data include several prominent examples of Digital Innovators. 3XN (Denmark), for instance, scored DM=4 and RE=4; this office is well-known for its parametric design approach and even established an internal research unit (GXN) to explore new materials and technologies, illustrating a concerted engagement with research. Other examples include BVN (Australia), EMBT – Miralles Tagliabue (Spain), and Hopkins Architects (UK), all of which we rated DM=4, RE=4. These practices frequently publish articles or reports on their design innovations and often maintain partnerships with universities or industry research programs. However, they may be somewhat smaller in scale or less comprehensively research-centric compared to the Pioneers. Innovators demonstrate that an office can achieve significant digital integration and benefit from research without necessarily having the extensive R&D infrastructure of a Pioneer. They are typically very forward-thinking and open to new ideas, even if they don't always originate those ideas themselves. In summary, Digital Innovators are leaders in adoption – quick to implement proven innovations and occasionally contributing to new ones – and they serve as a critical middle tier in the landscape of digital practice.

Digitally Emerging (DM=2–3, RE=2–3)

This category encompasses offices with modest levels of digital adoption and research engagement, in an early or developing stage of digital transformation. A Digitally Emerging practice might employ some digital tools – for example, basic BIM software for documentation, 3D modelling for visualisation, and perhaps occasional parametric scripts or generative design experiments – placing them in the low-to-mid range of maturity. However, their use of these tools is not yet pervasive or optimised; digital methods might only be applied on certain project types or at particular stages, rather than across all workflows. Similarly, their engagement with research tends to be limited. These offices are typically "research-aware" or lightly "research-informed": they stay abreast of major industry trends (for instance, following publications on sustainable design or noting what leading offices are doing with AI), and they might implement well-established best practices that originated elsewhere, but they rarely generate new research or formally collaborate on R&D. In Nutley et al.'s framework, such offices correspond to primarily conceptual use of research – external knowledge influences their thinking – with only basic instrumental use of specific findings. Many Digitally Emerging offices are smaller offices

or relatively young practices still consolidating their business. For example, our dataset includes AL_A (Amanda Levete Architects), Architecture Workshop, and Asif Khan Studio in this category – each scored roughly DM=2–3 and RE=2–3. These offices do use digital tools like BIM and create impressive digital visualisations for clients, and they are cognisant of contemporary design research (e.g. they may adopt sustainability principles developed by others). However, their focus tends to be on delivering projects using known methods; innovation is more incremental and internally driven (e.g. finding slightly better ways to manage projects or coordinate with consultants) rather than pushing the boundaries of the discipline. They are more pragmatic than pioneering in their approach to technology. It is important to note that being "emerging" is not a judgment of design quality, but rather a description of their strategic engagement with innovation: these offices are still in the process of building up digital capabilities and research integration, often due to resource constraints or different business priorities. In many respects, they represent the mainstream majority of practice that is exploring digital transformation but has not yet fully realised it.

These three categories – Pioneers, Innovators, and Emerging – are grounded in theory and reflect distinct strategies of engaging with technology and knowledge. Higher research engagement aligns with what the literature calls interactive models of knowledge use, which are associated with greater innovation outcomes. For example, Lomas (2000) argues that fostering "linkage and exchange" between researchers and practitioners leads to mutual learning and more effective use of knowledge – a dynamic clearly seen in the Pioneer offices – whereas organisations with minimal engagement tend to rely on passive uptake of externally produced knowledge. In our framework, the Pioneers essentially operate as knowledge generators within their projects (akin to having "embedded researchers" in practice), while Emerging offices predominantly act as knowledge consumers, implementing ideas developed elsewhere. The digital maturity dimension, on the other hand, follows a similar spectrum from ad-hoc adoption of basic tools in Emerging practices up to fully integrated, state-of-the-art toolsets in the Pioneers. As the next sections will show, these typologies are not just theoretical: they manifest in real offices internationally and help explain the different pathways and best practices observed in the field.

4.2. International Context: Analysis of Architectural Offices Practices

To ground the SFDAP framework in real-world practice, an international case study approach was adopted. In adopting a case study methodology, it is important to acknowledge its value for architectural research. Flyvbjerg (2006) argues that case studies capture rich, context-dependent knowledge and interrelated factors often lost in large-sample studies (Flyvbjerg, 2011). Groat and

Wang (2013) similarly note that case studies allow researchers to bridge theory and practice by observing design phenomena in situ, yielding insights beyond what purely quantitative methods can offer. Yin (2018) emphasizes that case studies are especially suited to probing "how" and "why" questions in depth within real-world settings, aligning with our goal of understanding how offices integrate digital fabrication and why certain practices succeed or falter. This theoretical grounding reinforces the choice of case studies as an apt strategy for examining digital fabrication in architectural practice.

A set of 47 architecture offices from around the globe was compiled, drawing on three seminal publications that highlight cutting-edge digital design practices: Mark Burry's Prototyping for Architects (2016), Philipp Staab's 3D Printing and Digital Fabrication in Architecture (2023), and Walliss & Rahmann's Landscape Architecture and Digital Technologies (2016). These sources provided a curated selection of innovative offices known for integrating advanced computation, fabrication, and research in design. By leveraging such authoritative references, the study ensured a robust international sample encompassing a range of office profiles and digital philosophies - from experimental boutique offices to established global offices. The large international sample was chosen to capture exemplar "best practice" offices that are at the leading edge of digital integration. In contrast, Portuguese case studies are presented through interviews in Section 4.3 due to the relatively smaller number of local offices at comparable levels of digital adoption. This combination ensures a global benchmark is established while still focusing analysis on Portuguese architectural practice.

The decision to employ a case study research strategy is grounded in its strong epistemological benefits for architectural inquiry. Scholars emphasize that in-depth case studies yield rich, context-dependent insights that complement broader theories. Flyvbjerg (2006), for instance, dispels the notion that case knowledge is inferior to general theory; he argues that concrete case experiences produce "exemplars" essential for disciplinary advancement (Flyvbjerg, 2006). In architectural research, Groat and Wang (2013) likewise affirm the value of case-based methods, noting that single or multiple cases allow researchers to investigate complex design phenomena holistically and in real-life context, something especially pertinent for studying integrative practices. Yin (2018) defines a case study as an empirical inquiry that examines a contemporary phenomenon "in-depth and within its real-world context". Such an approach is particularly suited to architecture, where the interplay of digital tools, human factors, and built outcomes can only be fully understood in situ. Moreover, rather than seeking statistical generalisation, case study research pursues analytical generalisation: theories are tested and refined through comparing findings across cases. As Groat and Wang (2013) observe, the power of generalisation in case studies "comes from the concept of replication, rather than the concept of sampling". In other words, examining multiple architectural cases for recurring patterns can validate broader principles about digital fabrication's impact. Embracing this methodology allows the

thesis to bridge theory and practice – using detailed cases to illustrate how digital fabrication is implemented, and in turn using those observations to inform theoretical understanding of architectural innovation. This strategy aligns with Flyvbjerg's view that a discipline lacking well-documented cases is "a discipline without systematic production of exemplars" (Flyvbjerg, 2006), underscoring why case studies are so critical for advancing architectural knowledge.

The international scope of this case study is crucial for evaluating digital maturity and research engagement across diverse scales and geographies. Digital transformation in architecture is a global phenomenon, yet adoption levels vary widely by context. Including offices from North America, Europe, Asia, and beyond allows observation of how different regional design cultures and market pressures influence technology uptake. Likewise, examining offices of different sizes (from <10-person offices to 300+ employee giants) highlights scale-related dynamics: smaller offices can be agile innovators but may lack resources for extensive R&D, whereas large offices can invest in dedicated research units but may face bureaucratic inertia. This broad selection provides a comparative backdrop to validate SFDAP: it tests whether the two axes (Digital Maturity and Research Engagement) meaningfully differentiate practice across varied contexts. In sum, the international case studies offer a rich, heterogeneous dataset to examine best practices in digital adoption and to verify that the SFDAP framework is both globally and scalably applicable.

While the selected sample covers prominent architecture offices across major regions, it is equally important to recognise digital fabrication initiatives in underrepresented contexts, which introduce unique socio-cultural and climate-driven perspectives. For instance, in Mendoza, Argentina, a university fab lab collaborated with an indigenous community to create a CNC-cut wooden loom that helps local artisans weave traditional patterns, blending high-tech fabrication with vernacular craft knowledge (ArchDaily, 2021). In Asunción, Paraguay, the FabLab CIDI developed a digitally fabricated guiding device for bricklaying, enabling local masons to construct complex brick patterns with greater ease and precision (ArchDaily, 2021). Such projects illustrate how digital tools can augment vernacular techniques and address local construction needs, even outside the usual high-tech hubs. In India, a collaboration between a New Delhi architect and an overseas university introduced parametric software and laser-cut moulds for shaping locally sourced clay bricks, allowing craftsmen to build intricate forms (inspired by 17th-century chimney designs) with the aid of digital templates (ArchDaily, 2021). And in the deserts of Egypt, designer Markus Kayser's experimental "Solar Sinter" project harnessed abundant sunlight and sand to 3D-print glass objects, a vivid example of tailoring fabrication methods to extreme climatic conditions (ArchDaily, 2021). These global examples broaden the narrative beyond the well-resourced practices commonly documented. They demonstrate that the integration of digital fabrication is not a one-size-fits-all phenomenon; rather, local culture, material availability, climate, and social needs drive diverse innovations. Recognizing this diversity ensures that

our understanding of "digital fabrication in architecture" includes not only the advanced workflows of famous offices, but also grassroots and context-specific applications – from humanitarian design efforts in developing regions to hybrids of digital and traditional craftsmanship. This wider lens reinforces the idea that any global framework or typology (such as SFDAP) must be applied with sensitivity to regional conditions, and that lessons from non-traditional contexts can be instructive for the broader field.

These global examples illustrate that integrating digital fabrication is not merely a technical upgrade but a strategic shift in every-day practice workflow processes. Notably, the common thread is organisational adaptability – the offices that succeeded treated digital fabrication as a core part of their service (sometimes even establishing dedicated 'fab' units), reinforcing the notion that our framework must speak to practitioners' organisational choices as much as technology itself.

4.2.1. Digital Adoption Across Global Offices

Using the SFDAP typology defined above, the international case studies were analysed to identify patterns of tool adoption and research behaviour characteristic of each office type. Each typological category corresponds to a distinct profile of digital practice – from trailblazers of innovation to those just beginning their digital journey. The best practices observed in each category are discussed below with illustrative examples from the cases. In this context, "best practices" are defined as the effective strategies and processes observed among leading offices for integrating digital tools into design and fabrication. These include actions like systematic BIM adoption, dedicated R&D teams, cross-disciplinary collaboration, and continual skill development. By examining these traits in our case offices, we identify patterns of adoption associated with high digital maturity.

Type 1: Digital Pioneers (DM = 5, RE = 5)

Offices in this category operate at the cutting edge of architectural digitalisation. They exhibit the highest level of technology integration, routinely employing advanced tools such as generative design algorithms, full BIM workflows, computational simulations, AI-driven design, and robotics in fabrication. Crucially, these technical capabilities are paired with a deep culture of research engagement. Pioneer offices exemplify knowledge co-production in line with Lomas's "linkage and exchange" model: many maintain formal R&D teams or labs and actively collaborate with universities, industry partners, and professional forums to both use and generate new knowledge. For instance, Archi-Union in China (a Pioneer identified in our dataset) combines advanced robotic fabrication techniques with in-house materials research, achieving top scores on both axes. Similarly, global design leaders like Arup, Snøhetta, or Zaha Hadid Architects fit this profile: they invest heavily in computation and digital fabrication while publishing their innovations and engaging in academic partnerships. Such

offices serve as exemplars of "leading" digital maturity, demonstrating how a strategic commitment to cutting-edge tools and research can push the boundaries of architecture. Notably, many Pioneers are medium-to-large offices with the capacity to support R&D internally, though a few small offices also appear in this category through very focused expertise (for example, Studio RAP, a ~7-person office specialising in robotic fabrication, scores at the Pioneer level due to its niche excellence). Best practices among Pioneers include establishing formal research units, adopting emerging technologies early (sometimes co-developing those technologies), and openly sharing knowledge through publications or industry events. These practices reinforce their position as digital and knowledge leaders in the field, setting benchmarks that other offices often follow.

Type 2: Digital Innovators (DM = 4, RE = 4)

This group represents architecture offices with a strong digital footprint and substantial engagement with research, though not to the extreme extent of the Pioneers. Typically, Innovators have fully integrated BIM and parametric design into their workflows (indicating an "advanced" maturity) and often experiment with tools like computational analysis, VR/AR, and digital fabrication on select projects. They make active use of research - applying up-to-date best practices from building science or collaborating on occasional research initiatives - but such activities tend to be focused and project-specific rather than a pervasive R&D culture. This aligns with Nutley et al.'s (2007) concept of instrumental evidence use (directly applying research findings) with some elements of process use (engaging in research intermittently). 3XN (Denmark) is a clear example: the office's integration of advanced design software and sustainability analytics earns it a DM=4, and its in-house innovation unit GXN facilitates research collaborations, yet its focus remains on implementing known innovations in practice. Likewise, BVN (Australia) or EMBT (Spain) leverage computational design and participate in applied research for select projects, without having dedicated labs like the Pioneers. Innovators often include mid-sized practices that have moved beyond ad-hoc experimentation to a more structured digital strategy, even if they lack the vast resources of the largest offices. Best practices observed in this group include systematic BIM implementation, formation of dedicated innovation committees or small R&D teams to guide new tool adoption, and participation in research consortia or design competitions as a way to spur creative uses of technology. In sum, Digital Innovators demonstrate that even without being at the absolute forefront, a strategic adoption of mature digital tools - coupled with ongoing learning and selective research engagement - can significantly enhance an office's design capabilities and output quality.

Type 3: Digitally Emerging (DM = 2–3, RE = 2–3)

This category comprises architecture offices that are in the early-to-intermediate stages of digital transformation. Their digital maturity is modest: such offices might use BIM primarily for documentation or employ 3D modelling and basic parametric tools in parts of their work, but advanced technologies (like custom algorithms, machine learning, or robotics) are not yet routine practice. Correspondingly, their research engagement is limited. These offices stay aware of industry developments ("research-aware" in evidence-use terms) and may adopt proven techniques from literature or attend professional trainings, but they rarely initiate formal research or original experimentation. In Nutley et al.'s framework, they mostly exhibit conceptual use of research – a general awareness influencing their thinking – with only basic instrumental use of specific findings. For example, London-based AL_A and New Zealand's Architecture Workshop were classified around DM=3/RE=3 in our data: they utilize BIM and occasionally prototype innovative ideas (as seen in AL_A's experimental installation projects), yet these efforts are intermittent and rely on well-established methods. Similarly, Asif Khan Studio (UK) was rated DM=2/RE=2 – it produces highly creative designs and occasional one-off experimental pieces, but its digital toolkit and research input remain relatively rudimentary compared to the leaders. Many Digitally Emerging offices are small offices or young practices focused on building a portfolio; their priorities centre on delivering projects with available tools, and research is usually an informal, ad-hoc pursuit. Best practices among this group tend to be pragmatic: for instance, investing in foundational BIM skills, using parametric plugins or outsourced fabrication services as needed, and leveraging external expertise (consultants or published guides) to improve outcomes. While they are not yet Innovators, these offices do show a readiness to learn – several follow published case studies of digital techniques or engage in occasional knowledge exchanges – positioning themselves to climb the maturity ladder as opportunities arise. The spectrum from Emerging to Pioneer underscores how increasing both technological capability and research involvement leads to progressively more innovative practice, consistent with theory that interactive engagement with knowledge yields greater innovation (Lomas, 2000; Nutley et al., 2007).

Overall, the international cases demonstrate distinct patterns of digital adoption that correspond to the SFDAP typology. The Pioneers illustrate "best-in-class" approaches – full integration of state-of-the-art tools combined with a research-driven ethos – setting benchmarks for the profession. The Innovators show the efficacy of broad digital integration paired with selective research activities, often acting as early followers of the Pioneers' breakthroughs. The Emerging offices reveal common first steps and challenges in digital uptake, highlighting the importance of incremental adoption and external knowledge sources for practices with fewer resources. Notably, these patterns support the idea that higher research engagement goes hand-in-hand with more transformative use of technology: offices that co-produce knowledge or maintain academic links can more readily innovate, whereas those with low engagement tend to restrict themselves to off-the-shelf solutions and established

practices. This aligns with knowledge-utilisation theory – interactive models of evidence use (as described by Lomas, 2000 and Nutley et al., 2007) foster mutual learning and innovation, whereas one-directional, passive use of knowledge often results in only incremental improvements. In practice, the international exemplars show that the most transformative impacts of digital tools on architectural practice are achieved when technological adoption is coupled with an active research culture.

Amid these findings, it is important to reflect on how "success" is framed in the chosen sample and by the practitioners themselves – what values are being prioritized, and which are overlooked, in judging the outcomes of digital fabrication integration. Notably, many of the above exemplars celebrate technological prowess and innovation as primary measures of success. For instance, achieving a high degree of automation or generative design complexity is treated as an inherent positive, and offices attaining full BIM implementation or employing robotics tout these milestones as evidence of leadership. Aesthetic achievements often accompany this narrative: digital fabrication is praised for enabling novel forms and intricate geometries that would be impractical by traditional means. Thus, success is frequently equated with pushing formal boundaries and technical limits – an orientation that reflects architecture's longstanding valorisation of visual and technological innovation. Economic and efficiency values also appear, but usually in a supporting role: large offices might highlight improved productivity or cost savings from parametric optimisation, yet economic metrics are less prominently discussed than design innovation. More conspicuously absent in these case discussions are social and human-centric values. Emerging critiques note that the social dimension of digital fabrication tends to be underrepresented in architectural discourse (Menichinelli, 2019). Few of the profiled offices, for example, frame their success in terms of community impact, user empowerment, or social equity outcomes; instead, the emphasis skews toward the architectural object and the design process itself. Similarly, qualitative aspects like craftsmanship, tactility, or experiential quality can be sidelined. A content analysis by Kayser (2022) found that "sense, experience, perception, intuition" – essentially the poetic and humanistic qualities of digitally fabricated architecture – are seldom foregrounded in publications, even though they are significant to end-users. This suggests that important criteria may be overlooked when success is defined narrowly by technical and formal innovation. By prioritizing what can be easily measured or showcased (e.g. parametric complexity, fabrication feats, performance data), architects might neglect harder-to-quantify values such as occupant well-being, cultural relevance, or the integration of social sustainability. The "best practices" in this chapter reveal this bias: architecture offices that excel in digital integration often tout their technological and aesthetic accomplishments, whereas discussions of how these innovations benefit broader society or address social needs are relatively sparse. This critical reflection does not diminish the genuine achievements of the sample study offices, but it

underlines the need for a more holistic definition of success – one that balances technological and artistic excellence with social, ethical, and user-oriented considerations.

Narratives of innovation in architectural practice invite deeper ethical and political reflection on how digital integration redistributes value, power, and responsibility. Within both industry and academia, innovation is frequently framed as inherently beneficial, a tendency sociologists have identified as a "pro-innovation bias" (Manseau & Seaden, 2001). This assumption can obscure the uneven consequences of technological change, particularly the ways in which benefits and burdens are distributed across different actors. Evidence from architecture and other sectors suggests that innovations that empower certain groups, such as large architectural offices or technologically advanced contractors, may simultaneously disadvantage others, including traditional craftsmen, smaller practices, or less-resourced stakeholders. In the context of digital fabrication, case studies demonstrate clear advantages in terms of design capability, efficiency, and formal experimentation; however, these gains are not uniformly experienced. Large, well-resourced offices may consolidate their market position through the adoption of robotics and bespoke fabrication, while clients may face increased costs or complexity, and contractors and fabricators may be required to retrain or risk the erosion of manual skill-based roles. Similarly, digitally bespoke architectural outcomes may enhance experiential quality for specific users while offering limited contribution to broader issues such as affordability or social equity. As Manseau and Seaden (2001) note, innovation is "not always desirable for all parties involved," and architectural production is no exception. Highly celebrated digitally fabricated projects may therefore coexist with less visible social and economic disparities, particularly when access to such innovation is restricted to elite clients or institutions. Moreover, the cultural and political dimensions of technological adoption are significant: introducing advanced digital fabrication methods without alignment with local labour practices, regulatory frameworks, or construction cultures can disrupt existing ecosystems rather than strengthen them. Collectively, these observations highlight that digital fabrication does not operate as a neutral or universally progressive force. Instead, it reshapes architectural practice within a broader political economy of design, where innovation often concentrates among actors with greater capital, expertise, and institutional support. A critical engagement with digital fabrication therefore requires attention to its ethical and social implications, recognizing that architectural innovation must be evaluated not only in terms of technical achievement, but also in relation to inclusivity, labour, and the public good.

Finally, the integration of digital design and fabrication in these architectural practices is materially reshaping the identity of the architect and challenging traditional professional norms. A recurring theme across the case studies is that architects are expanding their roles beyond conventional design services. Rather than operating solely as designers who hand off drawings for others to execute, architects in digitally advanced offices often become technologists, fabricators, and researchers. This

expansion of expertise is evident in Pioneer offices that establish in-house research labs and employ architects to develop custom software or robotic processes. It echoes Burry's observation that architects increasingly act as "toolmakers," crafting their own digital tools and scripts to realise design intent. Moreover, as Sheil (2005) noted, the act of "designing through making" blurs the line between design and construction, such that the information defining a building and the means of production become one and the same. Many of our case study offices exemplify this blurring: project teams include architects writing code for fabrication, and fabrication specialists informing design decisions from the earliest stages. The once-clear boundaries between architect, engineer, and contractor are thus increasingly fluid. On one hand, this convergence can be empowering – architects gain greater control over the building process and can pursue more ambitious, integrated visions. Offices that have embraced digital fabrication report a more collaborative, "workshop-like" culture replacing the old siloed model of practice. As Gramazio and Kohler (2008) suggest with the term "digital materiality," the architect's remit now spans from bits to atoms, merging design with making. The profession is witnessing a redefinition of authorship: design outcomes emerge from interactive loops of simulation and production, often involving teams with hybrid skill sets. In this sense, the digital turn can disrupt professional norms by valuing new competencies (coding, robotics, data analysis) alongside classical architectural skills. Young practitioners at these offices may find themselves as comfortable in a fabrication lab or writing Python scripts as they are sketching or drafting - a stark contrast to past generations. On the other hand, we should ask whether this shift is truly democratizing the field or subtly reinforcing existing hierarchies. It may be that only well-resourced offices can fully adopt these expanded roles, potentially widening the gap between "digital" practices and more traditional ones. There is also the question of specialisation: as architecture intersects more with software engineering and fabrication, will the profession splinter into sub roles (the computational designer, the robotic fabrication expert, etc.), or will the ideal of the architect as a polymath creator persist? The cases in this chapter largely portray the expansion of the architect's role – an integrated digital practice means the architect touches all aspects from concept to fabrication – and thus they indicate a disruption of the old norm where architects were detached from construction processes. Importantly, this evolution is prompting architectural offices to rethink their organisational models and education to adapt to the new skill sets required. In summary, the digital fabrication pioneers are expanding the discipline's boundaries: they show that architects can be inventors, material researchers, and builders in the digital age, which both enriches the profession and challenges it to uphold its core creative and ethical principles amid these new capabilities. Each case study, therefore, not only demonstrates a technical achievement but also serves as a glimpse into a possible future for the architectural profession – one in which the architect's identity is more fluid, collaborative, and empowered by technology, yet continually negotiating the tension between innovation and tradition in practice.

4.2.2. Data Collection and Analysis Approach

The international office data were gathered through a literature-driven survey of the above-mentioned sources. Each of the three books (Burry 2016; Staab 2023; Walliss & Rahmann 2016) contains detailed case studies and examples of offices using digital fabrication in architecture, identified for analysis. These offices were selected based on clear evidence of advanced digital fabrication – for instance, many are explicitly profiled in the literature for pioneering computational design, novel fabrication techniques, or integrating research into practice. From the source material, qualitative information about each office's technology use (tools, workflows, notable projects) and research involvement (mentions of R&D initiatives, academic collaborations, publications, etc.) was extracted. Additional context such as office size and location was noted from these publications or from the offices' websites to enrich the dataset. This approach of mining published sample ensured that data on each office's digital capabilities and ethos came from credible, documented accounts rather than hearsay. The 47 selected offices thus serve as an empirical sample to validate the SFDAP framework: by positioning each office on the Digital Maturity vs. Research Engagement matrix, we could examine real-world distributions and assess how well the framework captures variation in practice.

Table 4.1: Overview of international architectural practices and their positioning across digital maturity and research engagement.

Office Name	Size of Office		DM (X-Axis)		RE (Y-Axis)		webpage
3XN	150	Medium	4	Advanced use of BIM and digital tools	4	Research-Active, involved in sustainability research	https://3xn.com/
AL_A	50	Medium	3	Moderate use of BIM	3	Research-Informed, exploring material innovation	https://www.ala.uk.com/
Aranda\Lasch	6	Small	4	Advanced, uses digital tools and fabrication	3	Research-Informed	https://arandalasch.com/
Archi-Union	60	Medium	5	Leading, integrates robotics and AI in design	5	Research-Led, innovative research in digital fabrication	https://www.archi-union.com/
Architecture Workshop	10	Small	2	Basic use of digital tools	2	Research-Aware	https://www.architectureworkshop.co.nz/
Arup	300	Large	5	Leading in digital engineering	5	Research-Led, global research initiatives	https://www.arup.com/
Asif Khan	40	Small	3	Intermediate use of digital tools	3	Research-Informed	https://www.asif-khan.com/
ASPECT Studios	76	Medium	3	Intermediate, uses BIM and visualisation tools	3	Research-Informed, sustainability-driven	https://www.aspect-studios.com/
BKK Architects	23	Small	3	Intermediate use of BIM	2	Research-Aware	https://b-k-k.com.au/
BVN	400	Large	4	Advanced, uses parametric design tools	4	Research-Active	https://www.bvn.com.au/
ecoLogicStudio	6	Small	5	Leading, integrates AI, bio-digital research	5	Research-Led, focus on ecological innovation	https://www.ecologicstudio.com/
EMBT	27	Small	4	Advanced, uses digital tools and fabrication	4	Research-Active	https://www.mirallestagliabue.com/
Facit Homes	13	Small	5	Leading, uses digital fabrication	4	Research-Active	https://www.facit-homes.com/

Foster + Partners	1,800	Large	5	Leading, pioneer in BIM and parametric tools	5	Research-Led, with in-house R&D	https://www.fosterandpartners.com/
Franken\Architekten	20	Small	3	Intermediate	3	Research-Informed	https://franken-group.com/
GAP Architects	50	Medium	2	Basic	3	Research-Informed	https://www.gap-the-mind.com/
Grant Associates	50	Medium	3	Intermediate use of digital tools	3	Research-Informed, sustainability-focused	https://grant-associates.uk.com/
Greg Lynn	4	Small	5	Leading, computational and robotics research	5	Research-Led	https://glform.com/
Gustafson Porter	21	Small	3	Intermediate	3	Research-Informed	https://www.gp-b.com/
Hannah Office	2	Small	5	Leading, computational and robotics research	5	Research-Led	https://www.hannah-office.org/
HASSELL	88	Medium	4	Advanced, uses BIM and computational design	4	Research-Active	https://www.hassellstudio.com/
Hopkins Architects	140	Medium	4	Advanced	4	Research-Active	https://www.hopkins.co.uk/
HYBRIDa	20	Small	5	Leading	5	Research-Led	https://www.hybridarch.net/
Joris Laarman Lab	6	Small	5	Leading, digital fabrication and robotics	4	Research-Active	https://www.jorislaarman.com/
Kreysler & Associates	50	Medium	5	Leading, specializes in digital fabrication	3	Research-Informed	https://www.kreysler.com/
KTA Architects	30	Small	3	Intermediate use of digital tools	2	Research-Aware	https://kerstinthompson.com/
LAAC	15	Small	3	Intermediate	5	Research-Led	http://www.laac.eu/
LDA Design	245	Medium	4	Advanced, uses digital tools for large-scale projects	3	Research-Informed	https://www.lda-design.co.uk/
MAD Architects	200	Medium	5	Leading, advanced in digital tools and fabrication	4	Research-Active	http://www.i-mad.com/
Marble Fairbanks	10	Small	3	Intermediate	3	Research-Informed	https://www.marblefairbanks.com/
Marc Fornes & TheVeryMany	4	Small	5	Leading, computational design and fabrication	5	Research-Led	https://theverymany.com/
Mario Cucinella Architects (MCA)	111	Medium	4	Advanced	4	Research-Active, sustainability-focused	https://www.mcarchitects.it/
Massimiliano Locatelli | Locateli Partners	70	Medium	3	Intermediate	3	Research-Informed	https://www.locatellipartners.com/
MOS Architects	5	Small	3	Intermediate	3	Research-Informed	https://www.mosarchitects.com.au/
Nex-	50	Medium	4	Advanced	4	Research-Active	https://www.nex-architecture.com/
OCEAN Design Research Association	2	Small	5	Leading, focus on computational design	5	Research-Led	https://www.ocean-a-e.com/
ONL [Oosterhuis_Lénárd]	20	Small	5	Leading, integrates advanced computational methods	5	Research-Led	https://www.oosterhuis.nl/
PARKKIM	7	Small	3	Intermediate	3	Research-Informed	http://parkkim.net/home/
PEG office of landscape + architecture	5	Small	3	Intermediate	5	Research-Led	https://peg-ola.com/
Pragma	9	Small	3	Intermediate	2	Research-Aware	https://pragma.ae/
SHoP	108	Medium	4	Advanced	3	Research-Informed	https://www.shoparc.com/
Snøhetta	351	Large	5	Leading	5	Research-Led	https://www.snohetta.com/
Studio Gang	150	Medium	4	Advanced	4	Research-Active	https://studiogang.com/
Studio RAP	7	Small	5	Leading, focus on digital fabrication	5	Research-Led	https://studiorap.nl/
Thomas Heatherwick	300	Large	4	Advanced	4	Research-Active	https://heatherwick.com/
Zaha Hadid Architects	400	Large	5	Leading, pioneers in computational design	5	Research-Led	https://www.zaha-hadid.com/
Zecc Architecten	21	Small	3	Intermediate	3	Research-Informed	https://www.zecc.nl/nl/

Each office was coded along the two axes corresponding to the SFDAP dimensions: Digital Maturity (DM) and Research Engagement (RE). We operationalised these axes as numeric scores on a 5-point scale, using criteria developed from prior research and industry models. For Digital Maturity, the coding drew on existing digital transformation maturity models in AEC (Architecture, Engineering, Construction) that use staged levels from "Ad-hoc" to "Leading." In our rubric, a score of 1 indicates little to no digital integration (e.g. an office working primarily with traditional CAD and minimal computational tools), a score of 3 represents a moderate, intermediate engagement (e.g. some BIM use and occasional parametric design or digital fabrication on projects), and a score of 5 denotes a fully digitally integrated practice at the forefront of technology use. To assign scores, we looked for evidence of the tools and processes each office employs: extensive use of BIM, advanced parametric modelling software, use of automation or scripting, integration of AI or machine-learning tools, and routine use of digital fabrication or robotics would warrant a higher DM rating. For example, an office described as using custom algorithms on every project or operating a robotics lab would likely score 5, whereas one only recently adopting BIM might score around 2 or 3. This evaluation was informed by literature such as Perera et al. (2022), who outline key indicators of design digitalisation (BIM, data-driven design, etc.) and note that many offices still exhibit ad-hoc digital efforts in need of structured advancement. We also benchmarked against industry assessments (e.g. McKinsey reports on AEC digitisation and tools adoption) to calibrate what constitutes "basic" vs. "advanced" digital practice.

For Research Engagement, we defined the 5-point scale in line with knowledge-utilisation theory (Nutley et al., 2007; Lomas, 2000). A score of 1 indicates virtually no engagement with research (the office does not appear to use external research or generate new knowledge), while a 3 means the office is research-informed – it stays up-to-date with published best practices and might implement proven research findings (for example, using evidence-based design guidelines or sustainability data in projects). A top score of 5 signifies a research-led practice, where the office actively participates in creating new knowledge – evidenced by in-house R&D programs, frequent experimentation and prototyping initiatives, collaboration with universities or think-tanks, and publication of findings. Intermediate values (RE = 2 or 4) were applied for cases falling between these descriptors (e.g. RE = 4 for an office that occasionally co-develops research but not as a sustained culture). In making these judgments, we coded the presence of specific research activities mentioned in the sources: for instance, teaming up with a university on a funded research project, or a track record of design patents and journal articles by the office's team would indicate higher engagement. We also referenced models like Suter et al. (2009) from healthcare, which classify levels of research integration, to refine what deep engagement looks like (co-producing research vs. simply reading and applying it). Each office's profile from the literature was thus systematically reviewed and assigned a DM and RE score (1–5 scale for each) based on these criteria. The coding process was iterative and cross-checked: for

example, if an office was initially scored DM=4 but further evidence showed use of robotics on multiple projects, it was reconsidered for DM=5. Likewise, any ambiguity in research involvement was resolved by looking for formalized knowledge activities (if none were found, a lower RE score was assigned).

In addition to the two primary axes, office size was recorded as a contextual attribute. Each office was noted as Small (<50 staff), Medium (50–300 staff), or Large (>300 staff), following the categories described in Section 5.1.1. This was important because size often correlates with capacity for innovation investment. During analysis, we observed that several large offices in the sample (e.g. Foster + Partners, Arup) achieved DM=5 and RE=5, supported by their substantial resources and dedicated R&D departments. In contrast, many small offices lacked such infrastructure and tended to score lower on one or both axes, unless they had a very specialised focus. (An interesting exception was that a few small offices scored highly by focusing intensely on a niche technology – for instance, a 7-person practice specialising in computational fabrication could reach DM=5 by virtue of its niche expertise.) We used size as a descriptive factor rather than a direct input into scoring, but it helped interpret results – confirming literature suggestions that large organisations often lead in formal digital strategies while small ones innovate more sporadically.

Once each office had been coded, we plotted all 47 architectural offices on the two-dimensional SFDAP matrix (Digital Maturity on one axis vs. Research Engagement on the other). This mapping (see Figure 4.1) provided a visual validation of the framework: clear clusters emerged corresponding to the Pioneer, Innovator, and Emerging typologies identified earlier. For example, a concentration of offices in the upper-right corner of the grid (high DM, high RE) confirmed the presence of Pioneer-type offices internationally, while offices with mid-level scores populated the Innovator band, and lower scores clustered in the Emerging quadrant. We also conducted a comparative thematic analysis alongside the scoring. As we reviewed the literature on each office, we coded qualitative themes such as the types of digital tools emphasized (e.g. prevalence of BIM adoption, use of parametric design software, experiments with AI or robotics) and the forms of research engagement (e.g. presence of internal knowledge teams, external academic collaborations, evidence-based design approaches). This thematic coding was a structured note-taking process that allowed us to see recurring patterns across offices. It enriched the quantitative matrix by explaining how and why an office occupied a certain position. For instance, two offices might both score DM=4, RE=4, but our thematic notes would reveal if one achieved this via heavy use of simulation and optimisation tools plus occasional university research ties, whereas the other did so via a strong computational design culture and publishing technical papers. By cross-tabulating these themes with the DM/RE scores (essentially creating a matrix of cases by features), we identified best practices and common challenges for each category. This mixed-method approach – combining quantitative scoring with qualitative coding – improved the

rigor of analysis and ensured that our interpretation of the SFDAP typologies was grounded in concrete evidence from the cases.

The outcome of this analysis is a clearer picture of how architectural offices worldwide are navigating digital transformation. From the data, we discern prototypical behaviours at each maturity and engagement level, which directly inform the strategic framework. The clustering of offices validated that the two axes capture meaningful differences: for example, offices in the Pioneer cluster uniformly exhibited a culture of innovation and advanced toolsets, whereas Emerging offices showed patchy tool use and minimal research activity. These findings give confidence that the SFDAP matrix is an effective lens for assessing practice. It encapsulates a broad spectrum of real-world offices, with the 470international cases serving as evidence-backed validation of the framework's applicability and robustness. In the next section, we shift focus from the global scene to a specific national context to further test and apply the framework.

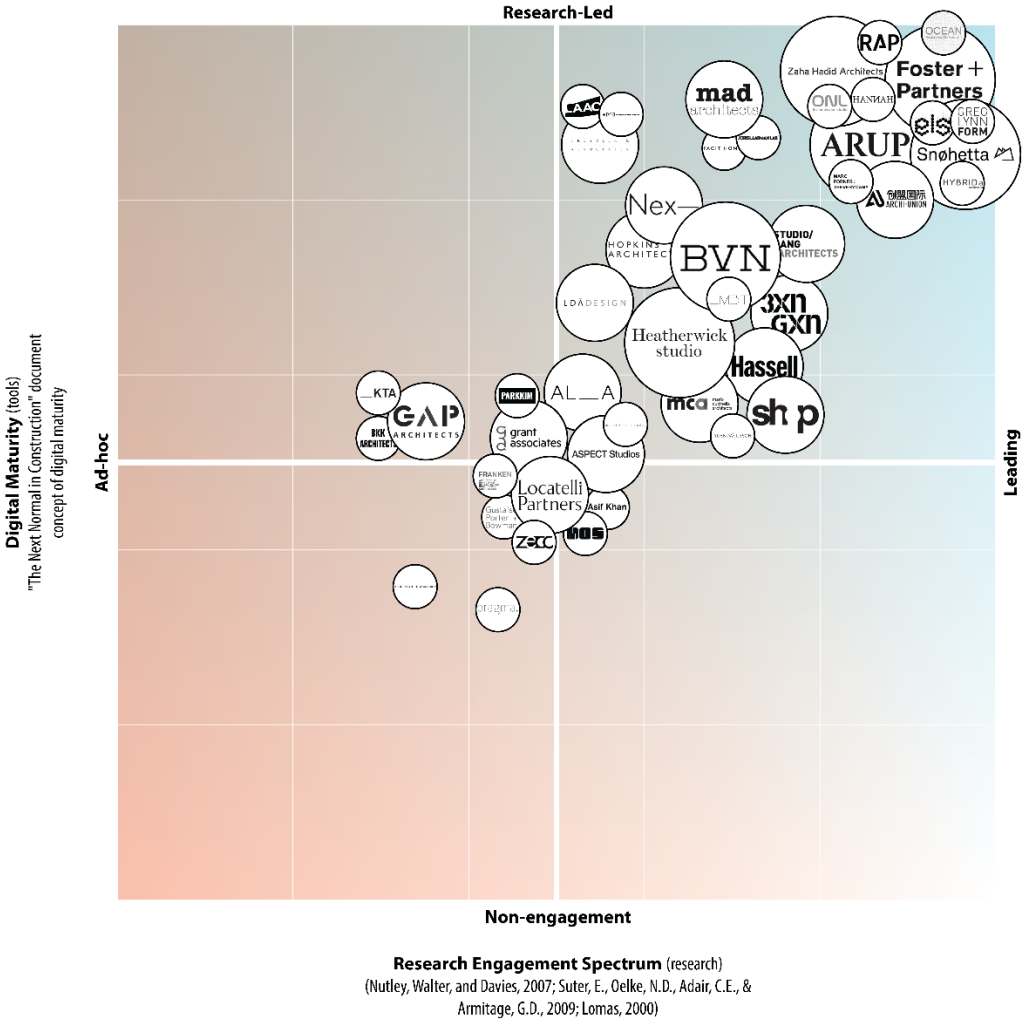


Figure 4.2: Mapping 47 International Architecture Offices within the SFDAP Framework.

This figure visualizes the distribution of 47 international architectural offices across the SFDAP. Each office is positioned based on its Digital Maturity (vertical axis) and Research Engagement (horizontal axis), using a five-point scale per dimension. The size of each circle reflects the relative size of the office. The map highlights three dominant typologies - Digital Pioneers, Innovators, and Digitally Emerging - demonstrating varying levels of digital tool integration and research activity in the global architecture landscape (Nutley et al., 2007; Lomas, 2000; Suter et al., 2009; McKinsey, 2020).

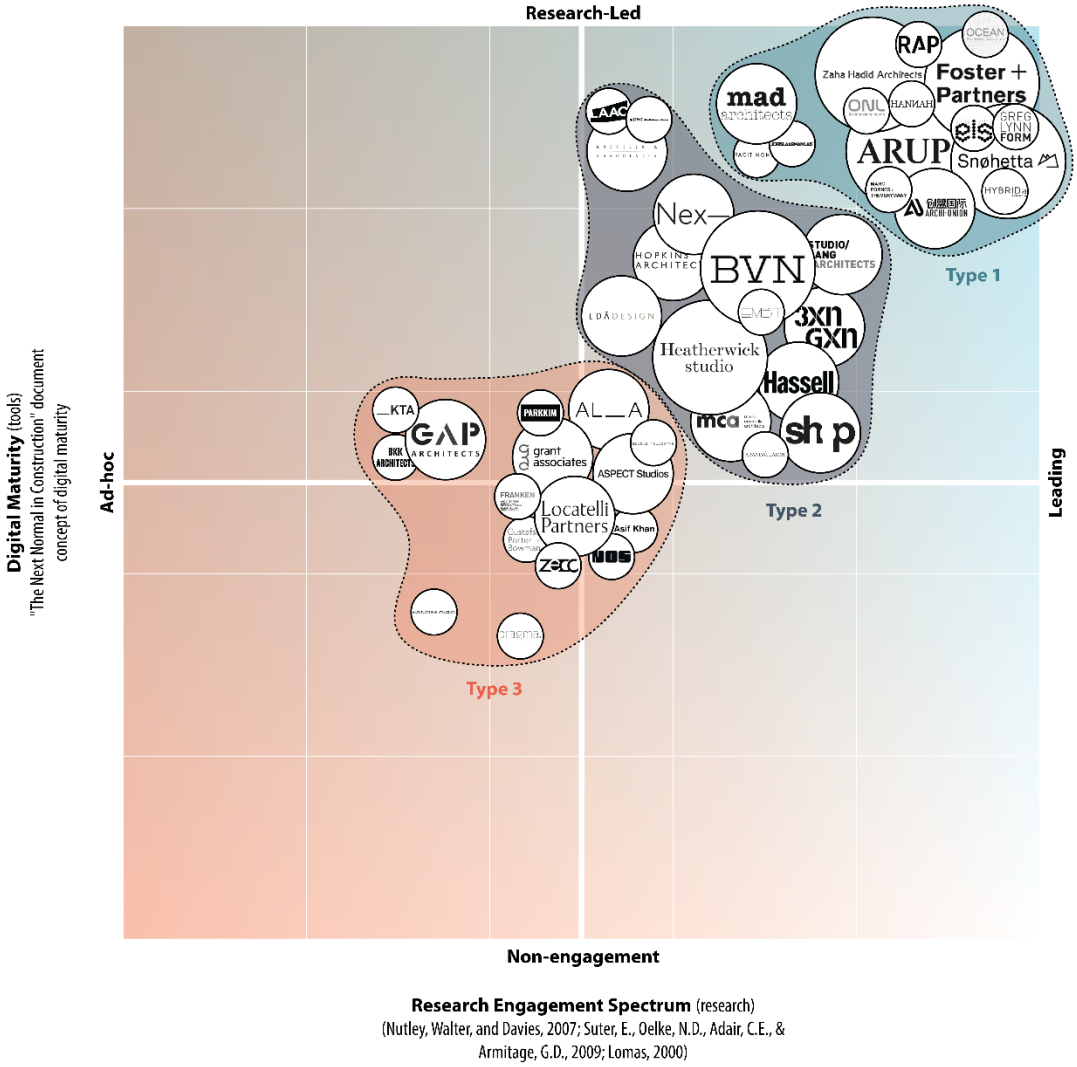


Figure 4.3: Classification of 47 International Architecture Offices into SFDAP Typologies.

This diagram overlays typological zones - Type 1: Digital Pioneers, Type 2: Digital Innovators, and Type 3: Digitally Emerging - onto the SFDAP matrix, positioning 47 elements of the Sample according to their Digital Maturity and Research Engagement. The visual demarcation highlights how offices cluster into distinct strategic categories based on their integration of digital tools and their involvement in research. The categorisation builds on theoretical foundations from Nutley et al.

(2007), Lomas (2000), and Suter et al. (2009), and visually reinforces the framework's capacity to differentiate practice types within the global architecture sector.

4.3. Portuguese Context: Analysis of Architectural Offices Practices

Having established the framework and validated it through international sample, this chapter now turns to the portuguese context, examining how architectural practices are navigating digitalisation under specific structural conditions. While Section 4.2 reviewed international exemplars of digital adoption, the analysis here foregrounds local constraints and enabling factors. Portugal's architectural sector is largely composed of small and medium-sized practices, operating within a construction market characterised by limited margins, fragmented supply chains, and historically modest investment in digital innovation. As a result, the pace and depth of digital uptake have lagged behind those observed in earlier-adopting contexts.

To examine this setting, 17 Portuguese architectural offices with demonstrated engagement in advanced digital tools and workflows were invited to participate in a focused best practice. Ten practices accepted, forming a purposive sample of offices positioned at the forefront of digital experimentation within the national context. Rather than aiming for statistical representativeness, this targeted selection enables a critical examination of how digitally proactive offices negotiate constraints, mobilize resources, and adapt global digital practices to local conditions. In doing so, the analysis situates Portuguese adoption pathways within the wider international discourse on architectural digitalisation, highlighting both convergence and divergence across contexts.

By examining these frontrunners, we gain insight into how global innovations in architectural practice are being interpreted and implemented in a specific national setting (Perera et al., 2022). In line with broader studies of technology uptake (RIBA, 2018), our approach recognises that context matters: analysing local cases can reveal unique barriers and catalysts that shape digital transformation on the ground, enriching the global narrative with grounded, place-specific understanding (Nutley et al., 2007; Lomas, 2000). In the Portuguese context, the architects interviewed consistently acknowledged that the absence of strong top-down mandates or large-scale governmental incentives for innovation places the responsibility for digitalisation largely on individual offices and their internal initiatives. This context potentially makes progress slower and more uneven than in countries with robust institutional support. The Portuguese patterns identified, therefore, highlight how external factors (market size, client demand, policy environment) influence the trajectory of digital adoption, while also confirming that many fundamental dynamics of digital transformation are universal.

4.3.1. Insights from Structured Interviews with Portuguese Architectural Offices

To explore the Portuguese context in depth, we conducted structured interviews with 9 architectural offices (drawn from the 17 invited). These offices - ranging from boutique design offices to one of Portugal's larger offices – were chosen due to their known engagement with digital tools in design and fabrication. This qualitative approach responds to observations like those of Canizares & Cohen that the history of digital fabrication is built on 'personal micro-histories and intimate experiences with machines', best understood through individual origin stories of practice. By capturing first-hand accounts from Portuguese architects, we ground the framework in the real-world decisions and experiences that shape digital fabrication's adoption in offices. The participating practices were:

Table 4.2: Overview of interviewed Portuguese architectural practices and their positioning across digital maturity and research engagement.

Office Name	Size of Office		DM (X-Axis)		RE (Y-Axis)		webpage
Research Studio for Architectural Visualisation: 18—25	17	Small	4	Advanced	5	Research-Led	https://www.1825.pt/
atelier peninsular	7	Small	3	Intermediate	2	Research-Aware	https://atelierpeninsular.com/
CVDB Arquitectos	12	Small	3	Intermediate	3	Research-Informed	https://www.cvdbarquitectos.com/
fahr 021.3	4	Small	4	Advanced	4	Research-Active	https://www.fahr0213.com/
Konceptness	20	Small	3	Intermediate	2	Research-Aware	https://konceptness.pt/
Rebelo de Andrade	30	Small	4	Advanced	4	Research-Active	https://www.rebelodeandrade.com/
Saraiva + Associados	150	Medium	4	Advanced	4	Research-Active	https://www.saraivaeassociados.com/pt-pt/
Summary	10	Small	4	Advanced	5	Research-Led	https://summary.pt/
TEKSTUDIO	8	Small	3	Intermediate	2	Research-Aware	https://www.tekstudio.pt/

Each interview followed a structured guide designed to elicit comprehensive insights into the office's digital journey. The discussion first addressed the motivations and conditions surrounding the initiation of digitalisation, examining when and why digital tools were adopted and which catalysts or inspirations influenced this process. It then focused on the barriers and challenges encountered in implementing digital workflows, including technical limitations, organisational constraints, and cultural obstacles within practice. The interviews further explored the evolution of digital adoption over time, analysing current workflows and the ways in which digital tools have reshaped collaboration and professional practice. Finally, participants were invited to reflect on future perspectives, considering anticipated digital trends and outlining how they plan to further integrate digital technologies moving forward.

The following section summarizes the key insights from these interviews, structured around these thematic areas.

Motivations for digital adoption

Across the interviews, a clear theme was the pursuit of greater efficiency and innovation as key motivators for early digital uptake. Many office leaders described a curiosity-driven initiation, often stemming from academic exposure or personal interest in emerging technologies. For example, one founder noted that he began experimenting with CAD and 3D visualisation during university, driven by "an enormous desire to discover new things" (Annex A) and to improve the precision of design communication. Initial catalysts frequently combined practical need with visionary influence: offices saw digital tools as a means to streamline workflows, enhance presentation quality, and gain a competitive edge. Several interviewees mentioned client expectations and international trends as contributing factors – seeing larger global offices using BIM or parametric design inspired them to follow suit in order to "keep up with digital evolution" (Annex G) and not be left behind. Overall, the perceived benefits that motivated adoption included time savings, improved accuracy, better collaboration, and the ability to communicate design ideas more effectively to clients. These findings resonate with global observations that early adopters are often spurred by a mix of visionary leadership and clear performance benefits (RIBA, 2018; Perera et al., 2022). The Portuguese architects in our sample were no exception: they viewed digitalisation as an opportunity to professionalise their practice, deliver higher-quality outcomes, and solve persistent problems (like design visualisation and coordination) that traditional methods struggled to address. This underscores the transformative impact that digital tools can have on architectural workflows and outcomes, serving as both a catalyst for innovation and a means to meet evolving industry standards.

Barriers and challenges

Despite strong motivation, the interviews revealed numerous obstacles that have tempered or delayed digital integration, many of which mirror challenges reported internationally (RIBA, 2018; Tan et al., 2023). A primary barrier is the cost and resource constraints of adopting new technology. High upfront costs were cited by every interviewee as a concern, especially for small offices (Silva & Paio, 2024). Investments in BIM software licenses, high-performance computers, or fabrication hardware (e.g. 3D printers, CNC machines) are often prohibitive. Closely related is the training and skills gap: small offices often lack dedicated IT or training departments, and sending staff for continuous professional development is costly and time-consuming. Several architects noted a steep learning curve for advanced BIM or coding; under-trained staff sometimes struggle to fully exploit the tools. This aligns with wider industry findings that skills and training deficits are pivotal barriers in digital transformation (RIBA, 2018).

Another significant challenge is cultural and institutional resistance. Adopting digital workflows represents a shift in mindset from traditional ways of working, and both internal and external

resistance were commonly observed. Interviewees mentioned that some senior architects and even clients remain sceptical of purely digital processes. Such sentiments point to a conservative streak in parts of the industry that slows down change – a phenomenon noted in other contexts as well, where embracing innovation requires overcoming entrenched habits and fear of the unknown (RIBA, 2018). Furthermore, external institutions in Portugal have not strongly pushed for digitalisation. Several practitioners highlighted that regulatory frameworks and client expectations remain traditional, providing little incentive for change. Unlike countries where government mandates (e.g. requiring BIM for public projects) have accelerated industry-wide adoption, in Portugal the lack of such drivers means uptake is often voluntary and internally driven. As a result, risk-averse clients can effectively veto innovation. These cultural and institutional factors underscore that technology alone cannot transform practice without a supportive ecosystem (RIBA, 2018). Indeed, our local findings echo the "shift in culture" identified by RIBA's survey, which noted that many offices have the tools available but lack the willingness or leadership to champion new methods (RIBA, 2018). In Portugal, this inertia is compounded by the prevalence of smaller offices and conservative clients, as also reported by Silva and Paio (2024), who identify resistance to change and limited demand as persistent issues. In summary, Portuguese practitioners face the same core barriers found globally – cost, training, cultural resistance – but these are often magnified by local conditions (Silva & Paio, 2024): fewer large projects to justify big investments, scarce public incentives, and a tradition-bound market that views digital experimentation as optional rather than essential.

Evolution and current practice

Despite the hurdles, all ten offices reported a gradual but notable evolution in their digital practices over the past decade. Many described an initial phase of tentative adoption – for example, starting with 2D CAD in the 1990s or early 2000s, then moving to 3D modelling and visualisation, and eventually to BIM or algorithmic design tools as those technologies matured. One large office, Saraiva + Associados, noted that from its founding in the mid-1990s it opted to use the digital tools available at the time, indicating an early commitment to CAD when hand-drafting was still common. Smaller offices often adopted digital methods on a project-by-project basis: a specific commission might necessitate learning BIM or collaborating with a fabricator, after which those skills were incorporated into the office's repertoire. By 2024 (the time of our study), most participating offices had integrated BIM (at least for complex projects) and were regularly using 3D modelling and rendering in their design process. Several have gone further: for instance, 18–25 Research Studio and SUMMARY each developed custom workflows (for virtual reality and for modular prefabricated design, respectively), demonstrating an advanced level of digital integration even as small practices.

This evolution in tools has been accompanied by changes in collaboration and workflow. Many interviewees reported that adopting BIM and other collaborative digital platforms has altered how they coordinate with consultants and clients. Digital models shared via common data environments or cloud platforms allow for simultaneous, multi-disciplinary collaboration, which was widely described as a benefit. Engineers, architects, and contractors can now iterate together on the same model, catching clashes or errors earlier in the design process. One architect noted that "with BIM, our interaction with structural engineers is more dynamic – we update the model in real time, and they respond with feedback within days rather than weeks," highlighting improved efficiency and tighter integration among project stakeholders. However, this new mode of working also introduced challenges in practice management: roles within offices have shifted (several offices have hired BIM managers or computational design specialists), and teams have had to establish standards to maintain model quality and data consistency. A few practitioners mentioned interoperability issues as an ongoing concern – for example, translating models between different software platforms for various consultants requires technical finesse to avoid information loss. Additionally, digital workflows changed internal dynamics: younger staff often become the "tech champions" leading implementation, which in some cases created a reverse mentoring scenario (junior members guiding senior colleagues) until the whole team became proficient. In terms of the design process itself, the consensus was that digital tools have made the process more iterative and exploratory. Several offices described how parametric design tools or algorithmic approaches now enable rapid prototyping of ideas, whereas previously they might only have developed one or two options by hand. This has improved design quality by allowing more experimentation, but also requires discipline to manage version control and decision-making (to avoid endless iteration). Importantly, digital proficiency has broadened some offices' reach: a few Portuguese offices have started engaging in international projects or collaborations precisely because digital platforms make remote work and global communication feasible. In sum, the offices' current practice is a hybrid of traditional architectural expertise and digitally enhanced workflows. Even if none claim to be 100% digital in all aspects, all acknowledged that digital tools are now indispensable in everyday work – from concept ideation through design development to construction coordination. This local progression reflects the global pattern of digital maturation, albeit on a smaller scale: practices incrementally adopt technologies as benefits become evident and as external collaborators begin to expect these capabilities (Perera et al., 2022).

Future perspectives

Looking ahead, the interviewees generally expressed optimism about further digitalisation of practice, tempered by realism about the challenges that remain. Many foresee that tools like BIM, parametric

design, and digital fabrication will become even more standard in the next few years, moving from "early adopter" novelties to industry-wide norms in Portugal. Several participants highlighted specific emerging technologies they are watching or beginning to pilot. Automation and artificial intelligence in design came up repeatedly – for instance, some offices are experimenting with generative design algorithms or are interested in how AI might assist with routine tasks like code compliance checking or generating design alternatives. However, they also noted that these technologies are still nascent in architecture: "We're curious about AI, but it's not plug-and-play – we'd need to invest in skills to actually use it," one interviewee said, indicating a cautious and measured approach. Digital fabrication and off-site manufacturing is another area of future growth mentioned, especially by innovative offices like SUMMARY which already works with prefabrication. They anticipate increasing integration of design with fabrication, possibly through tighter collaborations with fabrication labs or contractors who embrace CNC manufacturing and 3D printing. Notably, a few practitioners voiced hope that regulatory and educational shifts will support the next stage of digital adoption. They argued that if public agencies begin to require digital deliverables (e.g. mandating BIM for permit submissions) or if universities continue to produce digitally skilled graduates, the momentum for change will accelerate in Portugal.

In terms of their own practice, each office described plans to continue learning and investing in technology as finances allow. Commonly, they plan to upgrade software and hardware, train staff in advanced modelling or coding, and seek out partnerships – for example, collaborating with universities or tech companies on research projects was seen as a way to stay at the forefront. Indeed, several interviewees embraced the idea of greater research collaboration as part of their future strategy: they see value in participating in pilot projects or knowledge-sharing networks to jointly develop new digital solutions, reflecting a growing mindset of practice-based research engagement (Lomas, 2000; Nutley et al., 2007). At the same time, the architects remain mindful of enduring challenges: they expect that cost and scale issues will persist, meaning they must be strategic about which innovations to adopt. For instance, a small office might "leapfrog" expensive infrastructure by using cloud-based computational services (to avoid buying high-end local servers), or join consortiums for training programmes rather than going it alone. Overall, the future outlook articulated by these Portuguese practitioners aligns with international trends discussed in Section 5.2 – a trajectory toward more data-driven, collaborative, and technology-augmented ways of working. Yet, their perspective is grounded in local reality: they envision progress coming through gradual, pragmatic steps (incremental upgrades, pilot projects, skill-building) more than through any sudden digital revolution. In conclusion, the interviews paint a picture of a Portuguese architecture community that is cautiously embracing the digital future: enthusiastic about the possibilities (greater efficiency, creativity, and global reach) but

aware that success requires not just new tools, but also training, cultural change, and support from the broader industry environment.

Comparison with international patterns

The insights from these Portuguese case studies both echo and diverge from the international patterns identified earlier. On one hand, the core motivations and challenges observed locally are strikingly similar to those reported globally. Just as leading offices abroad adopt digital tools to enhance quality and efficiency (RIBA, 2018), Portuguese early adopters are driven by the same pursuits. Likewise, barriers such as high initial costs, skill deficits, and resistance to change are universal themes (RIBA, 2018; Silva & Paio, 2024) that surfaced repeatedly in our local interviews. This suggests that the fundamental dynamics of digital transformation in architecture – the need for clear value propositions, the importance of training and an open culture – are not bounded by geography. On the other hand, the local context clearly modifies the trajectory of these dynamics. Portugal's smaller market and lack of strong top-down mandates mean digitalisation often relies on individual office initiative, potentially making progress slower and more uneven than in countries with more robust institutional support. For example, whereas some countries have national BIM requirements or extensive R&D funding pushing practice forward (RIBA, 2018), Portuguese architects operate in an environment where external pressure is minimal and client demand for innovation is often conservative. As a result, the interviewed offices frequently act as self-driven pioneers in the local sense – they adopt digital methods out of internal conviction rather than external requirements. This leads to a scenario where pockets of innovation (like our sample offices) exist within a broader industry that is still catching up. In comparison to the international best practices of Section 5.2, which included some large global "digital leader" offices, the Portuguese cases are more modest in scale and scope. None of the local firms have the vast resources or dedicated R&D departments of a Zaha Hadid Architects or an Arup, and indeed none have yet reached the very highest level of digital integration (e.g. full automation or AI-driven design as routine practice). However, their trajectories and aspirations run parallel to those global leaders – indicating that, given sufficient support and time, a similar digital paradigm is attainable in Portugal. In sum, analysing these local case studies enriches the global discourse by highlighting context-specific nuances: it confirms that widely discussed trends in digital practice do permeate into smaller markets, but the pace and mode of adoption are shaped by local culture, economics, and policy landscapes.

In summary, Portuguese offices face challenges similar to those reported internationally – notably skill gaps, cultural inertia, and high costs – but these issues are often more acute in Portugal's context, given the prevalence of small practices and limited R&D investment. The analysis reveals that while

Digital Pioneers exist in Portugal, many offices remain in the 'Emerging' category, indicating significant room for growth in digital fabrication adoption.

4.3.2. Data Collection and Analysis Approach

The data collected from the interviews (see Annexes A–I for the full transcripts) were systematically coded according to predefined analytical categories—such as references to specific digital tools, training initiatives, and perceived obstacles—and subsequently used to evaluate each office's levels of Digital Maturity (DM) and Research Engagement (RE). This classification process placed the architectural offices into the SFDAP typologies, allowing direct comparison with the international sample. To systematically assess the digitalisation level of each case study office, the qualitative data from interviews (along with basic office attributes) were coded into the SFDAP matrix introduced earlier. The Strategic Framework for Digitalisation of Architectural Practice uses two key axes – Digital Maturity (DM) and Research Engagement (RE) – each measured on a 1–5 scale, to locate and classify architecture offices (refer to Section 4.2.1 for the typology definitions). In this analysis, we assigned each Portuguese practices a score for DM and RE based on evidence from the interviews and supplementary information about their workflows and organisational setup. The coding process was directly informed by the parameter definitions developed in Section 4.1.1: for example, a DM score of 1 corresponds to very minimal use of digital tools (essentially ad-hoc, isolated adoption), whereas DM 5 indicates a fully digital-integrated practice at the cutting edge ("leading" level of maturity in industry terms). Intermediate values (2 = basic, 3 = intermediate, 4 = advanced) reflect progressively greater integration of technologies like BIM, parametric modelling, computational design, and digital fabrication in the office's standard processes (Kolarevic, 2003; Walliss & Rahmann, 2016; Perera et al., 2022). On the research engagement axis, an RE score of 1 denotes virtually no engagement with research (practice driven by routine and intuition with little reference to new knowledge), whereas an RE of 5 denotes a practice that is truly research-led, actively generating or co-producing new knowledge (for example, through in-house R&D or formal collaborations with universities). Middle values mark offices that are aware of research (RE 2), informed by research (RE 3), or research-active (RE 4) to increasing degrees. These categories draw on evidence-use theory (Nutley et al., 2007; Lomas, 2000), where higher engagement corresponds to more interactive models of applying knowledge – at the high end, offices don't just consume research but help shape it, embodying what Lomas (2000) describes as a "linkage and exchange" approach.

In practice, assigning these scores involved evaluating qualitative indicators from each interview. For Digital Maturity, we considered factors such as: the extent of BIM usage (e.g. isolated use on only a few projects vs. integrated use on all projects), the adoption of advanced tools like generative design,

VR/AR or in-house digital fabrication, the presence of dedicated digital workflows or specialists, and the overall reliance on digital vs. manual processes in day-to-day work. For Research Engagement, we looked at evidence of whether the office participates in experimental projects or grants, whether they publish or share knowledge externally, if they collaborate with academic or industry research initiatives, and whether they have internal processes for continuous learning and innovation (such as R&D units, innovation committees, or regular training – even if informal). We also noted office size (Small, Medium, Large) for context, given that size can influence capacity for innovation: a larger office might have more resources to invest in new technology, while a small office may be more agile but resource-constrained. In our Portuguese sample, nine practices were small (fewer than ~50 employees) and one was medium (~150 employees); none qualified as a large multinational office. This reflects the makeup of the Portuguese industry and is important for interpreting the results.

After coding each architectural office, we plotted them on the DM–RE matrix. The distribution of the ten case studies revealed three distinct clusters corresponding to the typologies defined earlier in Section 5.1.2: Digital Pioneers, Digital Innovators, and Digitally Emerging practices. (Annex J shows the matrix plot for these offices) Notably, none of the Portuguese cases achieved the absolute maximum of DM 5 and RE 5 – the hallmark of a true "Digital Pioneer" in our framework, typically exemplified by world-leading offices. This is not surprising given the sample's composition (mostly small to mid-sized offices). However, two offices – 18–25 Research Studio and SUMMARY – emerged as local trailblazers approaching the Pioneer profile. Both scored DM 4 and RE 5, meaning they have advanced digital workflows (DM level 4, or "Advanced") coupled with a research-led practice (RE 5). These two stood out for their exceptional engagement with research: for instance, 18–25 not only adopts cutting-edge visualisation technology but even developed custom software and VR workflows, effectively contributing new methods to practice. SUMMARY, likewise, has been involved in prototyping innovative construction systems (e.g. modular cork-based building techniques) in partnership with universities, indicating a high degree of research co-production. In terms of our typology, we might consider them "near-Pioneers" – while their digital maturity is just shy of the maximum (advanced but perhaps not employing every latest technology), their research engagement is on par with the Pioneer ideal. This finding is significant: it shows that even small offices can attain a research-led stance, aligning with Lomas's (2000) interactive model of innovation use where practitioners and researchers work in tandem. It also suggests a nuanced view of the Pioneer category: in a local context, pioneers may manifest as agile small offices pushing boundaries in specific niches, rather than only as large global offices.

The largest share of the sample fell into the Digital Innovators category. Four offices – Fahr 021.3, Rebelo de Andrade, and Saraiva + Associados – all scored approximately DM 4 and RE 4, fitting well the description of Innovators. These practices have strong digital integration (BIM and computational

design tools are standard in their work, placing them at an advanced maturity level) and are actively informed by research (RE 4, i.e. "research-active"). They typically engage with new ideas and methods – for example, by collaborating on occasional research initiatives or internally experimenting with new technologies – but they may not lead research efforts to the same extent as a Pioneer would. This aligns with Nutley et al.'s (2007) notion of instrumental use of research: the Innovators are adept at applying existing innovations and adapting best practices from the industry, though they aren't usually originators of novel techniques. In our sample, this group interestingly included the one medium-sized office (Saraiva + Associados, ~150 staff) as well as several small offices, indicating that office size alone did not determine innovator status. It is encouraging that even the smaller offices (Fahr 021.3 under 20 staff) achieved DM4/RE4 – they demonstrate that with the right focus and talent, a boutique practice can implement advanced BIM, parametric design, etc., and stay engaged with the latest developments. The medium office Saraiva provides a useful contrast: as a larger office with more formalized processes and an early start (using digital tools since the 1990s), it also attained an advanced maturity and an active approach to innovation (for example, the office regularly updates its standards to align with new BIM software releases and maintains partnerships with software vendors). The inclusion of this office underscores that Innovators in Portugal are not limited to avant-garde offices; established corporate offices can also be Innovators when they institutionalize a culture of keeping up with technology.

Finally, the remaining four offices – Atelier Peninsular, CVDB, Konceptness, and TEKSTUDIO – were classified as Digitally Emerging. These had scores roughly in the DM 2–3 and RE 2–3 range, indicating more modest digital adoption and lower research engagement. For instance, Atelier Peninsular (DM 3, RE 2) and Konceptness (DM 3, RE 2) are aware of digital trends and have implemented basic BIM and 3D modelling (hence intermediate maturity), but they largely focus on pragmatic, project-driven use of technology rather than open-ended exploration, and they have minimal involvement in formal research (relying mostly on external knowledge in a passive way, fitting Nutley et al.'s "conceptual" use category). CVDB and TEKSTUDIO (both around DM 3, RE 3) are slightly more engaged – they use digital tools for visualisation and some coordination tasks and keep informed of new techniques (e.g. by attending conferences or training sessions, thus being "research-informed"), but they stop short of investing heavily in R&D or experimental work. These Emerging offices tend to be younger or smaller offices still finding their footing with digital practices. Their categorisation reflects that they are in an exploratory stage: digital tools are in use but not deeply embedded or pervasive in all operations, and their workflow still involves a mix of traditional and digital methods. Importantly, all Emerging offices in this sample are small practices, consistent with the idea that limited resources can restrict the pace of digital transformation. They face more acute versions of the barriers noted earlier – for example, a couple of these interviewees pointed out that while they aspire to implement more advanced BIM or

start an R&D initiative, the immediate pressures of day-to-day projects and tight fees make it challenging to do so. In terms of the framework, these offices correspond to the lower-left quadrant of the matrix (lower maturity, lower engagement), which are exactly the practices SFDAP is aimed to assist by providing a roadmap for growth.

The coding of the Portuguese case studies into the SFDAP matrix thus reveals a broad spectrum of digitalisation within a single national context. Even within Portugal's relatively small architecture community, we see clear typological differences: a pair of near-Pioneers pushing the envelope, a solid cohort of Innovators integrating digital methods in practice, and a group of Emerging offices gradually building their digital capacity. This local distribution can be compared to the international sample from Section 5.2: unsurprisingly, the Portuguese offices occupy the mid-range of the global matrix (no local office is at the extreme forefront globally, i.e. none reached DM5/RE5), but the presence of any RE=5 "research-led" offices and multiple DM=4 "advanced" offices in Portugal is notable. It indicates that the upper tiers of innovation are not exclusive to global corporate offices – small Portuguese offices can also attain high innovation profiles in certain aspects. The office size factor did play a role to an extent (none of the Emerging practices were medium or large, and the one medium office was at least an Innovator), yet the overlap in performance between some small and medium offices suggests that leadership and vision may count more than sheer size in determining an office's digital trajectory. This finding is consistent with research on organisational innovation which often highlights strategic leadership and knowledge culture as key drivers (Nutley et al., 2007; Lomas, 2000), sometimes more so than resources alone.

Ultimately, mapping these offices on the SFDAP matrix provides a diagnostic snapshot of where Portuguese architectural practices stand in their digitalisation journey. It also serves to validate the framework's applicability at the local level: the typologies (Pioneers, Innovators, Emerging) meaningfully differentiate offices in Portugal much as they do in the international context, reinforcing that the underlying dimensions of Digital Maturity and Research Engagement are robust and relevant (Jäkel et al., 2024; Perera et al., 2022). Furthermore, these findings underscore the centrality of research engagement to driving innovation: the offices that scored highest on RE were also those embracing the most transformative uses of technology. Meanwhile, differences between small and large offices were evident in resource capacity, but not determinative of outcomes – a committed small office can sometimes rival a larger one in innovation through focused effort. In the chapters that follow, this classification will inform tailored strategies for practice. Recognizing that a one-size-fits-all approach would be ineffective, we instead propose guidelines sensitive to whether an office is emerging, innovating, or pioneering in its digital practice. The insights from the Portuguese case studies thus not only shed light on local adoption patterns but also demonstrate the framework's practical utility. They reinforce that combining technological advancement with an active research

culture yields the most significant innovations in architectural practice, and they highlight how the SFDAP framework can be applied to guide practice-specific digital transformation strategies moving forward.

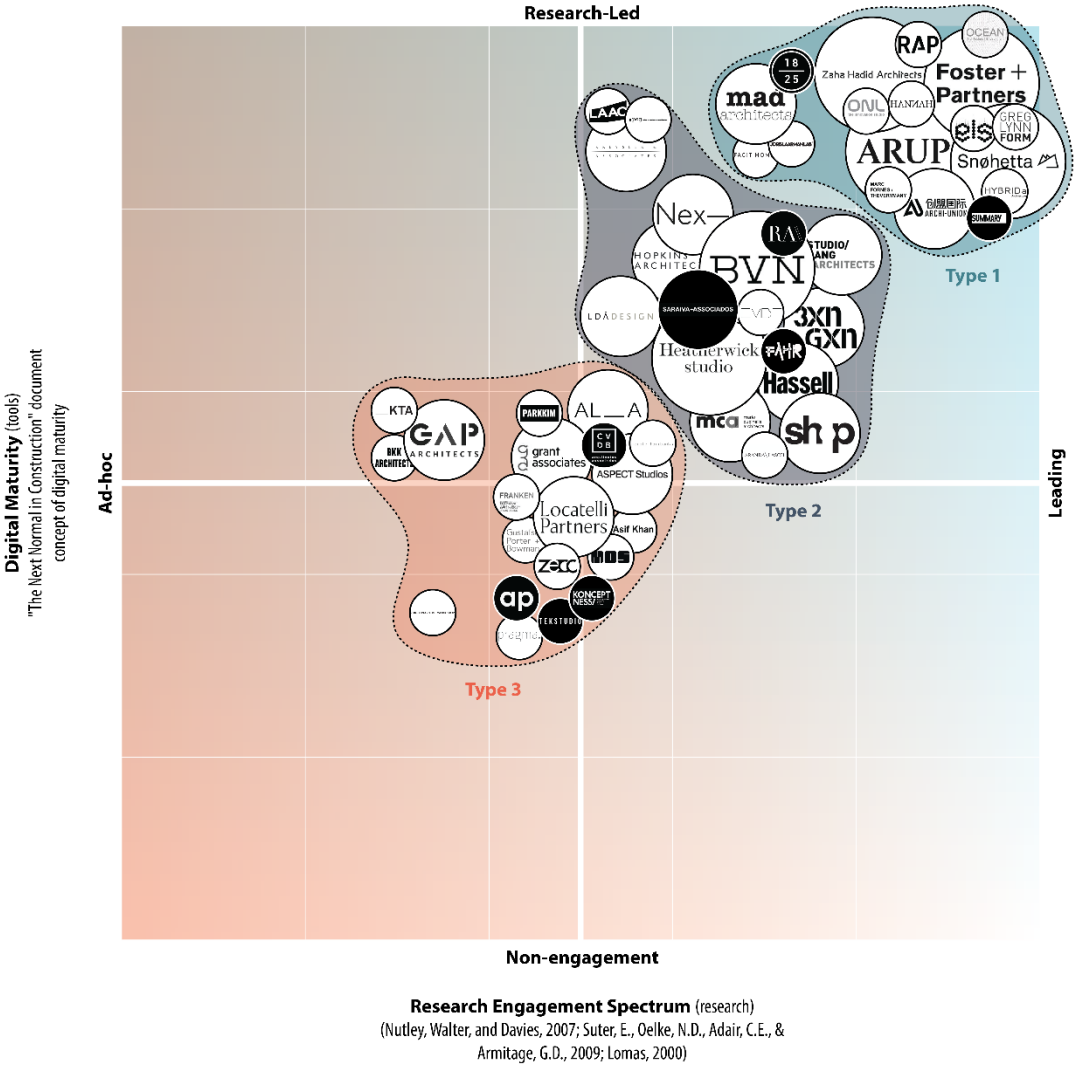


Figure 4.4: Comparative Typology of International and Portuguese Architecture Offices within the SFDAP Framework.

This figure overlays the typological zones (Type 1: Digital Pioneers, Type 2: Digital Innovators, and Type 3: Digitally Emerging) on the SFDAP matrix to compare the positions of Portuguese offices (in black) with the international dataset (in white). The visual representation reveals that while a few Portuguese offices align with global pioneers in digital and research leadership, the majority are situated within the Type 2 and Type 3 zones - highlighting moderate to emerging digital maturity and limited research engagement. This comparative mapping underscores regional disparities in digital transformation and research integration across the architectural sector. Sources: Nutley et al. (2007); Lomas (2000); Suter et al. (2009); McKinsey (2020).

The SFDAP establishes an evaluative model for positioning architectural offices along two key dimensions: digital maturity and research engagement. Applied to a sample of 47 international practices and a focused group of Portuguese offices, the framework enables the identification of distinct typologies, Digital Pioneers, Innovators, and Emerging practices, according to levels of technological adoption and research-driven culture. The analysis reveals that, within the Portuguese context, only a limited number of offices currently operate at the highest level of digital maturity, while the majority remain in emerging stages, highlighting substantial potential for deeper integration of digital fabrication. A central finding is that the most innovative practices are those that combine advanced fabrication capabilities with sustained research engagement. These results demonstrate that effective digitalisation is not solely a matter of technological investment, but is strongly shaped by how design and production processes are structured and integrated within the office. Building on this understanding, the research moves from a typological and strategic reading of practice toward a process-based perspective, proposing a framework that embeds fabrication intelligence across all phases of design and construction, and translates strategic positioning into concrete, workflow-level practices.

CHAPTER 5

Process-Based Model for Digital Fabrication Integration

5.1. Operationalising Digital Fabrication in Architectural Everyday Practice

Building on the typologies and case analyses from Chapter 4, this chapter develops a process-based model specifically aimed at embedding digital fabrication into the standard workflow of architectural practice. In other words, it maps how fabrication-thinking can be interwoven from design conception to construction within an architectural office's routine procedures, rather than remaining a one-off experiment. This responds to recent calls to examine the decision-making processes behind the technical details of digital fabrication adoption – shifting focus from what the tools are to how architects incorporate them in practice.

This model synthesizes these insights by integrating a human-centred Design Thinking cycle (inner loop) with the conventional architectural project phases (middle loop) and the suite of digital fabrication tools and methods (outer loop). In practice, the architect continually moves through empathize–define–ideate–prototype–test stages (Figure 5.1), while progressing through conceptual design, development, documentation and into construction. Rather than treating fabrication as a final step, we position it as a continuous driver that informs each phase. In other words, architects use computation, algorithms, and machine tools to explore form and material at every stage, echoing Oxman's notion of a "holistic integrated process" linking design to making (2014). This framework therefore clarifies when and how digital technologies support creativity and material innovation in practice.

Design thinking emphasizes a user-centric, iterative approach. As Gibbons (2016) explains, the design-thinking ideology is "a hands-on, user-centric approach to problem solving" that proceeds through six phases (empathize, define, ideate, prototype, test, implement) within three larger stages (Figure 5.1). This model parallels architectural office practice: architects repeatedly empathize with context (clients, site), define problems, and ideate solutions before building prototypes. In fact, Silva and Paio (2024) note that digital fabrication amplifies design thinking by adding precision and feedback at each iteration. For example, rapid prototyping encourages designers to "embrace failure as a learning opportunity" and continuously reflect on materials and processes. In this framework, the design-thinking layer ensures the architect's creativity and user-focus guide the integration of new technologies.

5.1.1. Design Thinking

The innermost layer of the framework is Design Thinking. This is a six-phase, iterative methodology that emphasizes a hands-on, user-centred approach to problem-solving. As described by Nielsen Norman Group (2021), design thinking proceeds through Empathize, Define, Ideate, Prototype, Test, and Implement phases, driven by continuous feedback and learning. In architectural terms, this maps onto office culture: architects empathize with users and context (programming), define problems (concept), ideate solutions (schematics), and rapidly prototype models or simulations before finalizing. Crucially, digital fabrication enhances this cycle. Rapid prototyping (3D printing, CNC models, etc.) allows early physical exploration of ideas, encouraging the team to "fail fast" and learn from material tests. In practice, architects report a hybrid process where sketches, digital models, physical models and full-scale prototypes inform one another. Thus, the design-thinking layer ensures the framework remains user-focused and exploratory. By embedding fabrication into the empathize–test loops, the framework makes digital tools active participants in creativity, not just outputs. This view aligns with conventional design theory that design is nonlinear and iterative (e.g. Cross, 2011), and simply shows that computational tools expand the creative vocabulary of that process.

In the framework (Figure 5.1), design thinking is thus not optional; it underlies every phase. It emphasizes creativity and a willingness to explore novel forms unconstrained by conventional methods. As Rowe (1987) and Archer (1981) long ago pointed out, design processes are inherently non-linear and knowledge-driven, and digital tools simply add more "vocabulary" to that process. By explicitly aligning digital fabrication with empathize–test loops, the framework highlights that digital tools are part of the creative iteration. This view aligns with Silva's earlier work: "the digital design appears as an integrated process from conceptualisation to … fabrication". In summary, the Design Thinking layer ensures the framework remains human-centred and iterative, with digital fabrication enhancing each loop of exploration and validation.

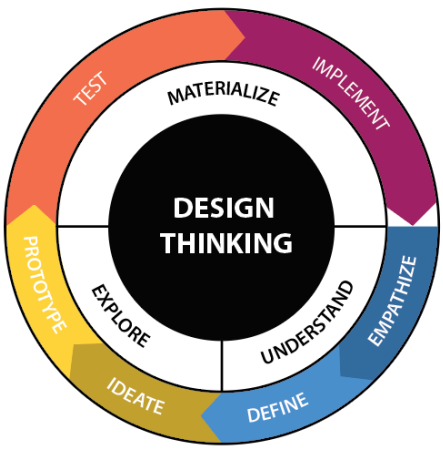


Figure 5.1: The classic design-thinking process (adapted from Nielsen Norman Group).

5.1.2. Architectural Process

Surrounding the design-thinking core is the Architectural Project Process layer. This represents the familiar stages of an architectural project (schematic design, design development, documentation, construction administration, and post-occupancy) and ties them to our design-thinking stages. For example, schematic design corresponds to early ideation and prototyping, while detailed design and documentation align with testing and implementation. We also explicitly add an Operations & Maintenance phase (often associated with post-occupancy BIM workflows) to capture building use and future feedback. In this view, each phase normally produces drawings or models – our framework suggests it should also yield appropriate fabrication artifacts. For instance, during design development the team might output CNC-cut models or 3D-printed details as standard deliverables. As one industry workflow shows, computational design and fabrication can be integrated into a single loop across phases. Consistent with Burry's (2016) observation that "architectural design continually evolves," we allow iterative loops between phases: a prototype failure in development may loop back to schematic design, and so on. By explicitly linking stages, this layer ensures that fabrication techniques (laser cutting, 3D printing, robotic milling, etc.) become part of the normal schedule. In essence, creativity (inner loop) is anchored to real-world milestones (middle loop), with iterations accommodated between them.

Each architectural phase traditionally outputs drawings or models; our framework suggests it should also output digital fabrication artifacts when appropriate. For instance, during design development an architect might produce CNC-cut models or 3D-printed details (digital fabrication methods) as part of the normal workflow. Hensel and Nilsson's "Digital Design and Fabrication Process" from Perkins+Will exemplifies this integrated workflow. By inserting digital production steps into the standard design phases, the framework clarifies how fabrication techniques (laser cutting, 3D printing, robotics, etc.) correspond to phases (Figure 5.2).

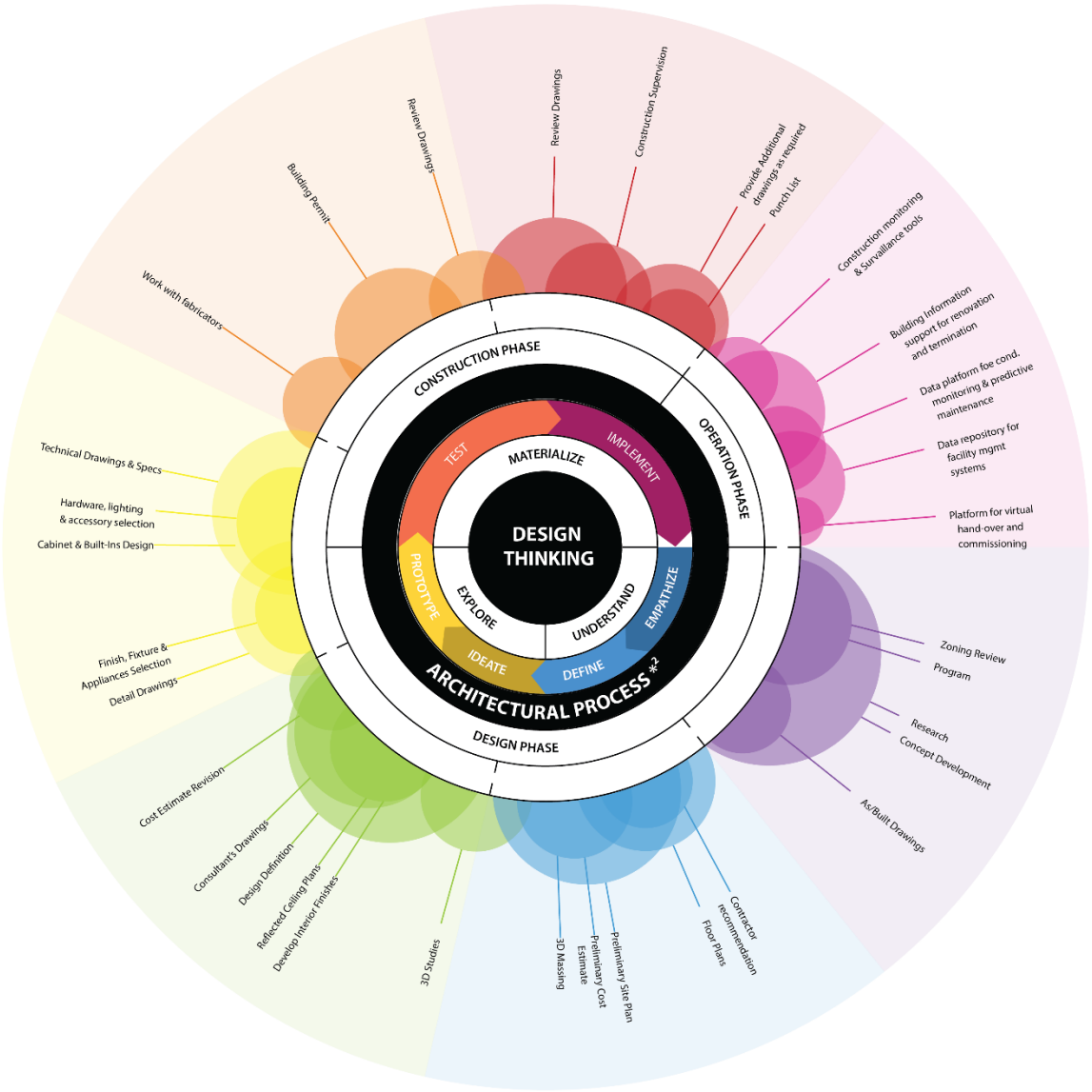


Figure 5.2: Architectural design workflow adapted from HMH Architecture + Interiors and Ventures.

In essence, this layer makes the framework concrete. It ties high-level creativity to real-world project milestones. As Burry (2016) notes, architectural design "continually evolves," so the framework must accommodate iterations between phases. For example, if a prototype fails, the process may loop from construction back to schematic design. The taxonomy constructed by Silva and Paio explicitly "connects Design Thinking with architectural practice", and by visualizing these connections (Figure 5.2) we make clear that digital fabrication should neither be an afterthought nor a bolt-on. Instead, it extends through every phase, linked by a common design intent.

5.1.3. Digital Tools and Production Methods

The outer layer of the framework consists of Digital Fabrication Tools and Methods – the computational and material technologies that realise designs. This includes parametric modelling software, simulation tools, CNC machines, 3D printers, robotics, and so forth. In our framework, these are not isolated deliverables but integrated resources that feed back into each design phase. For example, a team might iterate a parametric model, immediately generate machine tool-paths (e.g. for a robot or printer), and then fabricate a prototype; measurements from the prototype (or even data from embedded sensors) are then used to refine the model in real time. In practice, leading offices describe this as a feedback loop between the digital and physical: digital constraints guide fabrication, and insights from material behaviour inform the design model. Office research emphasizes that computation and fabrication can form "a single loop" (Hensel & Nilsson, 2016). Likewise, Oxman notes that digital design becomes "a holistic integrated process from conceptualisation to materialisation to fabrication." Figure 5.3 (adapted from Perkins+Will) illustrates this cycle: a parametric design leads to toolpath generation and physical prototype, which then generates new design input.

Together, the three layers produce a comprehensive taxonomy: the inner layer asks what to make (driven by human creativity), the middle layer defines when/how to make it (project timeline), and the outer layer determines how it is made (tools and processes). A key feature is the explicit inclusion of feedback loops: any phase can inform any other. For instance, discovering a construction challenge may prompt changes back in conceptual design. We also explicitly include post-occupancy feedback, noting that digital tools (like sensors or digital twins) can inform future building updates, closing the cycle. The visual taxonomy (Figure 5.3) thus helps architects see digital fabrication not as an add-on but embedded in the fabric of practice.

For example, the Perkins+Will "Digital Design and Fabrication Process" integrates computation and material fabrication into a single loop. Hensel and Nilsson (2016) describe how computational design can be directly linked to fabrication constraints, allowing architects to "think with and through" material possibilities. Similarly, Oxman (2014) argues that digital design becomes "a holistic integrated process from conceptualisation to materialisation to fabrication". In practice, this means an architect might iterate a 3D model, immediately test it on a 3D printer, and return insights (e.g. about structural feasibility or material use) into the model – all as part of one seamless workflow.

Figure 5.3 illustrates a generic digital fabrication loop: starting from a parametric model, moving to tool-path generation, and producing a physical prototype, which is then measured and fed back. This loop can itself be the basis of new design ideas (Silva, 2019). By formalizing this as the third component of the framework, we emphasize that digital technologies (software algorithms, hardware machines, sensors) are not just end-of-pipe deliverables. They become co-designers that inform design decisions. As one study notes, "most buildings are both designed and fabricated with computational

methods," highlighting that digital tools have permeated all scales of architectural work. In our framework, these tools occupy every phase of the design process (inner loops in Figure 5.3), making fabrication constraints and opportunities visible from the earliest sketches through construction.

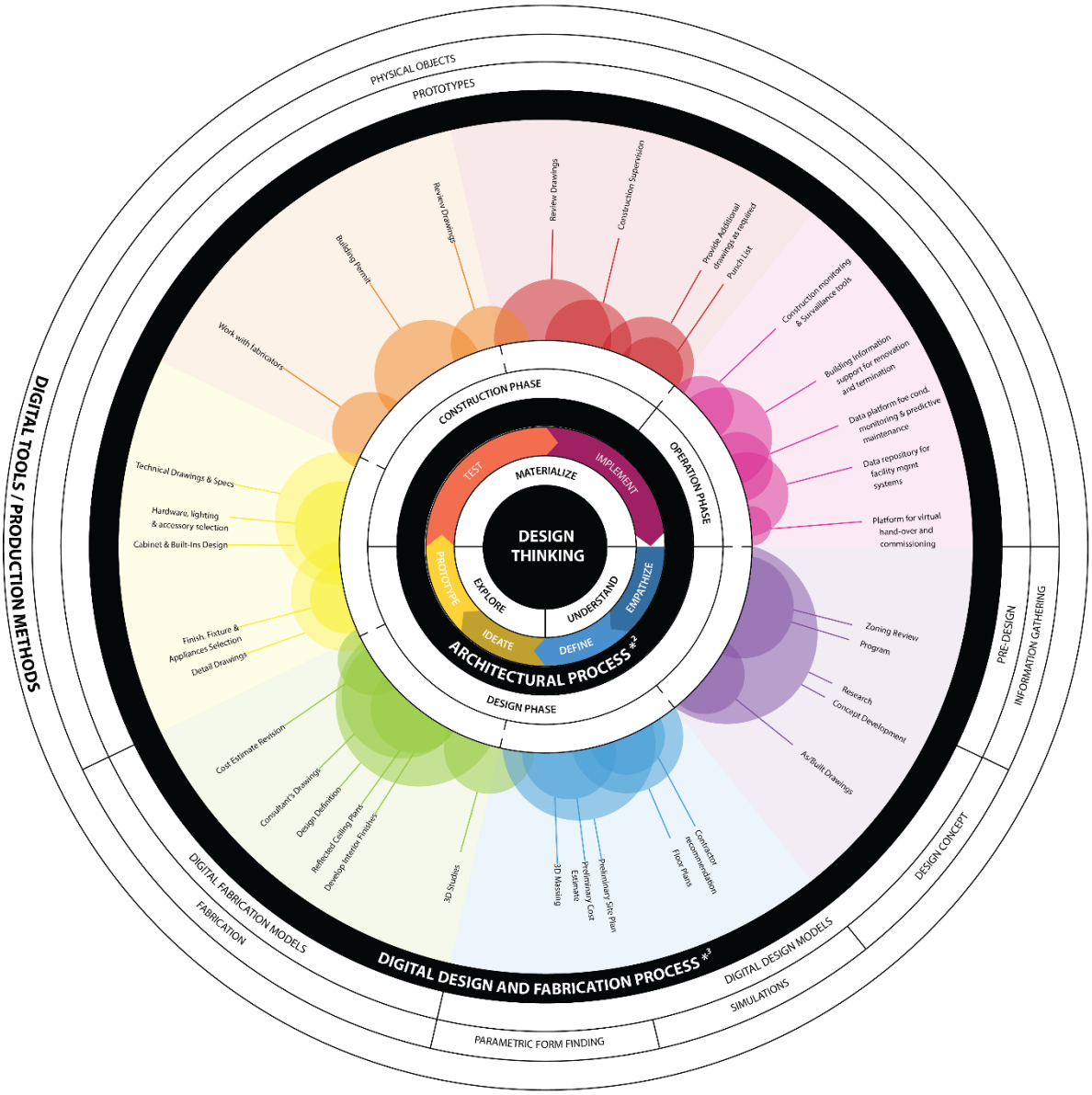


Figure 5.3: Digital design and fabrication loop (adapted from Perkins+Will) showing integrated computation and physical prototyping.

These three dimensions – the mindset of design thinking, the stages of the architectural process, and the arsenal of digital tools and fabrication methods – together form the basis of an integrated framework. Rather than treating them in isolation, the framework interweaves them: early-stage design thinking is informed by an awareness of fabrication possibilities; each phase of the architectural process (from concept to construction) is augmented with feedback from digital analysis and

prototyping; and the selection of tools or fabrication techniques is guided by the project's design intent and phase-specific needs. By aligning creative process with technical execution at every step, this integrated approach allows material constraints and digital capabilities to continuously inform design decisions. Taken together, the three layers produce a comprehensive view: design thinking guides what to make, the architectural process defines when and how to make it, and digital tools determine how it is made. A key structural improvement of this framework is the explicit addition of the Operations & Maintenance phase and the feedback loops between all phases. This extension clarifies the framework's application by reminding us that digital fabrication can even inform building use and future modifications, fully closing the loop. The visual taxonomy (Figure 5.3) helps architects see digital fabrication not as an isolated technique, but embedded into the fabric of design practice.

5.2. International Context: Process-Based Workflow Analysis of Architectural Offices

To ground the model in real-world, process-oriented architectural practice, we examined case studies of innovative architectural offices that exemplify an advanced integration of digital design and fabrication. The selection of case studies was guided by a set of explicit criteria: (i) demonstrable use of computational design workflows closely linked to material production; (ii) sustained engagement with digital fabrication techniques beyond one-off experimental projects; (iii) operation at a scale of practice and project delivery broadly comparable to the Portuguese context; and (iv) documented reflection on process, iteration, and decision-making across design and construction phases.

On this basis, offices such as HANNAH Office (USA) and Studio RAP (Netherlands) were selected. Their portfolios combine computational design with extensive fabrication in ways that are transferable to small- and medium-sized architectural practices. For example, HANNAH Office's Ashen Cabin (2019) is a prototype dwelling fabricated using robotics and 3D printing with reclaimed ash wood. The designers characterize their approach as "deliberately hybrid," involving constant feedback between sketches, digital models, physical mock-ups, full-scale prototypes, and simulations. This confirms a tightly integrated workflow in which digital and analogue modes mutually inform and refine the design process.

Similarly, Studio RAP's projects - such as the Circular Experience (2019) (Figure 5.4) - demonstrate the fusion of parametric design with robotic fabrication and assembly. In this project, factory offcuts of laminated timber were reused through a parametrically controlled robotic process to construct the pavilion's wall system. In both offices, design thinking and prototyping are embedded from the earliest stages, while CNC machining and robotic fabrication are deployed strategically to materialize complex geometries at later phases. These cases therefore provide robust empirical grounding for the proposed

process-based model, illustrating how digital fabrication can be systematically embedded within architectural practice rather than treated as an isolated technical exercise.

Moreover, the case studies were organised into a Process-based analysis chart (Figure 5.5) by year, fabrication type (3D printing, CNC, robotics, etc.), and design phase. This revealed patterns: for instance, both offices used 3D printing primarily in conceptual design for form-finding, and utilized robotics in later phases to realise complex components. Importantly, across cases the offices "view digital fabrication as a way to expand their research and enhance their craft's potential". In other words, they did not see fabrication as merely a means to an end, but as an exploratory tool that feeds back into design thinking. These case insights directly inform the proposed framework, ensuring it reflects not only ideal scenarios but also the constraints and opportunities architects encounter in practice.

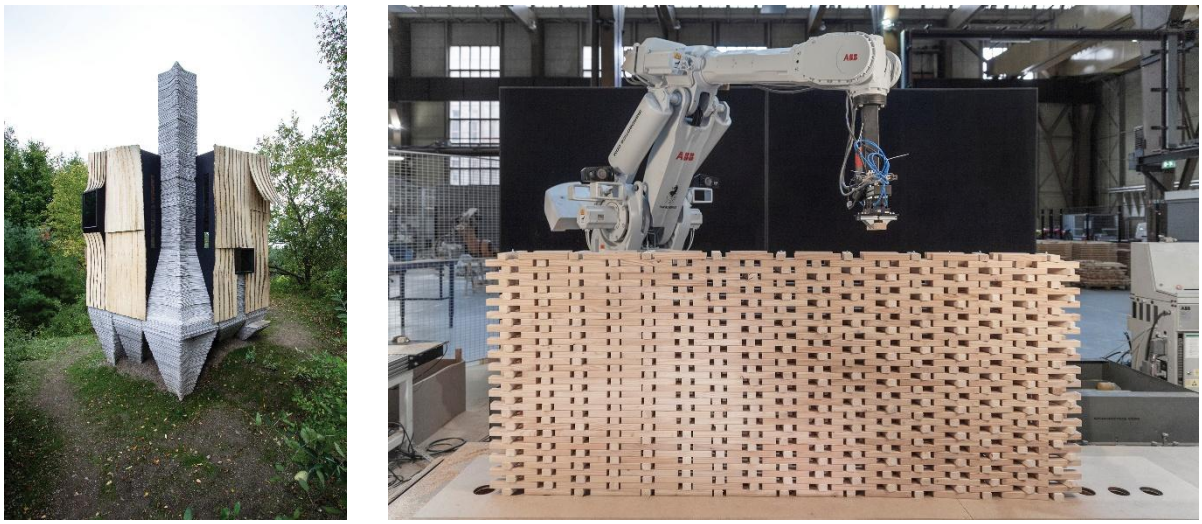


Figure 5.4: Left - Ashen Cabin. Source: HANNAH Office, 2019. Right – Circular Experience. Source: Studio RAP, 2019.

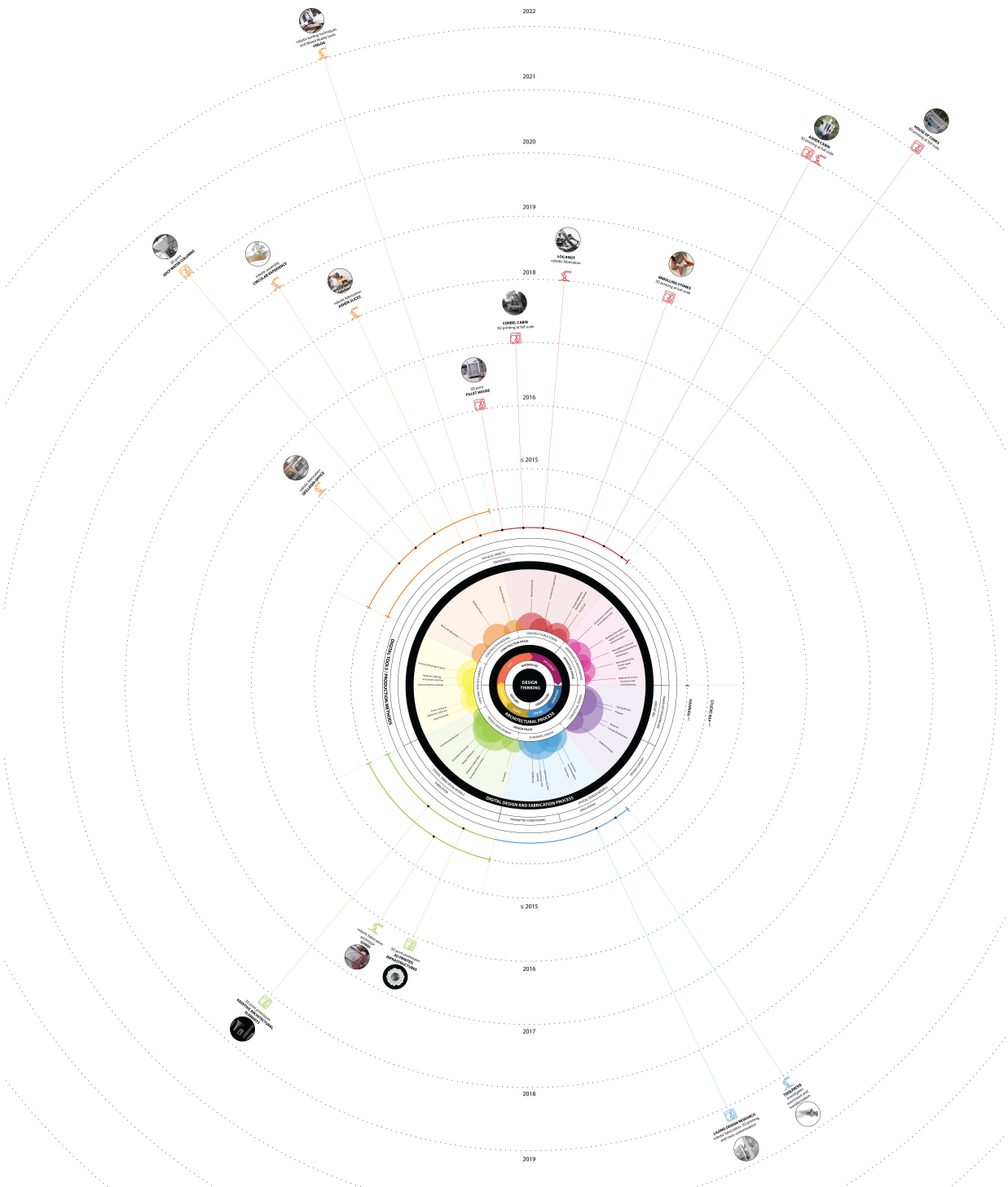


Figure 5.5: Process-based analysis of projects by HANNAH Office and Studio RAP.

5.3. Building a Process-Based Model Workflow for Digital Fabrication Integration in Architectural Offices

To construct the integration framework, this research followed a two-stage methodological approach. Stage 1 involved a theoretical mapping of digital fabrication opportunities across the standard phases of the architectural design process, informed by the literature reviewed in Chapters 1–3. Stage 2

comprised of the empirical derivation of a taxonomy based on the case studies and interviews presented in Chapter 4. The combination of these stages ensured that the framework is both conceptually rigorous and empirically validated.

The framework was developed through systematic data collection and analysis. Detailed information on each studio's projects was gathered from multiple sources, including academic publications, professional press, and project documentation. For each relevant project, data were recorded on the year of completion, the digital fabrication technologies employed (e.g. laser cutting, concrete additive manufacturing, robotic milling), and the design phase during which these technologies were applied. This process yielded a comprehensive dataset capturing workflows, technological choices, and temporal sequences across projects.

The analysis proceeded in two stages:

Stage 1 – Theoretical Mapping

Generic design-thinking stages were aligned with the architectural workflow to construct a three-layer chart (Figure 5.3). For instance, "programming" within studio practice was mapped onto schematic design, while "analysis" was associated with the design development phase. This conceptual alignment confirmed that user research, contextual understanding, and performance analysis are concentrated in the early phases of a project, whereas implementation corresponds primarily to construction documentation and site administration.

Stage 2 – Empirical process-based model

Empirical data from the case studies were then plotted onto a radial timeline diagram (Figure 5.5). Each project is positioned according to its year of completion and colour-coded by the design phase in which digital fabrication was applied. This visual taxonomy reveals how digital techniques propagate throughout the project lifecycle: early-stage projects tend to cluster around additive and exploratory prototyping, while later-stage projects are more strongly associated with subtractive processes and robotic fabrication.

Importantly, the taxonomy of digital fabrication applications developed in Stage 2 is structured to be legible and operational for practitioners. By translating abstract theoretical concepts into concrete categories of practice, it enables architects and firm leaders to identify the current position of their workflows and to envision pathways for their evolution.

The analysis generated several key insights. It confirmed that digital fabrication techniques are eventually present across all design phases, reinforcing the argument that fabrication transcends its traditional role as a merely supportive or terminal activity. The findings also prompted refinements to the framework. In particular, the identification of projects incorporating digital monitoring and

customisation during building use led to the explicit inclusion of an Operations and Maintenance phase, incorporating feedback loops into the overall model. By systematically classifying and visualizing projects within the proposed framework, architects are provided with clearer guidance on when and how to deploy digital fabrication strategically. In this way, the framework responds directly to calls for the more deliberate integration of fabrication within architectural workflows.

Key Takeaways

The process-based model consolidates core concepts developed in earlier chapters into a cohesive model. The Design Thinking layer ensures a human-centred and iterative approach to problem framing and solution development. The architectural process layer anchors these iterative loops to concrete project milestones. The digital tools layer incorporates the full spectrum of fabrication technologies observed in practice, as exemplified by offices such as HANNAH Office and Studio RAP. The empirical cases demonstrate that digital fabrication is not an isolated technical addition but is embedded throughout the design process. By positioning fabrication as an integrated axis of both creativity and construction, the framework offers architects actionable clarity on how to integrate digital methods at every stage of practice.

The process-based model highlights that early and iterative engagement with digital fabrication, through prototypes, simulations, and material testing, can enhance both design quality and operational efficiency. The central implication is that architectural offices can adopt a more agile and feedback-driven mode of practice by treating digital fabrication not as a final step in production, but as an integral component of thinking and making architecture.

PART III – GUIDELINES FOR IMPLEMENTING DIGITAL FABRICATION IN ARCHITECTURAL PRACTICE

CHAPTER 6

Strategic Adoption of Digital Fabrication in Architecture Practice in Portugal

Integrating digital fabrication into architectural practice requires not only new tools but also strategic planning, cultural shifts, and skill development. In Portugal, as in other contexts, the adoption of digital fabrication has been gradual and often confined to experimental projects or academia. This chapter outlines practical steps for architectural offices to integrate fabrication technologies and discusses how to cultivate the necessary workforce and mindset. Drawing on interview insights from Portuguese offices (Annexes A–I) and a sample of local offices and innovation hubs, it provides guidelines for aligning digital fabrication with design practice. Key themes include establishing core implementation principles, making informed decisions on fabrication technologies, developing essential skills through training and partnerships, and rethinking the design office culture for the digital era. While challenges such as high costs, skill gaps, and cultural inertia persist, opportunities are emerging through academic–industry collaboration and a growing network of fabrication labs. The following sections break down these considerations into actionable principles and illustrate them with examples from the Portuguese context.

6.1. Practical Steps for Digital Fabrication Integration

Successfully integrating digital fabrication in an architecture office is as much an organisational challenge as a technical one. Offices must take strategic and infrastructural steps to embed fabrication into their process-based model workflows, ensuring it adds value to the design process rather than appearing as an afterthought. International studies stress that merely acquiring cutting-edge tools is insufficient without addressing human factors like skills and organisational culture (RIBA & Microsoft, 2018). Interviewees from Portuguese offices echoed this, noting that technology alone "won't help if people aren't ready or able to use it." In practice, integrating digital fabrication requires a clear vision of how it will enhance an office's work, careful planning for implementation, and an openness to iterate and learn (Kolarevic & Klinger, 2008).

Ultimately, the goal is to make digital fabrication a normal, value-adding part of an architecture office's operations rather than a peripheral experiment. These guidelines are written from the practitioner's perspective, addressing everyday challenges like team skills, client communication, and risk management, to ensure that digital fabrication moves from the lab or demo project into the core of office practice.

Below, we outline core principles that guide the implementation of digital fabrication (Section 6.1.1) and discuss how architectural offices can evaluate and choose appropriate fabrication technologies (Section 6.1.2). These guidelines are informed by both the experiences of Portuguese architecture offices and broader literature on digital practice and fabrication strategy.

6.1.1. Core Principles for Implementing Digital Fabrication on the Process-Based Workflow

Implementing digital fabrication starts with foundational principles that align technology with an office's design ethos and business strategy. Rather than adopting tools for their own sake, leading practices ensure that fabrication methods serve clear goals, whether improving design quality, efficiency, or innovation capacity. The research identifies six core principles that guide architectural offices when embarking on the integration of digital fabrication into everyday practice workflows.

Principle 1: Align Fabrication with Design and Value

Digital fabrication should be integrated as a means to advance design intent and project value. This means identifying use cases where fabrication can enhance outcomes, for example, producing complex geometries that improve performance or craft, or accelerating the making of models and prototypes for client communication. The technology must serve the architecture, not vice versa. As one interviewee noted, "I prefer to use the tool in favour of the quality of the work rather than being a slave to the tool" (Annex E – Konceptness). In other words, fabrication tools should augment the architect's creativity and precision, enabling results that would be hard to achieve with traditional means. Gramazio and Kohler (2008) similarly emphasize using robotics and digital fabrication to achieve bespoke architectural elements that align with design objectives rather than technology for its own sake. Furthermore, Burry (2005) argues that digital tools should extend craftsmanship rather than replace it – the goal is to enhance quality through precision and innovation, not to bow to the novelty of the tool.

Principle 2: Leadership and Cultural Buy-in

Strong leadership and an innovation-friendly culture are crucial for digital fabrication adoption. Office leaders need to champion the integration, providing vision and resources. Interviewees observed that without an "internal driver" in the office, new techniques tend to remain sidelined. This internal driver

could be a passionate principal or a dedicated R&D team that advocates for digital methods. Equally important is fostering an office culture that encourages experimentation and accepts the learning curve associated with new tools. A senior architect from a Portuguese office remarked on persistent "resistance to change" among peers, noting that some still cling to familiar methods or even avoid innovation out of a desire to seem "non-technological" (Annex A – 18-25 Research Studio). Overcoming this requires internal communication of the benefits of digital fabrication and showcasing small wins to build confidence. In short, management support and a receptive mindset across the team form the bedrock for implementation (RIBA & Microsoft, 2018).

Principle 3: Incremental and Project-Based Implementation

Given the costs and learning involved, many offices benefit from a gradual approach – implementing digital fabrication in phases or pilot projects. A common strategy is to start with a specific project component or scale where digital fabrication clearly adds value (such as a custom facade element, or rapid prototyping of study models) and use that as a demonstration. By tackling a "low-hanging fruit" project first, the team can develop expertise and refine workflows in a manageable context. For example, Pedro Campos Costa's experience with the Lisbon Aquarium extension showed how focusing on a single building element (a custom ceramic facade) led the office to explore digital manufacturing methods with an industry partner. That initial foray built knowledge for future projects. An iterative implementation also allows the office to learn from mistakes and progressively integrate more complex fabrication tasks over time, moving from simple digital model-making to full-scale construction components as confidence grows. This pragmatic approach is echoed by Corser (2010), who observes that starting with small prototypes or isolated parts of a project can build expertise gradually and mitigate risk.

Principle 4: Infrastructure and Resource Planning

Strategic adoption involves planning the necessary infrastructure—both physical and digital—to support fabrication. Offices must assess what equipment to acquire in-house versus what to access externally. This includes evaluating space requirements (for machines like CNC routers or 3D printers), software and hardware needs (CAM software, compatible 3D modelling tools), and maintenance or training costs. In Portugal, interviewees emphasized the importance of financial planning: even mid-range 3D printers or small CNC machines represent significant investments, "equivalent to multiple years of office rent" in some cases. High costs were universally cited as a barrier, and offices often delay buying equipment until a project's budget can justify it. A core principle, therefore, is to invest wisely and seek creative ways to mitigate cost—such as sharing equipment between offices, using local fab labs, or applying for innovation grants when available. Gershenfeld (2005) notes that the rise of

Fab Labs and shared fabrication facilities worldwide has made tools like laser cutters and CNC machines more accessible without individual offices shouldering the full cost. It may also mean prioritizing multi-purpose tools (e.g. a robotic arm that can both mill and print with different attachments, rather than several single-purpose machines) for flexibility. Careful resource planning ensures that the technology investment aligns with office size and capabilities.

Principle 5: Collaboration and Knowledge Sharing

Embracing digital fabrication should not happen in isolation. Offices are encouraged to collaborate externally to boost their know-how. This can involve partnering with fabrication laboratories, universities, or industry experts. Many pioneering cases in Portugal resulted from such collaborations: the CorkCrete Arch project at Porto's DFL (Digital Fabrication Lab at FAUP) is a prime example, where architects and researchers worked with industry to develop a novel robotic construction system using concrete and cork. By tapping into external expertise, offices accelerate their learning and avoid pitfalls. Networking with peers through conferences or online platforms is another way to share experiences. A culture of openness – where architects share processes and results – can greatly aid strategic adoption, as it builds a community of practice around digital fabrication. This collaborative approach reflects broader calls for integrative practice models in architecture (Oxman, 2008), in which knowledge flows across disciplinary and organisational boundaries. In essence, collaboration acts as a force-multiplier for a single office's efforts, turning isolated experiments into collective advancement.

Principle 6: Clear Incentives and Client Communication

A strategic implementation addresses the "why" - the incentives that make digital fabrication worthwhile. These need to be clear to both the design team and clients. If the incentive is efficiency, it should be quantified (e.g. reducing assembly time by 50%, or enabling a design-build delivery within a tighter schedule). If it is quality or innovation, it should be demonstrated through prototypes or case studies. Several interviewees mentioned that client demand in Portugal is generally low – clients rarely request digital fabrication, and some are wary of unproven methods. Therefore, architects often must create the demand by educating clients on the added value. For example, showing a client an intricate 3D-printed model or a CNC-milled mock-up can make the benefits tangible. One practitioner noted that once clients experience the improved precision and visualisation that digital processes allow (such as catching coordination errors through BIM or early prototyping), they are more supportive – even if initially they lack the willingness to change. Indeed, industry surveys have found that better client outcomes (like cost certainty and quality assurance) are key drivers for digital adoption (RIBA & Microsoft, 2018). Communicating how fabrication integration ultimately serves the client's interests – be it through better quality, fewer construction errors, or unique design features – is key to securing

buy-in. Architects must also be honest about risks and how they will be managed. When clients understand the clear incentives, they are more likely to support and even invest in digital fabrication initiatives.

Implementing digital fabrication strategically in architectural practice calls for aligning technology with design value, securing leadership and cultural support, starting with manageable steps, planning infrastructure investments, collaborating to build knowledge, and articulating clear incentives. These core principles create a roadmap that can guide Portuguese offices beyond ad-hoc experimentation toward a more systematic integration. As one Portuguese office leader put it, when technology becomes "intrinsic to our way of designing" (Annex A – 18-25 Research Studio), the office is not just using new tools, but fundamentally evolving its practice to harness the digital era. Leadership in the field similarly stresses that without such holistic integration of digital methods, the profession risks stagnation; as Farmer (2016) warned in the context of construction, those who fail to modernize and embrace innovation may face obsolescence.

6.1.2. Choosing the Digital Fabrication Technologies

A practical aspect of strategic adoption is deciding which digital fabrication technologies to integrate. Architecture encompasses a spectrum of fabrication methods – from CNC milling and laser cutting (subtractive processes) to 3D printing (additive manufacturing) and robotic assembly – each with different applications, costs, and skill requirements. The "right" choice for a given office depends on its typical projects, available resources, and long-term goals. Decision-makers must evaluate technologies not in isolation, but in relation to their design workflows and the local industry ecosystem. In the Portuguese context, considerations of scale and support are especially pertinent: with most offices being small to medium-sized and budgets tight, it may not be feasible to adopt every new gadget. Instead, offices benefit from a targeted approach to technology selection. In a busy practice environment, these decisions must be pragmatic. Architects must therefore evaluate not only the technical specifications of fabrication tools, but also how these technologies align with project timelines, team competencies, and broader business objectives. In this context, the selection of fabrication technologies should be guided by a set of interrelated factors, including: (1) Project Needs and Design Focus; (2) Cost and Accessibility; (3) Skill Requirements and Team Capability; and (4) Scalability and Future-Proofing.

Project Needs and Design Focus

The most appropriate technology is one that complements the architecture office's design focus and the kinds of projects they undertake. For instance, if a practice frequently works on interior fit-outs or

furniture, a CNC router or laser cutter for wood and acrylic may provide immediate benefit, enabling rapid prototyping of custom pieces. On the other hand, an office engaged in complex free-form architecture might look to robotic fabrication or large-format 3D printing to realise non-standard components. The choice of technology should solve a real design or construction challenge the office faces, thereby integrating naturally into practice. As noted by Iwamoto (2009), different fabrication tools lend themselves to different scales and materials: e.g., laser cutting excels at precise sheet component fabrication (useful for models or partitions), while industrial robots can assemble or fabricate bespoke building elements at full scale. An example from Portugal is the use of custom ceramic elements in the Lisbon Aquarium extension: the architects needed a way to fabricate non-repetitive facade pieces and initially envisioned digital fabrication through a ceramic supplier. In that case, the technology choice (robot-assisted manufacturing of ceramics) was driven by a specific design problem – achieving a texture and form unachievable by standard products. Likewise, SUMMARY Architects' Gomos system illustrates alignment of tech with design: they developed a modular concrete housing system where each module is factory-produced with all finishes installed, drastically simplifying on-site construction. This approach required collaboration with a precast concrete factory (leveraging CNC-milled formwork and controlled production) rather than, say, investing in a 3D concrete printer themselves. The lesson is to let project needs guide technology adoption, an approach echoed by Gramazio and Kohler (2008) who demonstrated that robotic fabrication could fulfil unique design visions (such as intricate brick patterns or structural frameworks) beyond the reach of conventional methods.

Cost and Accessibility

Each technology comes with cost implications - not only initial purchase, but maintenance, materials, and training. Offices must realistically appraise what they can afford and sustain. In many cases, it may be more strategic to use external resources than to own a machine outright. For example, 3D printing has become relatively accessible; many Portuguese offices now own desktop 3D printers for model making since these devices are modest in cost and user-friendly. By contrast, a large CNC milling machine or industrial robotic arm involves a substantial investment and a steep learning curve. If an office only occasionally needs large CNC or robotic work (e.g. for a one-off installation or complex formwork), outsourcing to a local fabrication shop or partnering with a university lab can be a smarter choice. Interviewees noted that in Portugal, many offices hire specialists or use external workshops when advanced fabrication is needed, because in-house capacity is lacking. The burgeoning network of Fab Labs in the country also provides accessible technology: for instance, FabLab Lisboa is equipped with laser cutters, a medium-size CNC router, and 3D printers that local architects or students can use at low cost. Using such facilities can be a cost-effective way to experiment with digital fabrication

before deciding to invest internally. This strategy mirrors the vision of the Fab Lab movement (Gershenfeld, 2005), which advocates distributed access to fabrication tools as opposed to each entity owning expensive machines. The strategic approach is to match the scale of technology to the scale of the office - perhaps starting with smaller devices (a laser cutter for model components, a desktop 3D printer) that have multipurpose use, and relying on external partners for larger or more specialised fabrication needs. This staged approach manages risk and expenditure, ensuring the office is not overburdened by costs for tools that might sit idle.

Skill Requirements and Team Capability

Different fabrication technologies demand different skill sets. A laser cutter might only require basic training in preparing 2D CAD files, whereas operating a 5-axis CNC mill or programming a robot involves advanced CAM (Computer-Aided Manufacturing) knowledge and sometimes coding or algorithmic thinking. Therefore, the choice of technology must account for the current (and attainable) skills within the team. If no one on staff can generate G-code toolpaths, adopting a CNC mill will entail either significant training or hiring new talent. One strategy observed is that offices choose technologies that align with skills their younger architects or interns already possess (often from university experience). For example, many recent graduates are familiar with 3D printing and laser cutting from academic projects; hence these tools can be integrated quickly into practice. In contrast, expertise in robotic fabrication is rare, so an office might initially collaborate with a research lab like DFL in Porto or Vitruvius FabLab at ISCTE to utilize robotics, until their team gains experience. Some offices overcome skill gaps by learning-by-doing on pilot projects with expert partners. In one interview, a principal described how their team worked closely with a fabricator on a complex project and subsequently internalized those skills for future use. This aligns with observations by Oxman (2008) that architectural education has not yet fully equipped all graduates with digital fabrication competencies, leaving a gap that offices must fill through training or hiring. Indeed, a RIBA survey found that lack of staff expertise in new technologies is a major obstacle to adoption (RIBA & Microsoft, 2018). A realistic assessment of the team's skills (or the ability to acquire them) should guide which technologies to adopt. The aim is to ensure the office can actually operate the tools effectively – otherwise the machines may sit idle, a scenario Bob Sheil cautioned against, noting that some architects invest in machinery but lack the skills to use it proficiently (Sheil, 2012).

Interoperability with Design Workflow

Another criterion is how well a given fabrication technology integrates with the office's digital design workflow (software and process). For instance, if a practice is deeply invested in Building Information Modelling (BIM), they might prioritize technologies that can directly use BIM data for fabrication (such

as CNC machines that take profiles or schedules from the BIM model, or prefab systems driven by BIM outputs). If an office does primarily computational design with tools like Rhino/Grasshopper, they may prefer open-ended robotic tools or 3D printers that can be driven by custom scripts. Compatibility and data flow are important: the goal is a seamless pipeline from digital model to physical output. The easier it is to go from model to machine, the more routinely fabrication can be used as part of design exploration. Pioneers of the digital design-to-production approach have long argued for tightly coupling CAD with CAM to eliminate translation errors and delays (Kolarevic, 2003). For example, a parametric model that directly exports machine toolpaths ensures that what is fabricated matches the design intent exactly, reducing miscommunication. Thus, in choosing technology, offices should consider their primary software platforms and ensure the fabrication method can integrate with them. This might involve using standardised file formats (STL, DXF, etc.) or investing in software plugins that bridge design and fabrication (for example, Grasshopper plugins for generating robotic toolpaths). A well-integrated workflow not only saves time but also enables rapid iteration - architects can tweak a design and immediately test it physically, tightening the feedback loop between drawing and making.

Scalability and Future-Proofing

Offices should consider the future trajectory of both their practice and the technology. A strategic choice is one that not only meets current needs but can scale up or adapt as the office grows and projects evolve. This might mean favouring technologies with a modular or upgradable nature. For example, an office could start with a mid-sized CNC router and later expand its capabilities (adding a 4th axis or a larger bed) if their projects demand larger components. Or they might invest in a multi-functional robot that can handle various tasks with different end-effectors, providing flexibility as new fabrication techniques emerge. Staying informed about industry trends is part of strategic technology choice. If a certain fabrication method is rapidly advancing in the industry (say, large-scale 3D concrete printing for building components), an office might not jump in immediately but could prepare by training staff or partnering on pilot projects, so as not to be left behind. There is evidence that conducting or participating in full-scale demonstrator projects can help organisations understand and adopt new fabrication technologies. For example, an analysis of the DFAB HOUSE project in Switzerland – which integrated several cutting-edge digital construction methods – concluded that such demonstrators effectively increase acceptance of novel techniques and reveal practical challenges to address (Graser et al., 2021). Portuguese offices could similarly engage in or study demonstrative projects to gauge which technologies are likely to yield long-term benefits. In a balanced approach, offices adopt proven, mature technologies that fit their current practice, while keeping an eye on emerging ones and being ready to incorporate them when they become viable and necessary. This

mindset ensures the office remains agile and "future-proof," adapting as the digital fabrication landscape evolves.

Choosing the right digital fabrication technologies involves matching the tool to the task, budget, and talent of the office. Portuguese architects have shown creativity in this decision-making: some opt to design for available industry tech (as in the Gomos prefab system leveraging existing factories), while others build small in-house labs for rapid prototyping and rely on external makerspaces for bigger endeavours. What is clear is that there is no one-size-fits-all solution. A strategic selection is contextual – it plays to an office's strengths and partnerships. By carefully evaluating needs, costs, skills, and workflow integration, offices can adopt fabrication technologies that genuinely enhance their practice, setting the stage for more ambitious digital fabrication use in the future.

6.2. Workforce & Skill Development for Digital Fabrication

Technologies alone cannot drive innovation without people who know how to use them creatively. Therefore, a critical component of strategic adoption is developing the workforce – the architects, designers, and technicians who will implement digital fabrication. This section examines the human capital side of the equation, outlining the essential skills needed in a digitally fabricating practice, the training programmes and industry collaborations that can cultivate those skills, and the broader cultural shifts in the architectural office and education needed to sustain a digital mindset. The Portuguese context provides both cautionary tales and hopeful examples. Many architecture offices report a significant skills gap, as digital fabrication expertise is not yet mainstream in architecture programs. Yet initiatives such as fabrication labs and specialised courses are working to bridge this gap.

Interview data from Portuguese offices consistently highlighted the challenge of finding staff proficient in computational design and fabrication tools. Most architects currently in practice learned these tools informally - through workshops or self-teaching - rather than formal education. This points to an urgent need for up-skilling the existing workforce and updating architectural curricula. Encouragingly, some offices have taken proactive steps: partnering with universities for research, sending employees to courses, or even hiring non-traditional experts (like programmers or fabrication specialists) into the team. As we discuss the subtopics, we will incorporate examples such as how one office trains new hires for two years to get them fluent in BIM and related tools (Annex E), or how another leveraged the global Fab Academy program to gain cutting-edge skills. Ultimately, digital fabrication's strategic adoption depends on people – and investing in people yields perhaps the highest return in the digital transformation of architectural practice.

6.2.1. Essential Skills for Digital Fabrication-Enabled Architectural Practices

Digital fabrication in architecture sits at the intersection of design, technology, and making. Accordingly, the skill set required is both broad and specialised: architects must be computational thinkers, savvy with software and machines, yet also understand materials and construction. Based on literature and professional insights, essential skills for a practice embracing digital fabrication include:

Computational Design & 3D Modelling

At the core is proficiency in the digital design tools that generate fabrication-ready models. Architects should be skilled in 3D modelling (e.g. Rhino, Revit, other BIM software) and especially in parametric and algorithmic design platforms (such as Grasshopper, Dynamo, or scripting languages). Parametric modelling skills are crucial because they allow rapid generation and adjustment of complex geometries which can then be sent to fabrication. In Portugal, practitioners noted that many new graduates still lack exposure to BIM or parametric tools – "Many students graduate without even knowing what BIM is! … We don't invest in what we should – which is, ultimately, innovation." (Annex E – Konceptness). This gap at the entry level indicates a need for better computational design training in schools. Kolarevic (2003) was already emphasizing two decades ago that architects must become fluent in 3D digital modelling and CAD/CAM processes to fully exploit the possibilities of digital manufacturing. However, progress in education has been uneven (Oxman, 2008). For current professionals, it underscores that a baseline skill for digital fabrication is the ability to produce precise, data-rich digital models. Without a solid, well-structured model, digital fabrication cannot proceed. Thus, offices aiming to integrate fabrication must ensure their teams are fluent in relevant software and in organising digital models for fabrication (e.g. understanding layers, tolerances, and file formats).

CAD–CAM Translation & Fabrication Software

Beyond design modelling, architects need skills on the CAM side – using software to translate designs into machine instructions. This might involve using slicing software for 3D printers, toolpath generation programs for CNC mills (e.g. MasterCAM, Fusion 360), or robotic programming interfaces. While not every architect must be a master machinist, having team members who understand how to set up a laser cutter file, choose cutting strategies, or define 3D print parameters is vital. In interviews, several Portuguese offices admitted they often lacked staff who could program CNC machines and had to rely on external technicians. Closing this skills gap is essential for autonomy in digital fabrication. Bob Sheil observes that when architects take on tasks traditionally done by fabricators, they essentially remove the skilled hand-craft from the process, which means the responsibility for craft shifts onto the designer (Sheil, 2012). In other words, if architects wish to digitally "craft" their projects, they must develop the operational skills to handle machines and fabrication software adeptly. Practically, this

means training in specific CAM tools and understanding machine capabilities and limitations – knowing about cutter types and speeds, 3D printer nozzle sizes and layer heights, robot reach and precision, etc. An architect with CAM knowledge can proactively adjust a design for better manufacturability, embodying the idea of "design for fabrication" (Sass & Oxman, 2006). These technical skills ensure that the beautiful digital model actually becomes a buildable physical artifact without incessant back-and-forth with fabricators.

Material and Tectonic Knowledge

Digital fabrication doesn't eliminate the need for understanding materials – in fact, it heightens it. Architects must know how different materials behave under digital processes: e.g. how plywood might splinter on a CNC router, how concrete cures in a 3D-printed layer, or how thermoplastics respond in an extruder. Awareness of material properties and fabrication-informed detailing is often termed "material intelligence." Menges (2012) advocates for activating material intelligence in computational design, meaning that architects design with an understanding of material behaviour and constraints from the outset. This skill involves selecting appropriate materials for digital fabrication (for example, choosing sheet materials for laser cutting that have consistent thickness and low burn, or choosing a printable polymer with sufficient strength for a given component). It also means designing joinery, connections, and tolerances with fabrication in mind – a digitally skilled architect will account for the kerf of a laser or the bit radius of a mill when detailing parts to fit. Traditional architectural knowledge of construction and detailing must merge with digital know-how. One might need to decide when a hand-finish or assembly jig is required after a CNC cut, or how to incorporate allowances for material shrinkage or machine error. Rather than viewing digital fabrication as fully automated, architects should develop what some call a "computational craft" approach – blending computer-aided precision with an artisan-like understanding of materials and making. This blended skill set helps ensure that the output of digital fabrication is not only technically successful but also meets aesthetic and functional goals (Burry, 2011).

Collaboration and Communication Skills

While often overlooked, soft skills are crucial in a digital fabrication-enabled practice. The process frequently involves interdisciplinary collaboration – architects working with software developers, engineers, contractors, or specialised fabricators. Being able to communicate design intent to a CNC technician or to interpret feedback from an engineer about a digitally fabricated structure is important. Furthermore, within an office, projects that use new fabrication methods demand more teamwork and knowledge sharing: younger staff might mentor senior architects on software, while senior architects impart design wisdom on the digital outputs. The ability to collaborate in this cross-pollination

environment is a skill in itself. One interviewee emphasized that their BIM and tech implementation succeeded only through internal "evangelisation" and persistent communication, even in the face of sceptics (Annex E – Konceptness). Externally, architects must also articulate to clients and consultants what digital fabrication entails and why it benefits the project. Presentation and negotiation skills remain important - to advocate for innovative methods and manage expectations. In sum, a digitally adept architect is not the solitary tech wizard in a corner; they are often a coordinator between the digital and physical realms, requiring teamwork and clear communication. Industry reports also highlight this: the RIBA & Microsoft (2018) survey noted that successful digital transformation often hinges on practices fostering collaborative cultures and effectively conveying the value of new technologies to clients.

Continuous Learning and Adaptability

Given the pace of technological change, one of the most essential "skills" is the capacity to continually learn and adapt. Digital fabrication tools and software are evolving rapidly; new machines, new materials, and new techniques appear every year. Therefore, a mindset of lifelong learning is indispensable. Architects should be comfortable updating their workflows, picking up new programming or scripting techniques, or experimenting with unfamiliar fabrication methods. Several Portuguese architects expressed that their adoption of digital tools was driven by "an enormous desire to discover new things" (Annex A – 18-25 Research Studio) – an attitude of curiosity and not settling for old ways. Cultivating this mindset in a team (for example, encouraging attendance at fabrication workshops, hackathons, or simply giving staff time to tinker in the lab) can be more valuable in the long run than any one technical skill. In a field where today's cutting-edge becomes tomorrow's standard, adaptability is king. Farmer (2016) bluntly warns that offices which stick stubbornly to outdated methods "will close in the next five years" – a stark reminder of the professional imperative to keep skills up to date. Thus, an essential trait of architects in the digital fabrication era is the willingness to learn continuously and embrace change. The most successful practitioners often describe themselves as perpetual students of technology, always experimenting and refining their craft.

The palette of skills needed for digital fabrication in architecture spans technical, creative, and collaborative domains. Portuguese practices, like others globally, are in a transition where these skills are unevenly distributed: many practicing architects need re-skilling, while newer generations bring digital prowess but may lack practical construction sense. Bridging this gap is critical. By defining the essential skills (from parametric modelling to CAM, from material savvy to teamwork), offices can identify what areas their staff needs to improve and plan targeted development programs. Over time,

as more architects gain these competencies, digital fabrication will shift from a niche expertise to an integrated part of the architectural skill set - a trend already visible in leading international offices and slowly taking root in Portugal.

6.2.2. Training programmes and Industry Collaboration

Developing the required skills in digital fabrication calls for proactive training and strong collaboration between the architectural profession, academia, and industry. In Portugal, as elsewhere, one of the biggest hurdles to adoption is the lack of formal training opportunities for practicing architects in these emerging tools. Traditional professional development has not kept pace with the rapid evolution of digital techniques. Therefore, innovative approaches to training have emerged: from in-house workshops and mentoring, to external courses, to global programs like the Fab Academy. At the same time, collaborations with industry – whether with tech companies, fabricators, or material suppliers – have proven invaluable for offices wanting to climb the learning curve of fabrication. This section discusses how targeted training initiatives and partnerships can address skill gaps and foster a culture of continuous improvement.

Academic and Continuing Education Programs

One strategy to bolster skills is through formal programs that provide structured learning in digital fabrication. In recent years, Portuguese universities and institutes have begun offering specialised courses, often inspired by models abroad. For example, ISCTE's Vitruvius FabLab integrates digital fabrication training into its architecture curriculum, exposing students to CNC milling, laser cutting, and 3D printing as part of their design offices. The University of Porto's Digital Fabrication Lab (DFL) not only engages students in research projects like the CorkCrete Arch, but also opens its facilities for workshops that include practicing architects. Such university labs act as training grounds where professionals can join short courses or collaborative investigations, effectively refreshing their skills in an academic environment. Indeed, Portuguese practitioners have called for educational reforms to build relevant competencies in digital tools (Oxman, 2008). Internationally, architecture schools are increasingly integrating "design-to-fabrication" workflows in offices, and researchers have noted positive pedagogical impacts (Celani, 2012). Beyond degree programs, continuing professional development (CPD) courses are vital for those already in practice. Some professional bodies and private institutes offer workshops on BIM, parametric design, and fabrication. For instance, the RIBA in the UK has introduced digital design and fabrication modules as part of CPD, and similar offerings are slowly appearing in Portugal. However, many architects still turn to international programs for cutting-edge content. A noteworthy example is the Fab Academy, a global 5-month intensive course in digital fabrication founded by Neil Gershenfeld of MIT. Fab Academy has had nodes in Portugal (such

as Fab Lab Lisboa or Fab Lab Benfica), making it possible for local professionals to obtain hands-on training in everything from 3D printing and CNC machining to electronics and code. The program connects students to a worldwide network through weekly lectures and project-based learning (Gershenfeld, 2012). Such exposure can be transformative: participants not only learn technical skills but also join a community of innovators. More architects taking advantage of Fab Academy or similar bootcamps (like the AA Visiting School workshops on computational design) could significantly upgrade the skill level in practice. Interviewees highlighted that investment in skills is "core to digital transformation" and that under-trained staff are a major bottleneck in Portugal. Thus, supporting more structured training programmes - whether through office sponsorship, government grants, or personal initiative - is a crucial step.

In-House Training and Knowledge Sharing

On an office level, many offices have initiated their own training methods to develop staff competencies. Larger offices may set up internal "knowledge teams" or R&D groups that hold regular workshops for the rest of the office. For example, an office might run a weekly session on parametric modelling techniques or invite a specialist to train the team on using a new 3D printer or robotic arm. Some Portuguese offices reported adopting a mentorship approach, where the more digitally skilled team members coach others. In one interview, a director noted that when they started implementing BIM and digital workflows, it became "a work in progress – whenever a new person joins, it takes two years of training" to bring them up to speed (Annex E). This indicates a long-term commitment: the office understands that continuous in-house training is needed and they plan for a ramp-up period for each employee. While two years is substantial, it reflects reality – mastery of these tools is not instant. By institutionalizing training (through documented best practices, peer learning sessions, and dedicating a portion of work hours to skill development), offices can create an internal culture of learning. Some smaller offices even pool resources for training: for instance, several small offices might jointly organise a Grasshopper workshop, sharing the costs and building an informal local network of practitioners who learn together. The key is acknowledging that digital fabrication skills require maintenance and updates, just like software licenses or machines do. Offices known for successful digital integration often treat learning as an integral part of their operations.

Collaboration with Industry and Fabricators

Collaboration serves as both a means of project delivery and a form of practical training. When architects partner with fabrication experts or manufacturers on a project, a two-way knowledge exchange occurs: architects learn the nuances of fabrication processes, while the fabricators understand the designer's perspective. In Portugal, where not every office can afford in-house

machinery, such collaborations are common and often necessary. For example, in the Oceanário (Lisbon Aquarium) extension project, architect Pedro Campos Costa worked closely with the Spanish ceramics manufacturer Cumella to develop the custom facade panels. Initially, Cumella's facility lacked certain digital fabrication capabilities for the ceramic pieces, but as the project evolved, they upgraded their equipment and leveraged a network of partners to fulfil the design. Through this process, the architecture team gained exposure to advanced fabrication constraints and techniques in ceramics, effectively "learning by doing" in collaboration with industry. Another case is Digitalab (led by Ana Fonseca), which has a strong relationship with a cork manufacturer (Sofalca) to fabricate innovative cork components for interiors. By collaborating on projects like the Óbidos Technological Park or the Cortiça series of furniture, the designers learned about industrial cork production, while the manufacturer explored new architectural applications. This symbiosis shows how industry collaboration can up-skill architects in material processes and simultaneously drive innovation for the manufacturer – a win-win scenario. These examples echo research findings that partnering with experts and fabricators can significantly accelerate the adoption of digital fabrication in practice (Graser et al., 2021). To encourage such partnerships, some interviewees suggested developing network hubs or consortiums where architects and tech companies regularly interface. The Fab Lab network and innovation hubs like Building Global Imagination (BGI) in Lisbon partly serve this function by providing neutral ground for experimentation and matchmaking between designers and technologists. Corporate-sponsored labs (e.g., automotive or aerospace companies sponsoring architectural fabrication challenges) also present opportunities for architects to get involved and learn.

Internationally, programs such as incubators or residency programs allow architects to spend time in fabrication-driven environments. Implementing similar initiatives in Portugal – for instance, an exchange where an architect can work within a robotics company for a few months – could be highly beneficial. One barrier noted by practitioners is the limited public support for architecture offices in tech collaborations: architects lamented that many innovation funding programs are aimed at "technology startups" or manufacturing offices, and architectural offices often struggle to qualify, as if they were not considered "digital" enterprises. This highlights a policy gap. If architects had more access to innovation grants or R&D tax incentives to acquire training and collaboration, it could accelerate knowledge transfer. As one interviewee from Atelier Peninsular said, "here in Portugal, everything came out of our pocket" regarding tech investments. Despite this, many offices continue to pursue collaborations out of necessity and passion, even if self-funded, because the learning gained is invaluable. In summary, forging partnerships - with academic labs, industry fabricators, or even among peer offices - serves both to distribute the risk/cost and to collectively raise the expertise in digital fabrication.

Workshops, Conferences, and Knowledge Networks

Another avenue for skill development is active participation in broader knowledge networks - attending conferences, publishing case studies, and joining professional forums. Globally, events like the FABRICATE conference, ACADIA (Association for Computer Aided Design in Architecture), CAADRIA, and eCAADe bring together cutting-edge academic research and real-world practice in digital fabrication. Portuguese architects who attend such events can bring back insights and techniques. For example, the Fabricate 2017 conference (held in Stuttgart) and its published proceedings highlighted numerous projects and technical advancements; these proceedings (Menges & Sheil, 2017) serve as rich resources for practitioners to learn from others' experiences. Similarly, the Lisbon Architecture Triennale has in past editions hosted workshops on computational design and making, which local architects could attend. Engaging with these forums helps architects build a network of contacts and keeps them updated on the state-of-the-art. Some offices allocate a budget for key team members to attend an international workshop or summer school on digital fabrication, recognizing it as an investment in the office's capability. Additionally, online communities and open-source platforms have grown significantly. Architects in Portugal can tap into global forums (such as the Grasshopper3D forum, Arduino maker communities, or specialised Facebook/Slack groups) to ask questions and share knowledge. This openness and exchange are part of the ethos of digital fabrication culture. Embracing these networks is part of the collaborative skill-building strategy - no office is an island, and learning from others' successes and failures can accelerate one's own progress. In essence, the offices that progress fastest in digital fabrication are often those most plugged into the wider community of practice, continuously absorbing and contributing knowledge.

Addressing the skill gap in digital fabrication requires a multi-pronged approach: formal education reforms, targeted professional courses, in-house training programmes, and robust collaborations with industry and academia. There are encouraging signs: a RIBA report (2018) found UK offices identifying lack of skills as a major challenge but also pointed out the rise of hybrid professionals – "part architect, part maker" – who combine design and fabrication expertise. Portuguese interviews and research mirror these findings. By expanding training initiatives (like making university fab labs accessible to practitioners, or sponsoring more architects to attend programs like Fab Academy) and fostering industry-academic partnerships, Portugal can build a pipeline of skilled professionals and up-skill current practitioners. A practical recommendation is for stakeholders – professional associations, universities, government bodies – to collaboratively fund and promote digital fabrication training, seeing it as essential for the AEC sector's innovation capacity. Ultimately, as more architects acquire the requisite skills, the easier it will be for each office to implement the strategies discussed in Section 7.1. The next section turns to the broader cultural dimension, examining how the ethos of the design office itself must evolve in tandem with these skills.

6.2.3. Rethinking Design Office Culture in a Digital Era

Adopting digital fabrication is not just about tools and skills – it entails a cultural shift in how architecture is practiced and taught. The traditional design office culture, both in universities and offices, has been centred on manual drafting, linear project phases, and a clear separation between designers and builders. The digital era challenges these conventions by introducing new modes of collaboration, iterative prototyping, and blurred boundaries between design and making. Rethinking design office culture means fostering an environment where experimentation with technology is valued, where failure is seen as a learning opportunity, and where hierarchical structures give way to more interdisciplinary and dynamic workflows. In Portugal, many interviewees noted cultural inertia as a barrier: a "conservative mindset" in both education and practice that can impede innovation. This section discusses how office culture is evolving – and needs to further evolve – in offices and schools alike to fully leverage digital fabrication.

From Linear to Iterative Workflows

Traditional practice often follows a linear sequence – concept design, then detailed design, then hand-off to contractors who build. Digital fabrication encourages a more iterative loop, where design and making inform each other continuously. In a digitally enabled office, architects might cycle rapidly between digital models and physical prototypes, testing ideas and refining them. This approach resembles a "design-build-test" loop common in product design or engineering. Culturally, it requires accepting that designs are provisional until tested with materials, and that the process may loop multiple times. Offices that have embraced this report more agility and innovation in outcomes. For example, one interviewee described how their team "immediately test[s] [a design] on a 3D printer, and return insights… into the model – all as part of one seamless process." Such practices break the old attitude that a drawing must be perfected before anything is made. Instead, it's understood that early prototypes (scale models, 1:1 fragments, etc.) are part of design development, not just presentation. This approach resonates with the concept of "design through making" (Sheil, 2005) where the act of making is integral to the design process itself. Research by Sass and Oxman (2006) similarly found that incorporating rapid prototyping early in design fosters an iterative, exploratory mindset, leading to more innovative solutions. Many offices are physically integrating fabrication into the office space – for instance, setting up a corner with a laser cutter or a small CNC where designers can quickly fabricate components. When a junior architect can laser-cut a sketch model to explain an idea to a senior colleague on the fly, the office's communication and creativity benefit. Glynn and Sheil (2011) have characterized this shift as "making as a form of inquiry," where continuous prototyping and testing become central to the design process. It transforms the workflow from a one-way street

into a cyclical, laboratory-like environment. Portuguese offices that lack this culture sometimes "adapt old ways of working to contemporary instruments – drawing as if they were still at a drafting table," missing out on the more radical workflow improvements. The goal of cultural change is to move beyond simply using new tools in old ways, and instead reconfigure the design process to exploit the tools' capabilities (for instance, using parametric scripts to generate dozens of options, then using 3D prints or VR to evaluate each, rather than sketching just two or three options). This iterative, experiment-driven workflow can lead to designs that are better resolved and more innovative.

Flattening Hierarchies and Evolving Roles

Digital practice often empowers younger architects or those with specialised tech skills, which can challenge traditional hierarchies in an office. A healthy cultural response is to recognise and leverage diverse expertise. In a conventional office, design ideas typically flow from the lead designer downward; in a digitally fluent office, innovation can come from any level, since a junior team member might know a parametric technique that opens new design possibilities. One interviewee (a younger architect) recounted facing resistance when proposing BIM to an older colleague, being told "you don't know what you're talking about" simply due to hierarchical mindset (Annex E). Overcoming this generational friction is key. Offices succeeding in digital integration often have leaders who are humble and open to learning from their teams. Some offices create hybrid roles like "Computational Design Lead" or "Digital Fabrication Specialist" – positions that might be filled by relatively young experts but are given authority to influence project workflows. This indicates a cultural shift where value is placed on knowledge and skill rather than just years of seniority. Additionally, collaboration tends to flatten hierarchy: in a design session involving parametric modelling or a robotic fabrication setup, the team might include an architect, a software coder, and a fabrication technician – all bringing different expertise to the table. Office culture must encourage respect across these disciplines and break down silos (e.g., not seeing the programmer as a mere consultant but as a co-designer). A collaborative office culture treats everyone as a learner when new technology is introduced. As observed in one case study, a practice like 18-25 Research Studio sees technology as "part of our DNA" – an intrinsic element that all team members engage with, not a separate domain reserved for a specialist. This inclusive approach helps the whole team buy into digital methods. It also mirrors calls in literature for more integrative practice. Kolarevic and Klinger (2008) described how digital workflows blur lines between design, engineering, and making – similarly, within the office, the lines between roles can become more fluid. The result can be a more empowered and innovative workforce, with juniors and seniors alike contributing in new ways.

Embracing Experimentation and Accepting Failure

Traditional architecture culture, especially in established offices or schools, sometimes fostered a myth of the lone genius and placed high stakes on a single "masterpiece" design. Digital fabrication culture, by contrast, is inherently experimental and iterative. The process of prototyping means some ideas will fail or need major revisions, and that's acceptable – even valuable, as it provides feedback and learning. Cultivating an office culture that celebrates experimentation and tolerates failures (as long as they occur early and inform improvement) is essential. This can be a big mindset change in environments where architects are used to polishing drawings to perfection before any physical test. To encourage this shift, some offices hold internal hackathons or "design-make" charrettes where teams have a day to build something playful or experimental with digital tools, with no penalty for failure. Such exercises build familiarity with the tools and reinforce the idea that not every attempt yields a perfect result on the first try. Mark Burry (2011) emphasizes that architects must develop new ways of thinking in the digital age, embracing complexity, iteration, and a tolerance for failure as part of the creative process. In practical terms, this might mean management explicitly allocating time and budget for prototyping in project schedules, understanding that a certain amount of trial-and-error at the design stage can prevent costly errors later and lead to breakthroughs. Some academic voices also note the importance of blending digital and analogue thinking – for example, an academic interviewee mentioned architects need to "tease out the relationship between CAD/CAM and traditional craftsmanship", essentially learning through trial where to rely on digital precision and where to allow human touch. Embracing this symbiosis of high-tech and hands-on experimentation can lead to a richer design process. In educational office culture, this means encouraging students to iterate through physical models (be it laser-cut study models or 3D-printed components) and not grading merely on a final presentation but on the process and what was learned from each prototype. Schools that incorporate design-build competitions, fabrication workshops, or collaborations with engineering are instilling this experimental ethos. Over time, as these students enter the profession, they carry an expectation that such experimentation is normal and necessary, gradually influencing practice norms.

Client and Stakeholder Engagement

Rethinking office culture also extends to how architects engage clients and other stakeholders in the design process. With digital fabrication and visualisation tools (like parametric models, VR/AR, and rapid prototyping), clients can be involved in more interactive ways. A progressive practice culture might invite clients to the office for a "design lab" session to see multiple 3D-printed facade studies or to experience a space in virtual reality before it's built, allowing their feedback to shape the design in real time. This participatory approach can improve trust and outcomes, but it requires a culture shift from the old model where architects guarded the process until presenting a near-finished scheme.

Many clients, once they see the tangible output of digital processes, become more enthusiastic and confident in the design (RIBA & Microsoft, 2018). For example, using VR, a design team and a client can virtually walk through a proposed building together and discuss changes on the spot – a level of engagement that was not possible before. Architects must be willing to share unfinished work and adapt quickly to input, which can be unfamiliar to those used to more controlled presentations. However, offices report that when clients are educated about and involved in the digital process, they appreciate the greater certainty and creativity it brings (for instance, spotting coordination issues early through BIM or customizing details through digital models). Thus, a digital-era office culture is often more inclusive, bringing in voices of clients, fabricators, and end-users earlier than traditional practice. This can be seen as part of a broader trend of co-design and open collaboration in design.

Linking Academia and Practice

It's important to note that the culture in professional offices often mirrors that of educational design offices – with a time lag. If schools encourage siloed thinking (e.g., treating digital fabrication as a separate technical module rather than part of core design), graduates carry that mindset into practice. Conversely, if schools foster integrative, hands-on, tech-savvy office culture, those graduates will seek or create similar environments in their workplaces. Therefore, rethinking design office culture is a dual task: universities in Portugal need to modernize pedagogical approaches, and offices need to consciously shape their office environment. Some positive signs include workshop collaborations where students and practitioners work together (for example, international programs like the Architectural Association's Visiting School in Lisbon, which focused on parametric fabrication, bringing students and local architects together). These create a shared culture and often break down the "academic vs. practice" divide – everyone becomes part of a continuum of learning and making. Oxman (2008) argued that design pedagogy must evolve to produce graduates capable of working in the new digital paradigm; a decade later, this is still a work in progress, but the momentum is there. Interview evidence supports this synergy: one office leader noted that hiring digitally skilled graduates and integrating them well can accelerate cultural change in the office, as the enthusiasm of youth spurs older colleagues to try new methods. Overcoming the "resistance to change" requires infusion of new mindsets and a willingness by leadership to listen and adapt, as discussed earlier.

Rethinking design office culture is about creating an ecosystem where digital fabrication and innovation thrive. In Portugal, the challenge is pronounced because of the historically conservative bent in both practice and academia. Yet the opportunities are equally strong: the presence of active fab labs, a generation of young designers eager to push boundaries, and examples of offices that have successfully integrated digital processes all point to a cultural transformation underway. By encouraging iterative design, flattening hierarchies, embracing experimentation, and tightly linking

education with practice, the architectural community can cultivate a culture in which digital fabrication is not viewed as a high-tech novelty but as a natural part of the design process. Offices that achieve this cultural shift report a "very natural connection with technology" permeating their work – in such offices, technology truly becomes intrinsic to creativity, enabling architects to reimagine their role. They are not only form-givers, but also makers and innovators, as comfortable in a fabrication workshop as they are in a drawing room. The architect of the digital era operates within an office culture that continuously learns, makes, and adapts, ensuring that Portugal's architectural practice remains vibrant and forward-looking in the face of global technological change.

From a broader theoretical perspective, the patterns observed in Portugal's digital fabrication uptake can be understood through lenses of innovation and socio-technical change. For instance, classic innovation diffusion models provide insight: Rogers' Diffusion of Innovations theory holds that adoption rates depend on perceived attributes like relative advantage, compatibility, complexity, trialability, and observability. In the Portuguese context, we see this theory borne out – clear advantages (e.g., improved precision or design capability) and opportunities for low-risk trials (pilot projects, academic prototypes) have been key to convincing architects to adopt new fabrication methods, whereas high complexity and cost have tempered enthusiasm. At the same time, socio-technical and organisational factors play a pivotal role. An actor-network theory perspective reminds us that technology adoption is not just a technical decision but a negotiation among human and non-human actors (architects, software, machines, clients, policies) within a network. Portugal's experience exemplifies this: successful integration of digital fabrication required aligning diverse "actors" – from skilled personnel and office leadership to accessible fab labs and supportive institutional frameworks – into a coherent network of practice. The Strategic Framework for Digitalisation of Architectural Practice (SFDAP) developed in Chapter 5 offers a cross-chapter synthesis to interpret these findings. SFDAP maps offices along dimensions of digital maturity and research engagement, and our case studies reinforced that combining technological advancement with an active research culture yields the most significant innovations. Applying the SFDAP lens comparatively reveals both resonances and tensions between Portuguese and international practice. On one hand, a few Portuguese offices occupy the high-maturity, high-research quadrant akin to global "digital pioneers," validating that local leaders can match the world's best in innovation. On the other hand, the majority of Portuguese offices fall into moderate or emerging digital maturity zones (Types 2 and 3 in our typology), indicating a lag behind the international frontier. This disparity underscores how context matters: factors such as office size, funding, and education in Portugal have modulated the pace of adoption compared to countries with more robust innovation ecosystems. Nonetheless, the core themes align with global trends. The identified drivers and barriers – need for skilled people, leadership and vision, cost constraints, cultural openness – echo findings in other contexts (for example, UK surveys by RIBA also

highlight skill gaps and the rise of hybrid "architect-makers"). In short, our discussion connects theory and evidence across chapters: it confirms that while digital fabrication's benefits are universal, its implementation is socio-technical and must be attuned to local realities, a nuance that enriches both the SFDAP framework and broader innovation theory.

Another critical dimension of this discussion is the impact of digital fabrication on power dynamics, labour roles, and authorship in architectural practice. The introduction of computational design and fabrication tools can subtly reconfigure hierarchies within offices. We observed cases where younger architects or junior team members, by virtue of their coding or parametric modelling expertise, assumed greater influence in design decision-making – effectively flattening traditional hierarchies. This shift challenges the conventional top-down flow of ideas; an office culture that values digital knowledge allows innovation to bubble up from any level, promoting a meritocracy of skills over age or title. In parallel, the nature of architectural labour is evolving. Architects are increasingly becoming "hybrid professionals" – what one report called "part architect, part maker" – blending design with hands-on making and computation. This raises questions about the future division of labour: will architects take on tasks traditionally done by fabricators and coders, or will we see new specialisations (e.g., computational designers, robotic fabrication specialists) formally integrated into practice? Our findings suggest augmentation rather than simple replacement of roles. Digital fabrication often automates tedious, repetitive tasks, freeing architects to focus on creative and managerial aspects – but it also demands that they acquire new technical skills. Traditional craftsmen and model-makers are not so much rendered obsolete as invited to up-skill and collaborate in new ways (for example, a model maker might become a fabrication lab manager). Power can shift externally as well: as architects collaborate more with software developers or machine operators, the design process becomes a multi-authored venture, diluting the sole authority architects once held. This brings us to the question of authorship. The thesis has shown that authorship in the digital age becomes increasingly distributed. When a facade is generated by an algorithm and fabricated by a robot, who is the "author" – the architect who set the rules, the coder of the algorithm, or the machine? In theory, Mario Carpo's notion of the "second digital turn" posits that parametric tools and customisation challenge the Alberti-derived model of singular architectural authorship. Our evidence from Portugal confirms this tension: architects reported that using generative scripts made them feel more like curators of a design process than sole authors of a static object, aligning with Carpo's argument. Yet, rather than experiencing a loss of agency, many felt empowered by co-authoring with digital tools – they set the vision and constraints, and the computer explored permutations, extending their creative reach. This collaborative authorship, involving interdisciplinary input (architects working with engineers, software specialists, fabricators as equal partners), is redefining what it means to create architecture. It challenges architects to reassert their unique value – not by sole control over every line drawn, but by

orchestrating and integrating contributions from all participants (human or machine) into a coherent design. In summary, the strategic adoption of digital fabrication carries profound reflective implications: it can democratize innovation within offices, alter labour practices by blending design and making, and transform the notion of authorship from an individual act to a networked achievement. Acknowledging these shifts is essential for practitioners to navigate the cultural change that accompanies technological change.

6.3. Implementation Roadmap

Building on the findings of this research, a three-phase strategic roadmap is proposed to guide architectural offices in Portugal from initial experimentation to full digital integration. This roadmap consists of Phase 1: Initiation, Phase 2: Integration, and Phase 3: Innovation, each defined by increasing levels of digital maturity and research engagement. In Phase 1, an office pilots a small fabrication project and trains key staff; in Phase 2, the office invests in core fabrication equipment and incorporates digital workflows into standard projects; by Phase 3, the office establishes dedicated R&D teams and pursues experimental work as part of its practice. Each phase can be tailored to an office's specific context, but the general progression ensures manageable, stepwise growth in capability. Notably, this phased roadmap aligns with the international practice typologies identified earlier: Type 3 "Digitally Emerging" practices (low digital maturity and research engagement, DM ≈ 2–3, RE ≈ 2–3) correspond to the Initiation phase, Type 2 "Digital Innovators" (moderate maturity, DM = 4, RE = 4) align with the Integration phase, and Type 1 "Digital Pioneers" (high maturity, DM = 5, RE = 5) embody the Innovation phase. In other words, the roadmap is a structured path for a Portuguese office to evolve from a Digitally Emerging profile into an Innovator and ultimately a Pioneer in the realm of digital fabrication. To aid in planning, Figure 6.1 presents a timeline of these three phases and their key milestones, while Table 6.1 compares each phase's goals, actions, and required capabilities. Additionally, a conceptual diagram (Figure 6.1) relates the typologies to the roadmap, illustrating how progressing through Phases 1–3 raises an office's digital maturity and research engagement over time.

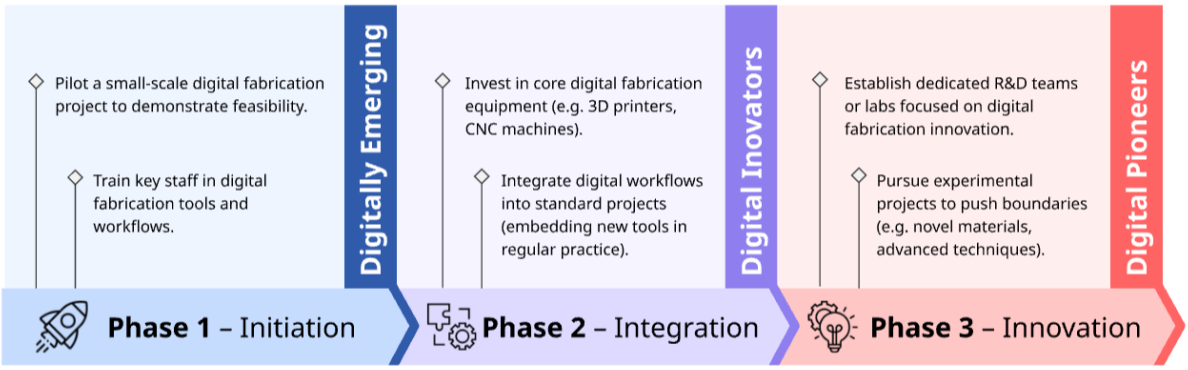


Figure 6.1: Timeline showing Phase 1 (Initiation) → Phase 2 (Integration) → Phase 3 (Innovation), with milestone for each phase.

Each phase is sequential, building on the previous to ensure manageable growth in the office's digital fabrication capability. This progression means that as an office moves from Initiation to Integration to Innovation, it evolves from mainly consuming external knowledge to actively producing new knowledge, while its use of digital tools grows from ad-hoc or basic to fully integrated and cutting-edge. In essence, moving through the three phases raises the office's digital capability and research engagement in tandem – transforming an initially tentative adopter into a mature, innovation-leading practice. The roadmap thus aligns with the typologies: Phase 1 offices typically map to the Digitally Emerging category, Phase 2 to Digital Innovators, and Phase 3 to Digital Pioneers, highlighting the path toward greater digital maturity and a deeper research orientation over time.

Table 6.1: Goals, Actions, and Capabilities by Phase.

Phase	**Goals (What to achieve)**	**Key Actions (How to achieve)**	**Required Capabilities (Needed to succeed)**
Phase 1 – Initiation	*Kickstart digital fabrication with minimal risk*	• Pilot a small fabrication project (proof of concept)	• Basic digital fabrication knowledge among staff
	Build initial internal support and skills	• Provide training for core staff on digital tools/workflows	• Management buy-in for experimentation
			• Access to entry-level fabrication tools (in-house or via partners)

Phase 2 – Integration	*Embed digital fabrication into regular practice*	• Invest in core fabrication equipment (e.g. CNC, 3D printers)	• Technically skilled staff to operate and maintain new tools
	Scale up use of digital workflows across projects	• Implement digital processes in standard design and construction projects	• Updated workflows integrating digital and traditional methods
			• Budget allocation for technology and training
Phase 3 – Innovation	*Lead industry innovation via digital fabrication*	• Establish a dedicated R&D team or innovation lab	• Advanced in-house expertise in digital fabrication and research
	Institutionalize continuous R&D and improvement	• Undertake experimental projects using advanced fabrication techniques	• Strong innovation culture supported by leadership
			• External partnerships for knowledge exchange (e.g. with universities)

The table synthesises the implementation pathway by outlining, for each phase, **(1) primary goals; (2) key actions; and (3) required organisational and technical capabilities**:

Phase 1 – Initiation
Goals: Introduce digital fabrication into architectural practice and establish initial familiarity.
Actions: Launch a pilot project; provide targeted training for a core group of staff in selected digital tools and fabrication methods.
Capabilities: Basic computational design literacy and foundational machine-operation skills.

Phase 2 – Integration
Goals: Scale up digital fabrication activities and embed them within routine design workflows.
Actions: Invest in core fabrication equipment; formalise and standardise digital design-to-production workflows across projects.
Capabilities: Cross-disciplinary collaboration, coordination between design and production teams, and data-driven design methodologies.

Phase 3 – Innovation
Goals: Position the office as a leader in design innovation and applied research.
Actions: Establish internal R&D teams or laboratories; undertake experimental or research-led projects in collaboration with external partners.
Capabilities: Advanced technical expertise, methodological experimentation, and the capacity to engage in research and industry–academia collaboration.

The accompanying conceptual diagram situates architectural offices along two intersecting axes: Digital Maturity (DM) on the horizontal axis and Research Engagement (RE) on the vertical axis, forming a 2×2 matrix. Progression across phases is represented as a diagonal trajectory from lower left to upper right, reflecting the co-evolution of technological capability and research orientation:

- **Type 3 – Digitally Emerging (Phase 1):** Characterised by low Digital Maturity (DM 2–3) and low Research Engagement (RE 2–3), located in the lower-left quadrant.
- **Type 2 – Digital Innovators (Phase 2):** Defined by medium levels of Digital Maturity (DM 4) and Research Engagement (RE 4), positioned at the midpoint of the trajectory.
- **Type 1 – Digital Pioneers (Phase 3):** Exhibiting the highest levels of Digital Maturity (DM 5) and Research Engagement (RE 5), situated in the upper-right quadrant.

Together, the phased table and the DM–RE matrix provide a structured yet flexible model for understanding how architectural offices can progressively integrate digital fabrication, moving from initial adoption to embedded practice and, ultimately, to innovation-led leadership.

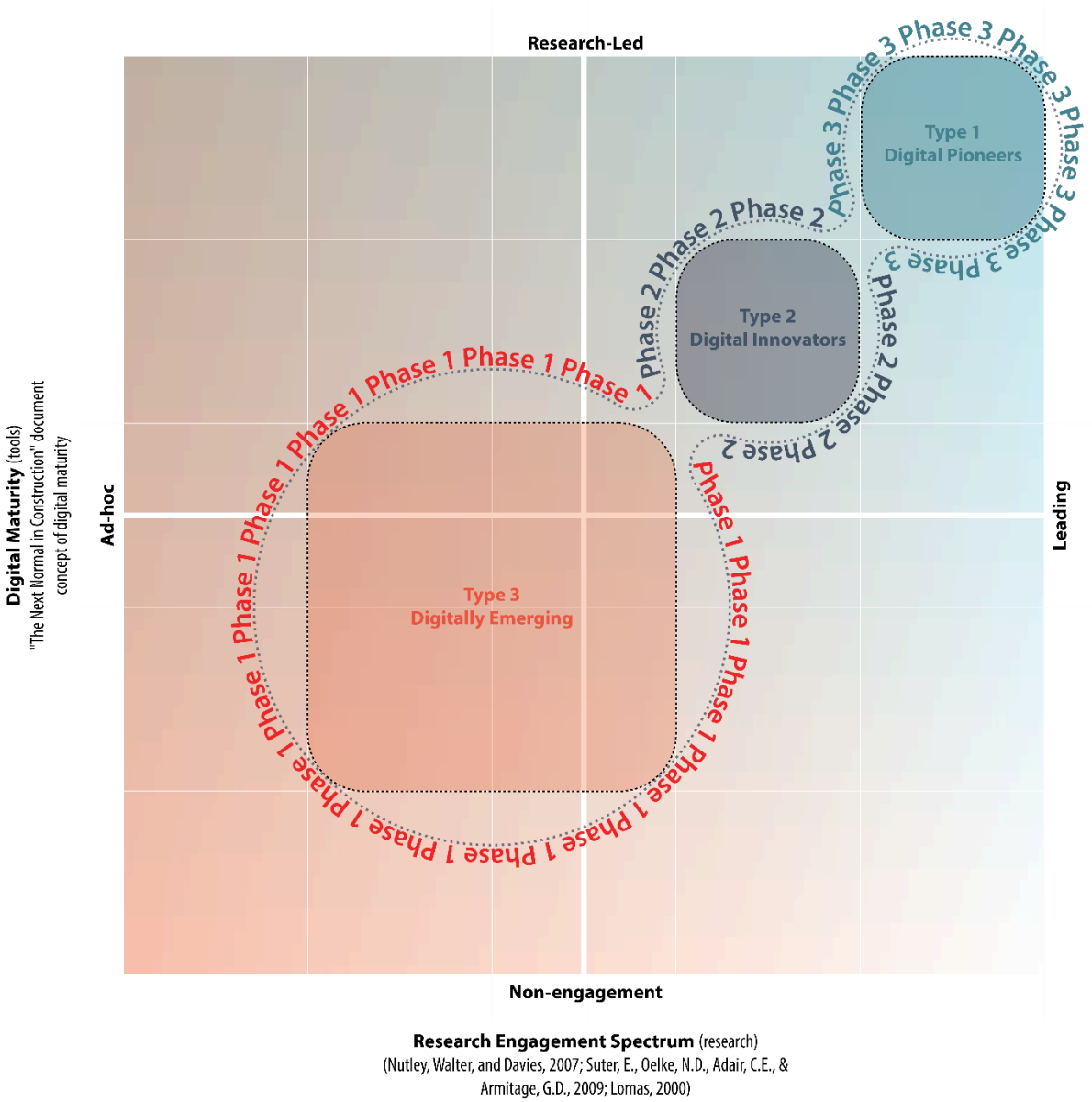


Figure 6.2: Conceptual diagram of Digital Maturity vs. Research Engagement Matrix vs. Phases.

Phase 1: Initiation – Pilot Projects & Skill Development

Initiation marks the beginning of an office's digital fabrication journey. In this stage, the goal is to start small and build foundational capacity. Offices pilot a limited-scope digital fabrication project (for instance, a custom installation, furniture piece, or a facade prototype) to demonstrate feasibility and learn by doing. A key strategy is to identify and train a core team or "champions" among the staff who can drive the initiative. Early training may involve workshops, courses, or collaboration with academic fab labs to quickly upskill the team. At this phase, digital fabrication is still peripheral to the office's main operations, so the emphasis is on incremental adoption and minimizing risk. Many "Digitally Emerging" practices operate in this mode: they possess only modest digital capabilities (e.g. basic 3D modelling or entry-level BIM) and undertake digital experiments on an ad-hoc basis. Best practices for

Phase 1 offices are accordingly pragmatic. These include investing in basic digital tools and foundational BIM skills, using simple parametric design plugins, and outsourcing fabrication when needed. In the Portuguese context, leveraging external resources is often crucial at this stage. For example, rather than immediately purchasing expensive machinery, a small office might use local makerspaces or university facilities (such as FabLab Lisboa or other Fab Labs) to fabricate parts, taking advantage of their CNC routers, laser cutters, or 3D printers available at low cost. This approach allows experimentation without heavy capital investment, mirroring the Fab Lab movement's ethos of shared access to fabrication tools. By the end of Phase 1, the office should have a successful pilot project (or prototype) and a nascent internal skill base, providing proof-of-concept that digital fabrication can add value to their work.

Key Phase 1 actions and goals include:

- **Pilot Project:** Execute a small-scale digital fabrication project (e.g. a pavilion, prototype component, or installation) to test workflows and demonstrate technical viability.
- **Staff Training:** Designate key staff members as digital fabrication leads and support their training through workshops or collaborations, ensuring the office builds in-house know-how.
- **External Collaboration:** Partner with fabrication labs, universities, or specialist consultants to access equipment and expertise. This reduces cost and risk while the office learns how to integrate new tools.
- **Process Documentation:** Document lessons learned from the pilot (what worked, what didn't) to build institutional knowledge and inform subsequent phases.

By focusing on a manageable pilot and skill-building, Phase 1 lays the groundwork for more ambitious integration. Many offices at this stage remain in the Type 3 (Emerging) category, demonstrating "a general awareness influencing their thinking" but only basic application of digital techniques. For instance, London-based office AL_A was noted to utilize BIM and occasionally prototype innovative ideas in one-off installations, yet these efforts were intermittent and relied on established methods. Similarly, Asif Khan Studio (UK), rated at the low end (DM=2, RE=2), produced inventive designs with the help of occasional digital experiments, but its overall toolkit and research input remained rudimentary compared to leading offices. These examples illustrate the Initiation phase: a period of exploration where digital fabrication is tested in isolated cases before it becomes a routine part of practice. The positive outcome of Phase 1 is confidence – an office gains enough

exposure to digital fabrication to envision broader applications, setting the stage for deeper integration in Phase 2.

Phase 2: Integration – Embedding Digital Workflows in Practice

Integration, digital fabrication moves from the periphery to the core of the office's standard workflows. After a successful pilot, the office now invests in key equipment and process integration so that computational design and fabrication tools become a regular part of project delivery. This often means acquiring or securing access to core digital fabrication hardware (such as a CNC milling machine, laser cutter, or medium-scale 3D printer) that addresses the office's project needs. Alongside hardware, Phase 2 focuses on process and culture changes: establishing protocols to incorporate digital fabrication in typical project phases (design, detailing, and construction) and ensuring broad staff buy-in and training. Many offices at this stage are approaching the "Digital Innovator" profile (DM ~4, RE ~4), having moved beyond ad-hoc experiments to a structured digital strategy. They likely have fully integrated BIM and parametric design in their daily work and are experimenting with advanced tools (like computational analysis, VR/AR, or direct fabrication techniques) on select projects. Crucially, their engagement with research, while not as pervasive as in Phase 3, becomes more systematic – for example, they may incorporate lessons from industry research or collaborate on targeted innovation projects.

During Integration, offices formalize internal structures to sustain innovation. It is common to form a dedicated "digital innovation" committee or a small R&D task force that guides new tool adoption and monitors progress. These teams coordinate training, evaluate emerging technologies, and champion digital methods across the office. Some mid-sized practices even establish an internal innovation unit (as 3XN did with its GXN division) to facilitate research collaborations and ensure knowledge flows into projects. Externally, Phase 2 offices often seek out partnerships – participating in research consortiums, industry workshops, or design competitions – as a way to spur creative uses of technology and stay at the forefront. Such activities exemplify Nutley et al.'s notion of instrumental use of research (directly applying new findings in practice), with elements of process use (engaging in research activities) to solve real-world design problems.

A hallmark of Phase 2 is that digital fabrication is now applied in billable projects, not just isolated pilots. For Portuguese offices, this phase might involve integrating a CAD-CAM workflow for custom building elements or using robotic fabrication for a signature design feature in a client project. A case in point is the Lisbon Oceanarium extension (by Campos Costa Arquitectos), where the architects needed non-repetitive, custom ceramic facade pieces. Rather than defaulting to conventional methods, the team explored a digitally fabricated solution through a ceramic supplier employing robotic manufacturing – effectively bringing an Industry 4.0 technique into a mainstream project.

Similarly, SUMMARY Architects (a small Portuguese practice) developed the Gomos modular housing system in collaboration with a precast concrete factory, leveraging CNC-milled formwork and off-site fabrication to produce complete building modules. This approach allowed SUMMARY to achieve an innovative construction solution without having to invest in expensive machinery like a 3D concrete printer in-house. Such examples illustrate the resourcefulness of Phase 2: offices integrate advanced fabrication by either investing strategically in equipment or by partnering with industry to access capabilities, aligning the technology choice with project-specific needs and the office's scale. By doing so, even smaller offices can punch above their weight – using external digital fabrication resources to deliver novel design outcomes that would typically require a larger R&D capacity.

Key Phase 2 actions and goals include:

- **Core Equipment Investment:** Acquire or arrange access to essential digital fabrication tools (e.g. a CNC router, laser cutter, or large-format 3D printer) that match the office's project types and scale. Ensure staff are trained to use these tools effectively.
- **Workflow Integration:** Incorporate digital fabrication into the standard project workflow. For example, develop guidelines for moving from parametric design models or BIM to fabrication files, and require a digital prototype or fabrication feasibility check during the design development phase of projects.
- **Dedicated Roles/Teams:** Establish a formal innovation committee or designate "digital fabrication leads" in the office. Their role is to continuously scout new technologies, run internal training, and maintain momentum for integration across all teams.
- **External Collaboration and Research:** Engage in applied R&D opportunities such as joint projects with universities, participation in innovation competitions, or government-funded technology pilots. These not only provide fresh knowledge but also signal the office's commitment to innovation, aiding internal culture change.
- **Policy and Culture Shift:** Leadership should adjust office routines and incentives to encourage experimentation – for instance, allocating time for teams to develop parametric alternatives for a project, or celebrating successful uses of digital fabrication in weekly design reviews. Over time, this builds a culture where digital methods are seen as integral to the office's design identity rather than optional add-ons.

By the conclusion of Phase 2, an office should consistently execute projects that benefit from digital fabrication. The practice will likely have transitioned into a Type 2 (Digital Innovator) profile, marked by "advanced" use of digital tools and moderate research engagement. A Phase 2 office, much

like noted Innovators such as Denmark's 3XN, demonstrates fully integrated computational design and has institutionalized innovation via mechanisms like GXN (3XN's internal R&D unit). They are not at the extreme frontier, but they are early adopters and adept adapters of proven technologies. These offices show how a structured adoption of mature digital tools – coupled with ongoing learning and selective research – can significantly enhance design capabilities and output quality. In short, Phase 2 embeds the "new" into the everyday: digital fabrication becomes a normal part of delivering architecture, improving efficiency and enabling designs that were previously impractical. This success sets the stage for Phase 3, where the office pushes beyond integration into genuine innovation leadership.

Phase 3: Innovation – R&D and Continuous Innovation

Innovation is characterized by the office fully embracing a continuous innovation model, where digital fabrication is not only integrated but constantly evolving through research. In this stage, a practice reaches a level comparable to the "Digital Pioneers" identified in our typology (DM=5, RE=5) – offices that operate at the cutting edge of architectural digitalisation with a deep culture of experimentation and learning. The hallmark of Phase 3 is the establishment of a formal R&D infrastructure within the office: for example, a dedicated research and fabrication lab, or a specialised "technology task force" with allocated budget and time to pursue exploratory projects. Digital Pioneers treat technology development as part of their business model; they routinely employ state-of-the-art tools (generative design algorithms, custom software, robotics, AI-driven fabrication techniques, etc.) and actively seek to develop new ones. Correspondingly, they maintain robust links with the broader knowledge ecosystem – collaborating with universities, industry partners, and professional forums to both use and create new knowledge in architecture. In essence, during Phase 3 an office becomes not just a consumer of digital fabrication technology but a contributor to its advancement.

Several shifts typically occur as an office enters Phase 3. First, experimental work and real projects begin to blur – the office might take on avant-garde commissions or self-initiated research projects (e.g. prototype structures, novel material systems, robotics research in construction) to drive innovation. Such projects, even if not immediately profitable, are seen as investments in expertise that yield long-term benefits. For instance, Archi-Union in China (one of the Pioneer offices in our study) combines advanced robotic fabrication techniques with in-house material research, demonstrating how Phase 3 practices achieve top performance on both technology and research axes. Similarly, global design leaders like Arup, Snøhetta, or Zaha Hadid Architects illustrate the Phase 3 ethos: they invest heavily in computational design and fabrication, often co-developing custom tools, and they disseminate their innovations through publications and conferences as part of an open research culture. These offices have formalized innovation pipelines – for example, Zaha Hadid's CODE group (Computational Design research), or Arup's internal research teams – which ensure a steady output of

new ideas and methods that feed back into practice. Another indicator of Phase 3 is a mindset of "early adoption": Pioneer offices tend to adopt emerging technologies early (sometimes even in beta or through joint development with tech providers) to stay ahead of the curve. They also prioritize knowledge sharing and community building, recognizing that disseminating their research enhances their reputation and spurs further innovation industry-wide.

For Portuguese offices reaching this phase, the implications are transformative. A Phase 3 office in Portugal would likely be the reference point nationally for digital fabrication in architecture – akin to what we see internationally with pioneer offices. It would have a stable of ongoing research collaborations (perhaps EU innovation projects or academic partnerships with local universities like IST or FAUP) and might host its own fabrication workshop with custom-built tools or robotics. While many Pioneers globally are large offices, it is noteworthy that scale is not the only path to Phase 3. Some smaller offices attain pioneer status through focused excellence; for example, Studio RAP in the Netherlands (≈7 employees) excelled in robotic fabrication for complex timber structures and thus scored as a Pioneer in our analysis despite its small size. This suggests that Portuguese offices with niche specialisation can also leapfrog into high innovation status by concentrating efforts on a particular aspect of digital fabrication (for instance, a practice could become a leader in 3D-printed rammed earth construction or robotic tile fabrication, in partnership with local materials industries). The key is that Phase 3 offices devote significant effort to research & development and treat it as integral to their identity, not an auxiliary function.

Key Phase 3 actions and goals include:

- **Establish R&D Lab:** Create a formal internal R&D unit or "digital fabrication lab" within the office, staffed with a mix of architects and specialists (computational designers, material scientists, etc.). This unit drives experimental projects, technology scouting, and prototyping of new construction methods, keeping the office on the cutting edge.
- **Innovate and Experiment:** Pursue ambitious experimental work alongside fee-earning projects. This could involve developing custom digital fabrication techniques (e.g., new toolpaths, custom robotic end-effectors, material processes) and implementing pilot projects that test these innovations in real-world scenarios. Some experiments might be done in collaboration with academic or industry partners to share risk and expertise.
- **Continuous Training and Hiring:** Continuously invest in expanding the team's skill set. Phase 3 offices often hire specialists or sponsor advanced education for staff, ensuring knowledge of the latest algorithms, software, and fabrication methods. They also foster an internal culture of knowledge exchange (e.g., weekly "tech talks" or cross-team workshops) so that innovations permeate the whole practice.

- **Thought Leadership and Knowledge Sharing:** Act as a thought leader in the architecture community. This includes publishing research outcomes, presenting at conferences, and contributing to open-source design/fabrication tools. Such dissemination not only raises the office's profile but also reinforces an internal ethos that values learning and innovation for its own sake.
- **Evaluating New Opportunities:** Regularly reassess and update the office's technology roadmap. Phase 3 is not a static end-state but a commitment to continual evolution. Offices at this level might annually review emerging technologies (AI in construction, new materials, IoT for fabrication, etc.) and allocate resources to pilot those with high potential. They also develop metrics for innovation performance – for example, tracking how experimental techniques improve design quality or efficiency – to justify R&D investments to stakeholders.

By reaching Phase 3, an office achieves a high level of digital maturity and research engagement that enables it to redefine architectural practice. It exemplifies how integrating cutting-edge tools with a research-driven mindset can push design boundaries and yield original solutions. In practice, these "Digital Pioneer" offices continuously innovate and often set new paradigms that others emulate. The reward for a Phase 3 office is not just prestige, but tangible competitive advantage – they can tackle complex projects that others cannot, deliver higher performance buildings, and adapt swiftly as technology advances. For the Portuguese AEC industry at large, cultivating a cohort of Phase 3 practitioners would mean having home-grown exemplars of digital fabrication excellence. This can create a positive feedback loop: as local pioneers prove the value of such innovation (through, say, iconic projects or efficiency gains), more offices and clients become receptive to investing in digital fabrication, thereby raising the innovation baseline of the entire industry.

From Initiation to Innovation: Toward Homing the Machine in Practice

The three phases above outline a scalable journey for offices to elevate their digital fabrication capabilities, moving from tentative beginnings to pioneering innovation. While presented linearly for clarity, in reality offices may cycle through iterations of these phases – for example, initiating a new experimental sub-project even during Phase 2 integration, or temporarily refocusing on integration if a leadership change occurs. The roadmap is meant to be flexible, yet its phased structure provides a clear strategic vision: start small, integrate thoroughly, then innovate continuously. A visual summary is provided in Table 6.1 (comparing the objectives, actions, and new capabilities gained in each phase), which can serve as a quick-reference for offices plotting their digital transformation strategy.

It is important to note that this roadmap is not only about technology adoption, but also about cultural change within architectural practice. Each step requires shifts in mindset – from openness to experiment in Phase 1, to cross-disciplinary collaboration in Phase 2, to a research-driven culture in Phase 3. As one Portuguese office leader aptly noted, the ultimate goal is for digital tools to become "intrinsic to our way of designing," not a novelty or afterthought. In other words, the office evolves such that digital fabrication is woven into its design DNA. This echoes Farmer's warning to the construction industry: those who fail to modernize and embrace innovation risk irrelevance or obsolescence. The phased roadmap mitigates that risk by providing a structured path to modernisation, ensuring that even resource-constrained offices can progress incrementally rather than being left behind. Indeed, international patterns support this stepped approach – research shows that Digitally Emerging offices benefit from incremental adoption and external knowledge sources until they have the capacity to build in-house expertise, whereas the most transformative innovations happen when high technical adoption is paired with active research engagement.

Ultimately, the aim of this roadmap is to embed digital fabrication at the core of architectural practice in Portugal. It is about moving digital fabrication from isolated "fab lab" experiments or one-off showcase pavilions into the everyday realities of how buildings are designed and constructed. In summary, "homing" the machine in architecture – to borrow Canizares and Cohen's (2024) metaphor – means bringing digital fabrication from the fringes into the heart of architectural practice. The strategies outlined in this section provide a practical guide for Portuguese offices (and others) to do exactly that: to ground the promise of digital fabrication in the reality of professional practice, ensuring that the next wave of architectural innovation is built not only in labs, but also on construction sites and in design offices. By following the Initiation–Integration–Innovation trajectory, an office effectively "homes" the digital fabrication machine – making it a familiar, trusted, and central member of the architectural team. This integration not only elevates the creative and technical capabilities of the practice but also contributes to a broader industry transformation where digital fabrication is standard practice. In achieving this, Portuguese architectural offices will be positioned at the forefront of the digital turn, demonstrating how local innovation can thrive by strategically embracing global technological advancements. The roadmap, therefore, is more than a set of steps – it is a vision for the future of architectural practice, one in which the boundaries between designing and making are fluid, and where the architect's workshop is as digitally empowered as any fabrication lab, truly realizing the concept of homing the machine.

Conclusions and Future Work

This section offers a comprehensive overview of the research developed throughout the thesis. It begins by revisiting the initial motivations and key contributions outlined in the Introduction, followed by a summary of the methodology and main research activities. The section then presents the specific conclusions drawn from the study, along with a discussion of its limitations. It concludes by proposing potential directions for future research.

Conclusions

This thesis set out to investigate how digital fabrication can become an integral part of architectural practice rather than a peripheral experiment. The research confirmed the initial hypothesis: early and iterative integration of fabrication processes unlocks new creative possibilities and efficiencies in architecture. Through a mixed-methods approach (critical literature review, practitioner interviews, and case studies), we developed the Strategic Framework for Digital Architectural Practice (SFDAP) and a complementary process model. The SFDAP provides architects a new vocabulary and assessment tool to guide design-to-fabrication workflows. It was applied to both leading international offices and Portuguese offices, revealing shared trends and unique local challenges.

Portuguese offices often face more acute resource constraints, such as limited fabrication equipment and weaker institutional support, resulting in slower, more uneven integration than in well-resourced international practices. These findings illustrate that while the broad benefits of fabrication-informed design are consistent, local market size and policy context critically shape how rapidly and deeply offices can adopt these methods.

Key contributions of this work include: (1) a new framework and vocabulary for integrating digital fabrication into architectural workflows (the SFDAP), offering a clear model of digital maturity and research engagement; (2) a practical assessment tool (the SFDAP matrix) that helps position any office's digital practice and identify strategies for advancement; (3) a set of empirical case studies (international and Portuguese) that document current workflows, motivations, barriers and innovations; and (4) actionable guidelines (from Chapter 6) for architects, educators and policy-makers to foster adoption. Importantly, the SFDAP was developed not only as a strategic/matrix tool but as a design-research artifact – essentially an 'architectural device' to stimulate reflection. As the thesis explains, the SFDAP is a tool to aid architects and offices in reflecting on and strategizing their digital transformation. This dual nature means SFDAP both guides concrete workflow choices and serves as a conceptual framework through which architects can explore and orchestrate the design-to-fabrication process. Collectively, these contributions advance both our understanding and our capability,

strategically positioning digital fabrication as a driver of innovation in architecture and fostering a more collaborative, human–machine-augmented mode of practice for the future.

The thesis unfolded in three phases. Part I (Chapters 1–3) established the context and motivation: it reviewed the evolution of digital design and fabrication in architecture (the "digital turn"), and surveyed the state of practice (especially in Portugal). Part II (Chapters 4–5) presented the analysis and framework development. Chapter 4 formulated the SFDAP by synthesizing interview and case-study data into typologies of practice (Digital Pioneers, Innovators, Emerging) and identifying key parameters (digital maturity, research engagement, office size). We compared Portuguese offices to international benchmarks, highlighting how culture and resources shape adoption. Chapter 5 then proposed a process-based integration model that embeds fabrication awareness across all design phases. This workflow model was illustrated with diagrams and project examples showing how digital fabrication tools can loop material feedback back into design development. Part III (Chapter 6) translated these findings into practical guidelines and strategies. We presented organisational (culture, leadership, skills), technical (choosing and integrating tools), and educational recommendations. These steps ensure the research outcomes are actionable in real practice.

To explore this, the study was structured around three core research questions – regarding the embedding of fabrication knowledge in early design, the generative role of material and tooling constraints, and the translation of these insights into a practical framework. Each question is addressed below, focusing on actionable insights and synthesized findings.

- How can fabrication-informed methodologies be systematically embedded within the early stages of architectural design workflows, ensuring a coherent design-to-production continuum?

This study confirms that introducing digital fabrication considerations at the conceptual and schematic design stages fundamentally improves the design-to-production continuum. Rather than treating fabrication as a late-stage technical add-on, architects can systematically integrate fabrication-informed methodologies from the outset by reconfiguring workflows and team structures. For example, many of the observed practices engage in iterative prototyping and early material testing during concept design, which creates a continuous feedback loop between designing and making. This approach expands creative exploration (rather than constraining it) by grounding design decisions in real-world production parameters. As a result, projects maintain a tighter alignment between the initial concept and the final built artifact.

The thesis developed a process-based integration model to guide practitioners in embedding fabrication knowledge into early design phases. This model maps out practical steps – such as involving fabricators or material specialists in initial design charrettes, using computational design tools that

directly output fabrication-ready models, and requiring early proof-of-concept prototypes for critical components – to ensure that design and making evolve in tandem. The case studies provide clear evidence of the benefits: architectural offices that deliberately embed fabrication logic early report greater precision in building components, the ability to realise more complex geometries, and faster design–build feedback cycles. In one instance, an office's early use of CNC-milled study models informed their design adjustments in real time, reducing costly downstream changes. These findings demonstrate that a coherent design-to-production continuum is achievable when early-stage design is informed by "how it will be made". For everyday practice, this means architects should adopt a mindset where each design decision is made with fabrication in mind, leveraging digital tools and collaboration across disciplines right from project inception. By doing so, offices can reduce late-stage surprises and inefficiencies, improve constructability, and ultimately deliver more innovative architecture without compromising design intent. The actionable insight here is clear: making fabrication-awareness a standard part of early design workflows leads to a more seamless, creative, and efficient journey from concept to construction.

- In what ways can material constraints, tooling logics, and production methods operate as generative design drivers rather than downstream technical considerations?

This research illustrates that material constraints and fabrication tools can act as powerful catalysts for design innovation when embraced from the beginning. Instead of viewing material properties or tooling limitations as obstacles to be dealt with after design, leading practitioners treat them as generative design drivers. The findings show that when architects design with their materials and machines in mind, the process becomes more exploratory and collaborative. For instance, several case studies described how early engagement with robotic fabrication methods or 3D printing influenced the form-finding process – in one project, the geometric pattern of a façade emerged directly from the logic of the robotic toolpaths. Such examples underscore that fabrication methods, when introduced as design parameters, can inspire novel aesthetics and solutions that might not surface in a conventional workflow. Essentially, the "constraints" of production become fertile creative parameters, spurring architects to innovate structurally and formally in response.

One clear outcome is the transformation of collaboration models. Integrating material logics early tends to blur the traditional separation between designer and fabricator. The everyday practice implication is significant: treating production knowledge as integral to design encourages teams to develop cross-disciplinary skills (e.g. architects who understand tooling, fabricators who contribute to design dialogue) and results in more buildable, expressive outcomes. Moreover, offices reported that this approach reduces later-stage errors and redesign, as many technical issues are resolved early through informed design choices. In sum, the thesis demonstrates that material and fabrication

considerations can drive design originality and quality, rather than simply imposing limits. Architects in practice can harness this by adopting a "design-for-fabrication" mindset – using the realities of materials and machines as inspiration. When material constraints and tool logics guide the creative process from the start, projects benefit from both imaginative forms and practical feasibility, aligning creative ambition with technical reality. This proactive integration ultimately enriches architectural practice, turning what were once downstream checks into upstream design inspiration.

- How can these insights be translated into a practical, operational framework that enables architectural offices to integrate digital fabrication knowledge into everyday practice?

To move from insights to implementation, the research formulated a strategic framework – anchored by the Strategic Framework for Digital Architectural Practice (SFDAP) – that architects can use as a roadmap for integration. This framework, developed and refined through empirical study, serves as a practical toolkit to embed digital fabrication knowledge into the daily operations of architectural offices. By applying this framework to both international exemplars and Portuguese offices, the study validated that it captures real patterns: for instance, "innovator" offices typically invest in R&D units or in-house fabrication labs, whereas "emerging" offices rely more on external partnerships. Recognizing these typologies helps an office chart a path forward – an emerging office might decide to build a small prototyping team as a next step, inspired by what the pioneers have done. Importantly, the framework is not a one-size template; instead, it operates as an adaptive guide. The case applications showed that SFDAP is most effective when used flexibly – as a set of guiding principles and checklists that teams discuss and tailor to their context, rather than a rigid mandate. In practice, this means the framework can accommodate different scales of office, local constraints, or project types while still pointing towards greater integration of design and making.

Alongside the diagnostic framework, the thesis offers concrete strategies and recommendations to operationalise digital fabrication on a day-to-day basis. These actionable guidelines cover multiple dimensions of practice. On an organisational level, offices are advised to cultivate a culture of innovation – for example, setting aside time and budget for experimentation, encouraging collaboration between design staff and fabrication specialists, and having leadership champion these initiatives. On a technical/process level, the research provides steps such as aligning digital design tools with production tools (e.g. establishing workflows to export parametric or BIM models directly to fabrication file formats), and instituting routine "fabrication checks" during design development (much like traditional design reviews) to ensure feasibility is continuously evaluated. There are also recommendations for investing in the necessary infrastructure and skills: some offices might start by acquiring modest digital fabrication equipment (like a laser cutter or desktop 3D printer) to enable in-house experimentation, while others may form partnerships with local fab labs or makerspaces.

Critically, the framework highlights the human resources aspect – upskilling and education. The study found that many architects need additional training to fully leverage fabrication technologies, so it recommends ongoing professional development and even curricular changes in architectural education. For instance, offices could implement mentorship programs where tech-savvy staff train others in parametric modelling or CNC machining basics, and universities could integrate more "design-to-fabrication" exercises in their offices. By addressing organisational, technical, and educational factors together, the framework translates the thesis insights into an operational blueprint that regular practice can follow. The early adopters profiled in our case studies exemplify this: they did not just buy new tools, but also adapted their team structures and project workflows to truly integrate those tools into everyday work. The ultimate outcome of applying this framework is that an architectural office becomes fabrication-aware at every level – from design concept to final detailing, staff skillsets to office strategy. In daily practice, this means decisions from the smallest scale (e.g. choosing a joint detail) to the largest (e.g. pitching a project to a client) are informed by an understanding of digital fabrication's possibilities and constraints. This operational integration empowers offices to be more innovative and efficient, and to offer clients enhanced services (like customised fabrication solutions) as a competitive advantage. In short, the research provides practitioners with a practical pathway to embed digital fabrication knowledge into the very fabric of architectural practice.

Taken together, these conclusions signal a transformative shift in architectural practice, with disciplinary, professional, and educational implications. On a disciplinary level, the work contributes to the ongoing architectural discourse about the "digital turn" by grounding abstract theories of computational design and digital tectonics in concrete practice-based evidence. It demonstrates how the fusion of design and making – long discussed in theory – can actually be achieved in real projects, thereby enriching architectural theory with examples of material agency and co-authorship between humans and machines. This insight highlights a shift in architectural authorship: the creative process becomes co-produced by people, algorithms, and material systems. Indeed, the thesis observes that the notion of authorship thus becomes more distributed: the designer, the toolmakers, and even the end-users may all imprint on the final outcome. At the same time, form is increasingly determined by material and fabrication logics, a practical enactment of digital tectonics, which underscores a "situated making" perspective. In this view, each project's design is explicitly shaped by its material, technological and cultural context, reinforcing that designing and making are inseparable and context-dependent in contemporary practice. In professional terms, the findings offer a clear vision for the future of architecture offices. Embracing fabrication-informed design workflows can elevate an office's creative and technical capacity, positioning architects at the forefront of innovation in the construction industry. If widely adopted, the principles outlined here could lead to an industry-wide evolution

where digital fabrication is standard practice and the boundary between designing and constructing becomes increasingly fluid. Architects equipped with these methods will be able to deliver more ambitious designs with confidence that they can be built efficiently and faithfully. The research encapsulated in this thesis is more than a set of case studies and frameworks – it is a call to action for the architectural discipline. It advocates for a new paradigm in which the act of designing is intrinsically linked to the act of making, and in doing so, charts a path toward a practice of architecture that is more innovative, responsive, and attuned to the possibilities of the digital age. Such a shift holds promise not only for more inventive buildings but also for a more empowered generation of architects who see fabrication as an inherent part of their creative palette. The broader relevance of these findings resonates at all levels – inspiring scholars to further explore the design–fabrication continuum, guiding professionals to transform their workflows, and encouraging educators to prepare students for a future where the coherent integration of digital fabrication in everyday practice is the norm rather than the exception. However, the research also notes that adoption is often partial and experimental. Core challenges, especially cost, skill gaps, and perceived risk, remain significant barriers. In practice, many offices engage in tentative pilot projects and incremental workflow changes as they learn new technologies. Rather than viewing these obstacles as failures, the thesis emphasizes they are intrinsic to an evolving professional culture: learning to design-through-making involves trial-and-error. In this sense, intermittent adoption and uncertainty are not anomalies but expected characteristics of an innovative, experimental practice. Over time, these cautious strategies allow offices to build confidence and gradually integrate fabrication more fully.

It must be acknowledged that these conclusions come with certain limitations. First, the empirical base of the study was a purposive sample of offices already engaged with digital tools, which likely over-represents forward-thinking practitioners while under-representing those struggling or yet to begin (the findings therefore skew toward success factors and may not capture all barriers). Second, much of our evidence is qualitative – drawn from interviews, self-reported practices, and published cases – which introduces subjectivity and potential biases despite efforts to triangulate data. Third, the research has a contextual focus: the framework and insights were developed with a deep dive into the Portuguese architectural sector. While many conclusions have broader relevance, the results are most directly applicable to contexts with similar cultural and economic conditions. SFDAP's criteria, for instance, reflect assumptions of Western practice and may require adjustment elsewhere. In short, the tools and conclusions offered here should be seen as guiding frameworks, not one-size-fits-all prescriptions. Each office or region may need to calibrate the framework to local realities, and further validation (through longitudinal studies or broader surveys) would help test and refine its universal applicability.

Future Work

While this thesis provides a foundational framework and evidence for integrating digital fabrication into practice, it also opens up many avenues for further investigation. At a practical level, an immediate next step is to field-test the SFDAP and associated guidelines in real architectural projects. Partnering with an architecture office to implement the framework on live projects – in an action-research format – would offer valuable longitudinal validation. Observing an office's progress over time (as it adopts the recommended workflow changes and strategic steps) would reveal how practices evolve through the SFDAP stages in reality. Such an applied study would not only test the efficacy of the framework's recommendations but also likely uncover new challenges and insights. Another priority is to broaden the empirical scope of the research by applying the framework in diverse contexts globally. Expanding the sample to a larger set of offices in other countries (with different scales of practice and different technology adoption histories) would test the generalisability of our conclusions. Comparative analysis – for example, juxtaposing the Portuguese findings with data from Northern Europe, North America, or Asia – could reveal how local industry conditions influence the digital fabrication integration process. This broader study could refine the SFDAP model's dimensions or thresholds based on patterns observed in other contexts, ensuring the framework is robust and globally relevant.

On the technological frontier, future work should explore emerging digital tools and their integration into the design-to-fabrication pipeline. The rapid rise of AI-driven design generation and machine learning suggests rich new possibilities for "intelligent" fabrication-aware design systems. For instance, one could investigate integrating generative algorithms or AI co-design agents into the workflow so that real-time feedback offers fabrication-friendly design alternatives. What might it look like if an algorithm continuously optimises a building's form for structural efficiency or material minimalism, providing architects with options that are automatically constructible? Research might also identify new metrics for design evaluation when such optimisations are in play (e.g. measures of fabrication complexity or material waste). Similarly, advances in robotics and augmented/mixed reality present unexplored potential for architectural fabrication. Robotic construction techniques beyond today's linear toolpaths (such as autonomous swarm fabrication or on-site robotic assembly) could dramatically expand what is feasible. Mixed-reality interfaces might enable architects to virtually "inhabit" a fabrication process during design, seeing constraints and results before anything physical is produced. Investigating these technologies in the context of our framework would help keep SFDAP up-to-date and could inspire entirely new modes of practice. In short, there is ample room for research at the intersection of computational design, artificial intelligence, and robotic fabrication, ensuring that as technology evolves, architects remain at the forefront of harnessing it creatively.

Equally important are the socio-technical and ethical questions surrounding the digital integration of architecture. Future research should examine how increasing digitisation might alter the architect's role, professional identity, and collaboration culture. For example, if design authorship is increasingly shared with algorithms or automated processes, how does this impact the notion of the architect as creator? Questions of authorship and agency arise when machines contribute to form-making: further studies could delve into how architects negotiate creativity and control in such scenarios. There are also labour implications to consider. If more building components are prefabricated via automation (robots or CNC) rather than crafted on-site, the workforce dynamics in construction could shift significantly. Research could explore how to retrain or redeploy traditional fabricators and craftsmen in a digitally enriched construction industry, ensuring that human expertise is not lost but rather augmented. Additionally, as one industry expert we interviewed noted, client awareness and demand play a crucial role in adoption. Future studies might focus on communication and policy: for instance, how can architects better convey the value of digital fabrication to clients (in terms of quality, cost, or design opportunities), and what policy incentives or certifications could encourage clients and developers to embrace these innovative methods? Understanding the market and policy side of the equation would complement the technical integration framework, leading to more holistic strategies for change.

Looking further ahead, more visionary research directions emerge. One promising thread is the exploration of bi-directional digital-physical workflows, where feedback from the physical world loops directly back into the digital design environment. For example, a future study could develop a system where prototypes or construction components embedded with sensors send performance data (structural behaviour, assembly tolerances, etc.) to the architect's design software, enabling real-time adjustments – essentially closing the loop between designing and making in a continuous cycle. Another frontier is the idea of mass-customisation ecosystems for architecture. As advanced fabrication and automation enable producing non-standard building components at scale, architects could start delivering highly personalized buildings without cost penalties, blurring the line between traditional architecture and product design. Research could investigate the practical and economic models for such ecosystems, and how design processes would need to adapt when every building element can be unique. There is also scope to study interdisciplinary convergence: as architecture increasingly intersects with computer science, materials science, and artificial intelligence, we may see the rise of new hybrid fields – for instance, computational tectonics or robotic craft – that demand mixed expertise. Exploring these cross-disciplinary frameworks and their impact on architectural research and practice would be a forward-looking avenue, shedding light on what the profession might look like in decades to come. Finally, building on this thesis's vision of human–machine collaboration, future research should consider how we educate and prepare the next generation of architects for this

digitally enriched practice. What new pedagogical models would support students in becoming equally fluent in design, coding, and robotics? Investigating educational innovations – from revamped university curricula to hybrid architect-engineer training programmes – would not only address the skills gap identified in our conclusions, but also ensure that the profession continues to evolve in tandem with technology.

The journey toward fully integrated digital fabrication in architecture is just beginning, and each of these questions represents a step further on that path. The big challenges and opportunities ahead invite bold exploration by both researchers and practitioners. By pushing these boundaries, future work can ensure that the promise of digital tools is realised not just as technical innovation, but as a truly transformative force for a more sustainable, resilient, and visionary architectural practice.

References

Adu-Amankwa, N. A. N., Pour Rahimian, F., Dawood, N., & Park, C. (2023). Digital twins and blockchain technologies for building lifecycle management. Automation in Construction, 155, 105064. https://doi.org/10.1016/j.autcon.2023.105064

Aish, R., & Bredella, N. (2017). The evolution of architectural computing: From Building Modelling to Design Computation. Architectural Research Quarterly, 21(1), 65–73. https://doi.org/10.1017/S1359135517000185

Aksamija, A. (2016). Integrating Innovation in Architecture. Wiley.

American Institute of Architects. (2022). Technology impacting practice: "No member left behind" roadmap and framework for digital transformation. Special Report.

ArchDaily. (2013, December 8). Vaulted cork pavilion / Pedro de Azambuja Varela + Maria João de Oliveira + Emmanuel Novo. ArchDaily. Retrieved December 18, 2025, from https://www.archdaily.com/455127/vaulted-cork-pavillion-pedro-de-azambuja-varela-maria-joao-de-oliveira-emmanuel-novo

ArchDaily. (2021, August 3). Hybrid architecture: Combining digital design and vernacular crafts. ArchDaily. Retrieved December 18, 2025, from https://www.archdaily.com/968825/hybrid-architecture-combining-digital-design-and-vernacular-crafts

Architexturez. (2022, February 16). Cedric Price: "Technology is the answer, but what was the question?". Architexturez South Asia. Retrieved December 18, 2025, from https://architexturez.net/pst/az-cf-225034-1645022697

Ayres, P., Thomsen, M. R., Sheil, B., & Skavara, M. (Eds.). (2024). Fabricate 2024: Creating resourceful futures. UCL Press. https://doi.org/10.14324/111.9781800086340

Baptista, S., Paio, A., & Silva, B. (Eds.). (2013). Processos digitais: Perspetivas críticas portuguesas (ARQA, 106).

Barcelona City Council, Digital City. (n.d.). Digital Fab Lab Network. Retrieved December 18, 2025, from https://ajuntament.barcelona.cat/digital/en/technological-entrepreneurship-and-digital-talent/make-culture-digital-manufacturing/digital-fab-lab-network

Brandão, F. J. da S. (2022). Open reWall: Survey-to-production workflow for building renovation (PhD thesis, ISCTE - Instituto Universitário de Lisboa). Repositório ISCTE. Retrieved December 18, 2025, from http://hdl.handle.net/10071/28257

Brandão, F. J. S., & Sousa, J. (2015). Cork Shell Pavilion. Retrieved December 18, 2025, from https://filipebrandao.pt/project/cork-shell-pavilion/

Breen, J. (2008). The medium is the matter: Critical observations and strategic perspectives at half-time. First International Conference on Critical Digital: What Matter(s)?, 129–136.

Brell-Cokcan, S., & Braumann, J. (2012). Robotic fabrication in architecture, art and design. Springer.

Brown, A. (2025). Computing, AI and architecture: What destinations are we moving to? International Journal of Architectural Computing, 23(2), 333–338. https://doi.org/10.1177/14780771251346596

Brozovsky, J., Labonnote, N., & Vigren, O. (2024). Digital technologies in architecture, engineering, and construction. Automation in Construction, 158, 105212. https://doi.org/10.1016/j.autcon.2023.105212

Burry, J., & Burry, M. (2010). The new mathematics of architecture. Thames & Hudson.

Burry, J., Sabin, J., Sheil, B., & Skavara, M. (2020). Fabricate 2020: Making resilient architecture. UCL Press.

Burry, M. (2003). Blurring the lines: Mediating between analogue and digital skill sets. In A. Lucas (Ed.), Architectural Design: Surface Consciousness (Vol. 73, No. 2, pp. 110–118). London: Wiley.

Burry, M. (2005). Homo Faber: Digital fabrication and the return of the maker. In B. Sheil (Ed.), Architectural Design: Design through Making (Vol. 75, No. 4, pp. 30–37). London: Wiley.

Burry, M. (2006). Gaudí and CAD. ITcon, 11, 437–446.

Burry, M. (2011). Scripting cultures: Architectural design and programming. Wiley.

Burry, M. (Ed.). (2007). Gaudí unseen: Completing the Sagrada Família. Jovis.

Burry, M., & Burry, J. (2016). Prototyping for Architects. London: Thames & Hudson.

Cache, B. (1995). Earth moves: The furnishing of territories (A. Boyman, Trans.; M. Speaks, Ed.). MIT Press.

Callister, R. (2025). How to use RIBA 2020 Plan of Work: RIBA design stages explained. Retrieved December 18, 2025, from https://urbanistarchitecture.co.uk/riba-plan-of-work-stages/

Caneparo, L. (2013). Digital fabrication in architecture, engineering and construction. Springer.

Canizares, G., & Cohen, Z. (Eds.). (2024). Homing the machine in architecture. Routledge.

Carpenter, W., Setiawan, A., & Welty, C. (Eds.). (2023). Digital Fabrication and the Design Build Studio (1st ed.). Abingdon, UK: Routledge

Carpo, M. (2011). The Alphabet and the Algorithm. Cambridge, MA: MIT Press.

Carpo, M. (2013). The digital turn in architecture 1992–2012. Wiley.

Carpo, M. (2017). The second digital turn: Design beyond intelligence. MIT Press.

Carpo, M. (2023). Beyond Digital: Design and Automation at the End of Modernity. Cambridge, MA: MIT Press.

Carpo, M. (2025). AI Tectonics, or the culture wars of building technology. Architectural Intelligence, 4, Article 2. https://doi.org/10.1007/s44223-024-00081-0

Celani, G. (2012). Digital fabrication laboratories: Pedagogy and impacts on architectural education. Nexus Network Journal, 14(3), 469–482.

Centre for Studies in Architecture and Urbanism. (n.d.). Laboratório de Fabricação Digital [Digital Fabrication Laboratory]. CEAU/FAUP, University of Porto. Retrieved December 18, 2025, from https://ceau.arq.up.pt/pt/about/research-groups/laboratorio-de-fabricacao-digital

Chapman Taylor. (2023, October 18). Artificial intelligence and architecture: How it is evolving. Chapman Taylor. Retrieved December 18, 2025, from https://www.chapmantaylor.com/insights/artificial-intelligence-and-architecture-how-it-is-evolving

Codarin, S. (2021). The Robots Are Leaving the Cage. Imagining the Future of Construction. FORUM A+P Interdisciplinary Journal of Architecture and Built Environment, 84–94. https://doi.org/10.37199/f40002309

Corser, R. (2010). Fabricating architecture: Selected readings in digital design and manufacturing. Princeton Architectural Press.

Dai, S., Li, Y., Grace, K., & Globa, A. (2023). Towards Human-AI Collaborative Architectural Concept Design via Semantic AI. Computer-Aided Architectural Design Futures.

Danish AM Hub. (2024). Additive manufacturing in construction. Retrieved December 18, 2025, from https://am-hub.dk/construction

de Azambuja Varela, P., de Oliveira, M. J., & Novo, E. (2013). Stand Amorim Isolamentos - Concreta 2013. Retrieved December 18, 2025, from https://pedroazambujavarela.net/stand-amorim-concreta-2013/

Digital Fabrication Laboratory. (n.d.). About [Research group description]. CEAU/FAUP, University of Porto. Retrieved December 18, 2025, from https://dfl.arq.up.pt/about/

Domus. (2018, December 26). The first digital manufacturing laboratory for architecture and design in Africa. Domus. Retrieved December 18, 2025, from https://www.domusweb.it/en/design/2018/12/26/the-first-digital-manufacturing-laboratory-for-architecture-and-design-in-africa.html

Duarte, J. P. (2013). Form and architecture. Joelho, 5, 30–31. https://doi.org/10.14195/1647-8681_5_11

Dunn, N. (2012). Digital fabrication in architecture. Laurence King Publishing.

El Khateeb, S., Abdulghany, R. A., & Youssry, M. (2022). Digital fabrication as an approach for innovative architecture education. MSA Engineering Journal, 1(4). Retrieved December 18, 2025, from https://www.researchgate.net/publication/367376877_Digital_fabrication_as_an_approach_for_innovative_architecture_education

El Moussaoui, M. (2025, April 9). Redefining authorship: How AI is changing what it means to be an architect. CommonEdge. Retrieved December 18, 2025, from https://commonedge.org/redefining-authorship-how-ai-is-changing-what-it-means-to-be-an-architect/

ETH Zürich, Chair of Architecture and Urban Design. (n.d.). Keller Easterling: Medium design. ETH Zürich. Retrieved December 18, 2025, from https://www.nsl.ethz.ch/en/keller-easterling-medium-design/

ETH Zurich, School for Continuing Education. (n.d.). MAS ETH in Architecture and Digital Fabrication [Master's program description]. Retrieved December 18, 2025, from https://sce.ethz.ch/en/programmes-and-courses/search-current-courses/mas/mas-eth-dfab.html

ETH Zurich/Swiss Federal Institute of Technology. (2017). Digital fabrication in architecture. ScienceDaily. Retrieved December 18, 2025, from https://www.sciencedaily.com/releases/2017/02/170217160931.htm

European Commission. (2022, June 30). Shaping Europe's digital future — Digital Strategy. Publications Office of the European Union. Retrieved December 18, 2025, from https://digital-strategy.ec.europa.eu/en

European Commission. (n.d.). Industry 5.0: Towards a sustainable, human-centric and resilient European industry. Retrieved December 18, 2025, from https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en

Fab Foundation. (n.d.). Getting started with Fab Labs. Retrieved December 18, 2025, from https://fabfoundation.org/getting-started/

Fahfouhi, K., Freitas, D. M., Poullain, P., Craveiro, F., & Bártolo, H. (2023). Digital fabrication in construction industry in Africa. In Proceedings of the 2nd International Conference on Water Energy Food and Sustainability (ICoWEFS 2022) (pp. 470–479). Springer. https://doi.org/10.1007/978-3-031-26849-6_48

Farmer, M. (2016). The Farmer Review of the UK Construction Labour Model: Modernise or Die. Construction Leadership Council.

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. Qualitative Inquiry, 12(2), 219–245. Retrieved December 18, 2025, from https://vbn.aau.dk/ws/portalfiles/portal/3790172/BF_Qualitative_Inquiry_2006_vol_12_no_2_April_pp_219-245.pdf

Flyvbjerg, B. (2011). Five misunderstandings about case study research, corrected. In M. Savin-Baden & C. Howell Major (Eds.), Qualitative research: The essential guide to theory and practice (pp. 165–166). Routledge. Retrieved December 18, 2025, from https://www.researchgate.net/publication/235951966_Five_Misunderstandings_about_Case_Study_Research_Corrected

Fure, A. (2018, May 22). What does it really mean to be "post-digital" in architecture and beyond?. The Architect's Newspaper. Retrieved December 18, 2025, from https://www.archpaper.com/2018/05/postdigital-for-the-record/

Gamal, A., Nashaat, B., Shahda, M. M., & Nosier, S. R. (2024). Ten questions concerning the integration of digital fabrication techniques into the architectural design process. Architectural Engineering and Design Management, 20(1), 120–149. https://doi.org/10.1080/17452007.2023.2269559

Garber, R. (2014). BIM design: Realising the creative potential of building information modelling. Wiley.

García, R., & Costa, F. (2017). Opening digital fabrication: Transforming architectural education and practice. Springer.

Gengnagel, C. et al. (2013). Rethinking Prototyping (Design Modelling Symposium Proceedings). Berlin.

Gengnagel, C., et al. (2014). The Challenge of the Bespoke: Design, Simulation and Optimisation of a Computationally Designed Plywood Gridshell. Proc. eCAADe 2014.

Gengnagel, C., Kilian, A., & Burry, J. (2015). Design thinking in architectural practice: Collaboration and digital fabrication. In C. Gengnagel, E. Hamann, B. Dannecker, & G. Scheuermann (Eds.), Rethinking Prototyping (pp. 123–138). Springer.

Gengnagel, C., Kilian, A., & Menges, A. (2013). Material behaviour. In R. Oxman & R. Oxman (Eds.), Theories of the digital in architecture. Wiley.

Gengnagel, C., Kilian, A., & Nembrini, J. (2011). Structures as design strategies: Towards integrative and iterative design processes. In A. Menges & S. Ahlquist (Eds.), Computational design thinking. Wiley.

Gershenfeld, N. (2005). Fab: The Coming Revolution on Your Desktop – from Personal Computers to Personal Fabrication. Basic Books.

Gershenfeld, N. (2012). How to make almost anything: The digital fabrication revolution. Foreign Affairs, 91(6), 43–57.

Get Therapy Birmingham. (n.d.). Parametricism: The new digital paradigm in architecture. Retrieved December 18, 2025, from https://gettherapybirmingham.com/parametricism-the-new-digital-paradigm-in-architecture/

Gibbons, S. (2016, July 31). Design Thinking 101. Nielsen Norman Group. Retrieved December 18, 2025, from https://www.nngroup.com/articles/design-thinking/

Giftthaler, M., Sandy, T., Dörfler, K., Brooks, I., Buckingham, M., Rey, G., Kohler, M., Gramazio, F., & Buchli, J. (2017). Mobile robotic fabrication at 1:1 scale: The in situ fabricator. arXiv preprint arXiv:1701.03573.

Glynn, R., & Shafiei, S. (2009). Digital Architecture, Passages Through Hinterlands.

Glynn, R., & Sheil, B. (Eds.). (2011). Fabricate 2011: Making Digital Architecture. UCL Press.

Glynn, R., & Sheil, B. (Eds.). (2013). Fabricate: Making digital architecture. Riverside Architectural Press.

Gramazio Kohler Research. (n.d.). Human-machine collaboration in computational design and robotic fabrication, ETH Zürich, 2018-2023. ETH Zürich. Retrieved December 18, 2025, from https://gramaziokohler.arch.ethz.ch/web/e/forschung/372.html

Gramazio, F., & Kohler, M. (2006). Digital materiality. Architectural Design, 76(4), 16–21.

Gramazio, F., & Kohler, M. (2008). Digital Materiality in Architecture. Baden: Lars Müller Publishers.

Gramazio, F., & Kohler, M. (2014). The Robotic Touch: How Robots Change Architecture. Zürich: Park Books.

Gramazio, F., Kohler, M., & Langenberg, S. (Eds.). (2014). Fabricate 2014: Negotiating design & making. UCL Press. https://doi.org/10.2307/j.ctt1tp3c5w

Graser, K., Kahlert, A., & Hall, D. M. (2021). DFAB House: Implications of a building-scale demonstrator for adoption of digital fabrication in AEC. Technology|Architecture + Design, 5(2), 219–232.

Hall, W. (2015). Brick. Phaidon Press.

Han, D., Zhao, W., Yin, H., Qu, M., Zhu, J., Ma, F., Ying, Y., & Pan, A. (2025). Large language models driven BIM-based DfMA method for free-form prefabricated buildings: Framework and a usefulness case study. Journal of Asian Architecture and Building Engineering, 24(3), 1500–1517. https://doi.org/10.1080/13467581.2024.2329351

Hauschild, M., & Karzel, R. (2011). Digital processes: Planning, designing, production. DETAIL Practice / De Gruyter Brill. https://doi.org/10.11129/detail.9783034614351

Hensel, M., & Nilsson, F. (2016). The Changing Shape of Practice: Integrating Research and Design in Architecture. Routledge.

Hensel, M., Menges, A., & Weinstock, M. (2006). Techniques and technologies in morphogenetic design. Wiley-Academy.

Herrera, P. C. (2016). Digital fabrication and revival craft in Latin America: Alliance between designers and artisans. Proceedings of the 10th International Conference on Design History and Design Studies. https://doi.org/10.5151/despro-icdhs2016-03_019

Hettiarachchi, C. (2019). Digital fabrication labs (FabLabs) for implementing Sustainable Development Goals (SDGs) in solidarity and social economy (SSE) in Sri Lanka [Conference presentation]. International Conference on the Localization of the SDGs and the Co-Construction of the Means of Implementation, Yonsei University, Wonju Campus, Republic of Korea. Retrieved December 18, 2025, from https://www.local2030.org/library/610/Digital-Fabrication-Labs-FabLabs-for-Implementing-Sustainable-Development-Goals-SDGs-in-Solidarity-and-Social-Economy-SSE-in-Sri-Lanka-.pdf

Hirsch, M., Benabdallah, G., Jacobs, J., & Peek, N. (2023). Nothing like compilation: How professional digital fabrication workflows go beyond extruding, milling, and machines. ACM Transactions on Computer-Human Interaction, 31(1).

HMH Architecture + Interiors. (2014, December 18). Design Process. Retrieved December 18, 2025, from https://hmhai.com/design-process/

Hsu, C. L., Wang, J. T., & Xie, H. J. (2024). Modelling exchange with blockchain for the collaborative design of a building envelope in BIM. Open Construction and Building Technology Journal, 18.

Hudson, D. (2013, June 16). Campos Costa Arquitectos extend the Lisbon Aquarium. Designboom. Retrieved December 18, 2025, from https://www.designboom.com/architecture/campos-costa-arquitectos-extend-the-lisbon-aquarium/

Interreg Europe Policy Learning Platform. (2022, May 16). Fab Labs: A flexible policy tool for place-based challenges [Web story]. Interreg Europe. Retrieved December 18, 2025, from https://www.interregeurope.eu/find-policy-solutions/stories/fab-labs-flexible-policy-tool-for-place-based-challenges

ISCTE – Instituto Universitário de Lisboa. (n.d.). Vitruvius FabLab. Retrieved December 18, 2025, from https://www.iscte-iul.pt/research-5303/laboratories

Iuorio, O., Wolf, A., Figueiredo, B., Knaack, U., & Cruz, P. J. S. (Eds.). (2025). AM perspectives 2: Research in advanced manufacturing for architecture and construction. Lab2PT; ISM+D; DABC; SOAP. ISBN 978-94-93439-04-7.

Iwamoto, L. (2009). Digital fabrications: Architectural and material techniques. Princeton Architectural Press.

Kieran, S., & Timberlake, J. (2004). Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction. New York: McGraw-Hill.

Kolarevic, B. (2001). Designing and manufacturing architecture in the digital age. Proc. eCAADe 2001.

Kolarevic, B. (2001). Digital fabrication: Manufacturing architecture in the information age. In W. Jabi (Ed.), Reinventing the discourse: How digital tools help bridge and transform research, education and practice in architecture: Proceedings of the 21st Annual Conference of the Association for Computer-Aided Design in Architecture (pp. 268–278). ACADIA.

Kolarevic, B. (2003). Architecture in the Digital Age: Design and Manufacturing. New York: Spon Press.

Kolarevic, B. (2008). The (Risky) Craft of Digital Making. In B. Kolarevic & K. Klinger (Eds.), Manufacturing Material Effects: Rethinking Design and Making in Architecture (pp. 119–128). New York: Routledge.

Kolarevic, B. (2015). From mass customisation to design "democratisation." Architectural Design, 85(6), 48–53. https://doi.org/10.1002/ad.1976

Kolarevic, B., & Klinger, K. (2013). Manufacturing material effects: Rethinking design and making in architecture. Routledge.

Kolarevic, B., & Klinger, K. (Eds.). (2008). Manufacturing material effects: Rethinking design and making in architecture. Routledge.

Kolarevic, B., & Malkawi, A. (2005). Performative architecture: Beyond instrumentality. Spon Press.

Lally, S., & Young, J. (2007). Softspace: From a representation of form to a simulation of space. Routledge.

Leach, N. (2009). Digital morphogenesis. Architectural Design, 79(1), 32–37.

Lloret-Fritschi, E., Ercan, S. J., & Jenny, D. J. (Guest Eds.). (2024). AD: Constructing Change [Special issue]. Architectural Design, 136 pp. Hoboken: Wiley.

Lynn, G. (1993). Architectural curvilinearity: The folded, the pliant and the supple. In Architectural Design, 63: Folding Architecture (pp. 24-31). Academy Editions.

Lynn, G. (1999). Animate form. Princeton Architectural Press.

Lynn, G. (Ed.). (2013). Archaeology of the Digital. Sternberg Press.

Manseau, A., & Seaden, G. (Eds.). (2001). Innovation in construction: An international review of public policies. Routledge.

Marble, S. (Ed.). (2012). Digital workflows in architecture: Design—assembly—industry. Birkhäuser.

Marcos, C. L., Garofalo, V., & Allepuz Pedreño, Á. (2024). Authorship, co-authorship, and creativity in architecture: Drawing, notation and representation. Architectural Projects, 13(26), Article 11. https://doi.org/10.18537/EST.V013.N026.A11

Martin, H., Watson, C., & Brooks, T. (2025). Synergizing BIM and RIBA in architectural practice – technology workflow efficiencies, challenges, and insights. Architectural Engineering and Design Management, 21(1), 35–59. https://doi.org/10.1080/17452007.2024.2361284

Massachusetts Institute of Technology, Department of Architecture. (2023, Spring). Architectural Design Workshop – Towards an understanding of potentials for AI in architectural design and fabrication [Workshop]. MIT Department of Architecture. Retrieved December 18, 2025, from https://architecture.mit.edu/classes/architectural-design-workshop-towards-understanding-potentials-ai-architectural-design-and

McCullough, M. (1996). Abstracting Craft: The Practiced Digital Hand. Cambridge, MA: MIT Press.

McKinsey & Company. (2020). The next normal in construction. Retrieved December 18, 2025, from https://www.mckinsey.com/capabilities/operations/our-insights/the-next-normal-in-construction-how-disruption-is-reshaping-the-worlds-largest-ecosystem

Menges, A. (2012). Material resourcefulness: Activating material information in computational design. Architectural Design, 82(2), 34–43.

Menges, A., & Ahlquist, S. (Eds.). (2011). Computational Design Thinking: Computation Design Thinking. Chichester: Wiley.

Menges, A., & Hensel, M. (2008). Designing morpho-ecologies: Versatility and vicissitude of heterogeneous space. Architectural Design, 78(2), 102–111.

Menges, A., Krieg, O. D., & Schwinn, T. (Eds.). (2016). Advancing wood architecture: A computational approach. Routledge. https://doi.org/10.4324/9781315678825

Menichinelli, M. (2019). A research through design framework from the evaluation of a meta-design platform for open and collaborative design and making processes. Proceedings of the Design Society: International Conference on Engineering Design, 1(1), 21–30. https://doi.org/10.1017/dsi.2019.5

Microsoft & Royal Institute of British Architects. (2018). Digital Transformation in Architecture. London: RIBA Publishing.

Mitterberger, D., Dörfler, K., Sandy, T., Salveridou, F., Hutter, M., Gramazio, F., & Kohler, M. (2020). Augmented bricklaying: Human-machine interaction for in situ assembly of complex brickwork using object-aware augmented reality. Construction Robotics, 4(3–4), 151–161. https://doi.org/10.1007/s41693-020-00035-8

Mortati, M. (2023). New design knowledge and the fifth order of design. Design Issues, 39(2), 21–31.

Myers, l. (2019, October 21). codesignlab builds a low-cost and off-grid housing prototype in cameroon. Designboom. Retrieved December 18, 2025, from https://www.designboom.com/architecture/codesignlab-african-fabbers-house-cameroon-10-21-2019/

Nagy, F., Mandour, A., & Abdelsabour, I. (2023). The digital transformation toward an integrated design process. Engineering Research Journal, 177(1), 31–58. https://doi.org/10.21608/erj.2023.293853

Neves, S., & Paio, A. (2016). Social challenges meet architecture – from participation to digital fabrication. In Architectural Research Addressing Societal Challenges. Routledge.

Neves, S., Beirão, J., & Rocha, J. (2017). The impact of digital fabrication in contemporary Portuguese architecture: Witnessing four practical cases. In M. J. de Oliveira & F. C. Osorio (Eds.), From Nature to Architectural Matter: Proceedings of Kine[SIS]tem 2017 (pp. 137–149). Lisbon: ISCTE-IUL.

Neves, S., Beirão, J., & Rocha, J. (2019). The impact of digital fabrication in contemporary Portuguese architecture. Retrieved December 18, 2025, from https://www.scribd.com/document/855675823/Kines-Ys

Newcastle University. (n.d.). Diffusion of innovations. OpenNCL. Retrieved December 18, 2025, from https://open.ncl.ac.uk/theories/8/diffusion-of-innovations/

Nicholas, P. (2021). Machining and machine learning: Extending architectural digital fabrication through AI. In The Routledge Companion to Artificial Intelligence in Architecture. Routledge.

Nimkulrat, N., Oussoren, A., Fraser, H. D., & Doyle, K. (2019). Collaborative craft through digital fabrication and virtual reality. In Proceedings of the 4th Research Through Design Conference.

OPO'Lab. (n.d.). OPO'Lab – Manufacturer of Ideas. Retrieved December 18, 2025, from https://www.opolab.com/

Güneş, Y. B., & Öztürk Kösenciğ, K. (2022). A content analysis on poetic and artistic qualities of digital fabrication in architecture. Journal of Computational Design, 3(1). https://doi.org/10.53710/jcode.1062471

Oxman, N. (2010). Material-based design computation (Doctoral dissertation). Massachusetts Institute of Technology.

Oxman, N. (2017). Material ecology: Advances in computational design and fabrication. MIT Media Lab.

Oxman, N. (2020). Material ecology. New York: Museum of Modern Art.

Oxman, N., & Oxman, R. (2010). The new structuralism: Design, engineering and architectural technologies. Architectural Design, 80(4), 14–23.

Oxman, R. (2006). Theory and design in the first digital age. Design Studies, 27(2), 229–265.

Oxman, R. (2008). Digital architecture as a challenge for design pedagogy: Theory, knowledge, models and medium. Design Studies, 29(2), 99–120.

Oxman, R., & Oxman, R. (Eds.). (2014). Theories of the Digital in Architecture. London: Routledge.

Paio, A., Eloy, S., Rato, V. M., Resende, R., & de Oliveira, M. J. (2012). Prototyping Vitruvius, new challenges: Digital education, research and practice. Nexus Network Journal, 14, 409–429.

Paio, A., Osório, F., Oliveira, S. M., Valenti, G. M., & Guimarães, N. (2018). Architecture in-play, future challenges. Nexus Network Journal, 20, 9–23. https://doi.org/10.1007/s00004-017-0365-5

Passa ao Futuro. (2020, August 19–29). Design & Build 2020: Craftsmanship meets digital fabrication. Retrieved December 18, 2025, from https://www.passaaofuturo.com/design-build-2020/

Picon, A. (2010). Digital culture in architecture: An introduction for the design professions. Birkhäuser.

Picon, A. (2021). The Materiality of Architecture. University of Minnesota Press.

Pigram, D., & McGee, W. (2011). Formation embedded design: A methodology for the integration of fabrication constraints into architectural design. International Journal of Architectural Computing, 9(1), 45–62.

Pigram, D., Maxwell, I., & McGee, W. (2016). Towards real-time adaptive fabrication-aware form finding in architecture. In Robotic Fabrication in Architecture, Art and Design 2016 (pp. 325–338). Springer.

Pottmann, H., Asperl, A., Hofer, M., & Kilian, A. (2007). Architectural geometry. Bentley Institute Press.

Pottmann, H., Brell-Cokcan, S., & Wallner, J. (2009). Discrete surfaces for architectural design. International Journal of Architectural Computing, 7(1), 157–177.

Pottmann, H., Schiftner, A., Bo, P., Schmiedhofer, H., Wang, W., Baldassini, N., & Wallner, J. (2008). Freeform surfaces from single curved panels. ACM Transactions on Graphics, 27(3), 1–10.

Puj, R. L., & Bruscatto, L. M. (2020). Teoria da tectônica: do tradicional ao digital. Revista Brasileira de Expressão Gráfica, 8(2), 22–43. Retrieved December 18, 2025, from http://hdl.handle.net/10183/217226

Rendell, J. (2006). Art and architecture: A place between (Introduction). Critical Spatial Practice. Retrieved December 18, 2025, from https://criticalspatialpractice.co.uk/wp-content/uploads/2019/03/Jane-Rendell-Art-and-Architecture-Intro-2006.pdf

Royal Institute of British Architects (RIBA). (2018). Digital transformation in architecture. RIBA and Microsoft. Retrieved December 18, 2025, from https://www.scribd.com/document/437467231/MicrosoftRIBADigitalTransformationreportfinal180629pdf

Sass, L., & Oxman, R. (2006). Materializing design: The implications of rapid prototyping in digital design. Design Studies, 27(3), 325–355.

Schodek, D. L., Bechthold, M., Griggs, K., Kao, K., & Steinberg, M. (2005). Digital design and manufacturing: CAD/CAM applications in architecture and design. Wiley.

Schumacher, P. (2008). Parametricism as Style – Parametricist Manifesto. (Presented at the 11th Architecture Biennale, Venice, 2008). Retrieved from https://patrikschumacher.com/

Schumacher, P. (2009). Parametricism: A new global style for architecture and urban design. Architectural Design.

Schumacher, P. (2011). The Autopoiesis of Architecture, Vol. 1: A New Framework for Architecture. Chichester: Wiley.

Sheil, B. (2014). High definition: Zero tolerance in design and production. AD, 84(3), 6–13.

Sheil, B. (Ed.). (2005). Design Through Making (AD Vol. 75, No. 4). Wiley.

Sheil, B. (Ed.). (2012). Manufacturing the Bespoke: Making and Prototyping Architecture (AD Vol. 82, No. 4). Wiley.

Sheil, R., Menges, A., Glynn, R., & Skavara, M. (Eds.). (2017). Fabricate 2017. UCL Press: London.

Silva, D. (2019). Digital fabrication – from tool to a way of thinking: Toward redefining architectural design methodology. Proceedings of CAADRIA 2019, 2, 463–470

Silva, D., & Paio, A. (2024). Digital transformation in Portuguese architecture studios: Insights from the field. In Proceedings of the XXVIII Congress of the Ibero-American Society of Digital Graphics (SIGraDi).

Silva, D., & Paio, A. (2024). Framing digital fabrication in the architectural research practice through a taxonomy. Blucher Design Proceedings, 12(3), 106–115. https://doi.org/10.5151/sigradi2023-346

Silva, D., Paio, A., & Sousa, J. P. (2017). How digital fabrication can enable new methods in the architectural practice? In Proceedings of SIGraDi 2017: XXI Congreso de la Sociedad Iberoamericana de Gráfica Digital (pp. 242–248). Blucher Design Proceedings. https://doi.org/10.5151/sigradi2017-039

Singh, P. (2024). Digital fabrication's influence on architecture: Transformations, opportunities, and future prospects. Journal of Xidian University, 18(12), 365–378. https://doi.org/10.5281/Zenodo.14507204

Song, Y., Koeck, R., & Luo, S. (2021). Review and analysis of augmented reality (AR) literature for digital fabrication in architecture. Automation in Construction, 128.

Sousa, J. P. (2014). Digital fabrication technology in concrete architecture. In Fusion: Proceedings of the 32nd International Conference on Architectural Research through Design.

Sousa, J. P. (2017). Robotic technologies for non-standard design and construction in architecture. Nexus Network Journal, 19, 73–83. https://doi.org/10.1007/s00004-016-0312-x

Sousa, J. P., Castro Henriques, G., & Xavier, J. P. (Eds.). (2019). Architecture in the age of the 4th industrial revolution: Proceedings of the 37th eCAADe Conference and the 23rd SIGraDi Conference (Vol. 2). Education and Research in Computer Aided Architectural Design in Europe (eCAADe); Iberoamerican Society of Digital Graphics (SIGraDi). Retrieved December 18, 2025, from https://ecaade.org/downloads/eCAADe-SIGraDi2019-proceedings-volume2.pdf

Sousa, J. P., Martins, P., & de Azambuja Varela, P. A. (2016). The CorkCrete Arch Project: The digital design and robotic fabrication of a novel building system made out of cork and glass-fibre reinforced concrete. In M. Schnabel, W. Nakapan, S. Roudavski, S. Chien, & M. Kim (Eds.), *Living Systems and Micro-Utopias: Towards Continuous Designing – Proceedings of CA.

Ventures. (2022). Building Information Modelling (BIM) guidelines and operations. (Industry white paper).

Vicente, A. C. S., & Santos, D. M. dos. (2023). Teorias da tectônica digital: Discussões e sínteses. Tríades em Revista: Transversalidades, Design e Linguagens, 12, 1–18. https://doi.org/10.34019/1984-0071.2023.v12.44865

Vitruvius FabLab ISCTE-IUL. (2012). A living system – Discursive wall [Workshop documentation]. Retrieved December 18, 2025, from https://vitruviusfablab.iscte-iul.pt/conteudos/workshops/1819/living-system

Vrachliotis, G. (2022). The new technological condition: Architecture and design in the age of cybernetics. Birkhäuser.

Walliss, J., & Rahmann, H. (2016). Landscape Architecture and Digital Technologies: Re-conceptualising design and making (1st ed.). Abingdon, UK; New York, NY: Routledge.

Wang, F.-Y., Carley, K. M., Zeng, D., & Mao, W. (2007). Social computing: From social informatics to social intelligence. IEEE Intelligent Systems, 22(2), 79–83. https://doi.org/10.1109/MIS.2007.41

Yuan, P. F. (2025). Tectonics as the disenchantment of Generative Artificial Intelligence. Architectural Intelligence, 4, Article 13. https://doi.org/10.1007/s44223-025-00090-7

Yuan, P., Menges, A., & Leach, N. (2017). Digital fabrication. Tongji University Press.

ANNEX A – INTERVIEW TRANSCRIPT

18-25 Research Studio for Architectural Visualisation

18—25 Research Studio for Architectural Visualisation is a laboratory for the construction of architectural images. Our work is a support tool for designers that allows not only to test light and spatial relations but also to fine-tune chosen materials. In our research on new architectural representation methods, we look for alternative paradigms and specific atmospheres. We believe that an image should quickly communicate the character of a certain environment while having the ability to seduce and stay withheld in our memory. Our constructive principles are based on the rules of classic perspective, the canons of proportion, optical guidelines and photographic composition. 18—25 seeks a balance between scientific vision and a dreamlike representation of an atmosphere. The choice between an accurate point of view, the best frame and the most expressive lighting associated with an attention to detail creates 18—25's reality.

Interview conducted at the office on 19/02/2024 and 27/02/2024.

PART I: INTRODUCTION AND MOTIVATION

Daniela Silva (DS) - Q1: When and why did your office start incorporating digital tools into architectural practice? What was the initial catalyst?

Luca Martinucci (LM): I had a university and academic background that I consider fundamental, but I only used the computer in the last years of that training. I learned to draw perspectives by hand, with a drafting table, vanishing points, compass... a whole set of technical instruments that trained us to be quick at drawing. I remember that, at the time, I was one of the fastest in the class at making perspectives. I even sold them to classmates who didn't want to do them. But that kind of speed no longer exists today. And what did being fast mean? You had to be absolutely sure about the point of view before even knowing exactly what you were going to see. In other words, you had to have a huge capacity for visualisation and imagination.

DS: The ability to imagine the point of view…

LM: Exactly. But sometimes that chosen point of view - let's say, that "expensive" point of view — wasn't the best. Then you had to redo everything to get a new perspective. Sometimes it worked for one elevation, but then it didn't work on another side, a corner, and you lost the volume. You realised you were losing a part of the building you hadn't even imagined. Today, with any simulator - even with SketchUp - you can easily rotate a solid, even on your phone, and choose the right point of view super

quickly and intuitively. You can generate endless perspectives of the same object until you find the ideal one. And I don't think this represents a reduction in ability. Back then the process was tougher, more synthetic, yes, but today, if we use these tools well, it's much easier to find the right point of view. We can control the point of view, control the light, change the lens. If we impose some limits on our presentation, we can see the project much better - and that's only possible with technology. That's why we build our own machines. I'll show you our lab later, where we assemble them, and also the data centre we built for ourselves. Technology isn't something external to the process - it's intrinsic to our way of designing.

DS: Yes, that's something I've always noticed in your office. There's a very natural connection with technology. It's part of your DNA, right?

LM: I think so, the technology thing is not just synthesis, it's hyper-technological at the same time. I don't think it's possible to imagine the future without going through those two points.

DS – Q1.2: What were the main motivations for adopting these technologies? Was it a response to digital evolution, or were there other reasons?

LM: Stay angry, stay foolish. There's no research that doesn't come from an enormous desire to discover new things. Sometimes, that even happens in different fields. For example, the first goggles of this new era we bought were for video games, but there wasn't even compatible software to run on them. I think they were probably the first to arrive in Lisbon, and the order didn't even include any software that could be used with them. It was all very new. The goggles were designed for gaming, but we couldn't even do with them what already seemed possible to us. So, we developed our own software, created our own workflow to use the goggles the way we wanted. To be able to show what is created, to be able to sample the creature, so to speak — the content. Today it seems like everyone can do that, but we literally started ten years ago working with goggles from this new era.

Now, of course, there's huge curiosity about Apple's new goggles. They're technically impressive in terms of content and what can be done with them — we're already there. What's gained now is a better machine, a better instrument. But we haven't had that revolutionary leap we had with the first goggles. It's like comparing the first gasoline car to a Tesla. Of course, the Tesla is faster and even cheaper, but the first Mercedes-Benz... that one revolutionized everything, including cities.

DS – Q1.3: Can you describe a project where the adoption of digital technology was crucial to its success?

LM: Honestly, I'd say all of them.

DS: Right, I was expecting that answer.

LM: Because it's true: all of them. In fact, it's not just in small or unimportant projects that we use technology. Usually, when a client, architect, or investor comes to us, it's because they have a problem that needs solving. That problem might be project development or a representation issue — how to better communicate an idea that isn't being understood. Or even because we ourselves aren't understanding what's happening. And that's the real challenge.

DS: So, they already come looking for that answer or that process, right?

LM: Yes, because it's a process that helps find balance or solutions. I wouldn't say we are the solution, but we're an instrument that helps get there faster. For example, I remember a very interesting project we did about a year ago with Appleton. He was studying several apartments inside a building dating back almost to the 17th century - around 1600. It had a very old architectural structure and almost everything had to be preserved. The challenge was to reconcile conservation with a new spatial distribution - finding a new way to inhabit the existing spaces. When we reached the roof part, the issue of dormer windows, attic levels, apple trees — well, all the volumes going up and down - made it very difficult to represent with just plans, sections, and elevations. It was really hard to understand the space only with drawings. So, we virtualized everything. I remember perfectly when we entered with the VR goggles to correct the architecture and improve the spatial experience. We could simulate the space, virtually enter it, and check all the points - us, João, João's family. It was like entering the construction site before construction began, which allowed for a great debate.

The process was going perfectly well, but during construction a small issue came up. There wasn't enough time to make the change in virtual reality and then apply it on site. The correction was made already during construction, and in that case, a small error had to be accepted - economically it was the most viable solution. But in other projects where we can control everything from the start, the result is much better. If we can control, we can reduce time — and that means reducing costs.

DS – Q1.4: Was there any model or example (national or international) that inspired your transition to using digital tools?

LM: That's not an easy question because our two universes are quite distinct. Mine is much more experimental, linked to engineering and perspective. For me, the most technological period in history is the 16th century - the year 1500 - because of the revolution it represented. Undoubtedly, it was a turning point in any topological dimension. If we look, for example, at the perspective of Giovanni Battista Berti or Piero della Francesca, when we see those representations of the "ideal city," we clearly understand they are projects. But the most interesting thing is that, despite those very clear representations, the Renaissance city still didn't exist. What existed in reality was a Gothic city, maybe Romanesque - but not Renaissance. There weren't yet groups of buildings, elevations, or squares like those in those projects. In other words, we were seeing the first "render" in history. We were seeing

the first urban project with a true design intention, but with no real parallel at the time. That "ideal city" showed a path, a vision of the future. There was a square, a facade completely drawn according to architectural perspective principles - but with no real correspondence. That square… it wasn't an existing square. It was a square of the future. It's like today when we look at hyper-futuristic images, with artificial sneakers and projected data - they're visions of what could be, not what is. But there, in the 16th century, we were seeing a projection 500 years ahead.

DS – Q1.5: What were the main perceived benefits that motivated the adoption of digital tools?

LM: Our workflow developed over time, becoming more and more refined. Since we started changing and adapting, we realised that our workflow isn't static — it's always evolving. We are constantly developing and implementing new tools, new technologies, new software... we even develop our own plugins. That ability to create new instruments is fundamental.

(Parenthesis, because I think it makes sense to share this.) My grandfather was a precision mechanic; he worked on ships during World War II. He prepared ship engines, did precision metalwork. I remember that his first job, still during his training, was to make an anvil. But to make the anvil, he first had to build a file. In other words, he would take a piece of iron, cut grooves to make the file, and only then use that file to make the anvil. He always said: "The craftsman makes the tool, and the tool makes the craftsman." That idea stayed with me, radically. I have a huge passion for manual skills. I know how to do various professions, some better than others, of course, but I like to try them all. I have tools to do almost everything. There are very few things I don't do at home — exactly because I'm curious, I like to know how things work. I was that kid who always took apart a toy when it broke, just to see how it worked.

DS: To take things apart...

LM: Exactly! A classic. And that curiosity is what leads me today to develop new tools. Whenever we find a more refined, more efficient path, we adapt quickly. For example, in the case of artificial intelligence: our first commercial AI job was almost two years ago. At the time, we told the client — a very sensitive client — that the image had been made with AI. We explained why that was important because it was something emerging. At that time, nobody was talking about it. Nowadays, every app has AI. But two years ago, they were just the first experiments.

What we did was, instead of using external images on the panels, we created our own AI images. Images and videos specific to each room — tailor-made content. We created images inside the image itself. And since we had the ability to work spatially, we no longer needed to look for a random image — we could generate our own, for that specific space. That project took a lot of work, but I really enjoyed doing it. It allowed us to create extremely sophisticated and interesting images. But at the time, it wasn't even communicated as something special.

Instagram, for example, didn't even recognise it as an artificial image. It simply wasn't seen as something important for communication.

DS: Because it was still way ahead…

LM: Exactly. And that happens often. But that's fine. Someone has to be ahead, to clear the path. It's exhausting, yes, but also extremely fun.

DS: And rewarding. Exhausting, but you also feel a sense of achievement, right? That pleasure of being ahead.

LM: Yes. Working on new paths pushes us.

PART II: BARRIERS AND CHALLENGES

DS – Q2.1: What were the main barriers you faced in implementing digital fabrication technologies?

LM: Setting up a company is, in fact, something very complicated. There's no manual for building an effective company. Usually, it all starts with debts, loans, or that structure like: "I have to open a company, I need to have this or that." We started exactly like that. Today, we still face problems, but we manage to be largely self-sustainable. We went through an evolutionary path, structured and rationally thought out. Each investment was essential for development, and we always reserved a percentage for technological development and investment in ourselves. Our shareholders were ourselves. In the first project, we allocated a computer. In the second, we paid Filipe's partner with that same computer - it was the first one we had. From there, we went through a rational and progressive growth path, always based on a clear logic of evolution. Of course, there are limits - economic limits - that don't allow us to do everything we'd like. For example, I'd love to have a printer that prints one metre by one metre. But that's not realistic right now. Either we do a project to get there, or it's simply not possible at the moment.

Not everything is immediate. Sometimes what seems like a barrier or difficulty - like developing software, which is very demanding, especially financially - can be transformed into a step forward. If the path is well calibrated and well thought out, problems become steps. You need to dismantle obstacles and move forward. I'd say nothing really blocked our path. Everything that seemed like an impediment, we managed to dismantle and use as momentum for the next step.

DS – Q2.2: Are there any local policies or regulations that facilitated or hindered the adoption of digital fabrication in your practice?

LM: No. We are part of a professional path where it's really possible to join an office - or establish a partnership with one - and be part of that structure.

Anyway, I'm fully aware of the problems with submissions: whether in BIM, to the City Hall, to the client, in Lisbon or even in the US. There's always a set of specific requirements that must be met. For example, the issue of photomontage. Photomontage is actually a photographic process that has existed for 60 or 70 years. Many architects used to cut and paste manually to achieve that effect.
Today, for us, a photomontage is a simulation of reality - as accurate as possible. It's unacceptable for a photomontage or a photographic insertion not to be as rigorous as reality. And nowadays there's no excuse: we have all the instruments to guarantee that accuracy. To be able to state with precision that a building, with that height, will have a certain impact - whether it will block or not block something - there's only one way: use the right tools to ensure the necessary accuracy. That's how it has to be.
LM: We've even had situations where the City Hall contacted us to understand exactly what should be required of applicants, in order to better control the process. They wanted to know how to develop a more effective system of viewpoints - and that's obviously work that we do. At a certain point, when you start analysing projects, you realise there are obvious differences between insertions, and the City Hall wanted to know how to ensure a more effective viewpoint system in photomontages. Some guidelines were correct, others weren't. But at least there's a willingness to follow a more rigorous process - and that's important. After all, we're talking about a technical drawing in four dimensions. It can't just be a matter of "I think it's like this" or doing something quickly in Photoshop. That's not it.
DS: Are your clients always offices and investors?
LM: Yes, we've already worked with big groups. In the world of architecture, the execution process usually involves four stages: who invests, who designs, who builds, and who sells. And yes, we've had clients in all four stages. There were cases where someone who wanted to sell the project came to us because they needed images — or because they liked the project but didn't have a way to communicate it visually. Usually, that last phase is the most undervalued in the world of architecture. There's almost this idea that architecture is only made of light and space — as if no one sells space or as if construction doesn't involve millions. But the truth is architecture has a cost. Architecture is investment. And if all this is well done from the start, we can have quality architecture. If we ignore these points, we have a serious management problem.

DS – Q2.3: How has client perception influenced or affected the implementation of digital tools in your practice?
LM: It's very difficult to communicate what we do. Even today, for us, that's something we need to qualify better: how to communicate our process, what it means to "do morally," how the work is actually done.
DS: Did you feel you had to explain to clients…
LM: Communication is really the most delicate part of winning over a new client.

We have to explain what we do, show that we're not a threat or an excessive cost. Because what you gain with this process is more information, more awareness.

We can make decisions faster, more informed, based on real data. That's an area we're trying to improve today - communication. We're implementing several strategies because those who already know us end up being stable clients. Or sometimes there's an incompatibility issue, different goals, which can also happen. We're not for everyone. We're for those who want to work with us, who share with us a desire for quality. All the architects who collaborate with us understand this. And the process runs better when the decision-maker, the project leader, talks to us directly. If they at least do the first briefing or follow the process, they understand that creativity is not in the final result but in the process itself. We change, correct, modify. There's a phrase by Eduardo Souto de Moura that really marked us. In an interview, he said:

"Lucas, change this."

And I replied: "I won't change it."

"Change this."

"I won't change it."

Until he says: "Then change the project."

The example he gave was about a reflection on the glass.

He said: "Remove the reflection."

And I: "Eduardo, I can't remove the reflection, glass has reflection. I can only place what's there."

And he answered: "But I don't like it. Then change the project."

And he changed the project because he realised what he was seeing didn't match what he imagined. And that's not a flaw, it's actually a point of trust in the process.

Trusting enough to change the project. For me, that's where the architectural process reveals itself: it's spatial thinking. It's the entire process - being a critical and supportive instrument.

Not a passive instrument, but an active one, which allows those who design to make decisions.

Today, doing architecture requires a team. It's not the work of just one individual, although there is someone who coordinates and decides. But they decide based on multiple pieces of information, arriving at the same time and coordinated. You can't make a functional project without engineering, HVAC, specialties. Without all that working together, not even a simple aesthetic decision - like the colour of a building - makes sense. I remember a competition we did many years ago, FPM41. The building was going to be grey, like Mac computers. We were the ones who suggested to Diogo: "What if it were gold? What do you think?" From then on, the building became gold. For me, this moment shows that it's not just about making an image. It's really designing with different instruments and supporting the entire creative process. That's the dialogue.

DS – Q2.4: Was there ever a case where technological or financial barriers prevented the implementation of digital tools in a project?

LM: Sometimes there are situations where the client can't immediately see the advantages of our work. Then they end up seeing us only as an extra cost - or worse, as a problem generator. Because if I ask for something to be done in a certain way, it has to be done like that. And if it's not, then they look for someone else to do it.

Because of that, we've lost some jobs. Probably not a big loss, but there were cases like, for example… or when they said: "That plan is too high, it has to be lower," or "I want to see more," because the room was small and there was a wall that limited it. But the demand was always: "No, I want to see more." That's when you start distorting the project, pretending… as if the image didn't really represent the project. And that happens when projects are not managed correctly. Of course, you need some tact to say this, but it happens when the process is too detached from reality. Now, when there's openness - as happens with Eduardo or other of our clients - and they understand that our accuracy is not a problem but an advantage, everything changes. Because if we don't follow that rigorous path, we're going to have problems later. For example: that image, at that moment, with that light, that reflection, that material, and that framing… will give exactly that result. Everything else we can adjust - everything possible, photographically, scientifically, and coherently. There's an ethic in our work that requires us to represent the project as it really is - and in the best possible way. The presentation allows us, of course, to make the photography the best possible, with the best framing, all photographic requirements. But that process is only possible if we represent architecture as it really is, following a rigorous way of working. Plan, section, elevation, material list, finishes… all of that has to be done accurately. If that's right, then everything else happens naturally.

PART III: EVOLUTION AND CURRENT IMPLEMENTATION

DS – Q3.1: Do you identify any historical milestone that you consider pivotal in the evolution of digital fabrication in architecture?

LM: Yes, in terms of technologies, I would say there are three or four points that were - and still are - fundamental for us.

First, real-time processing. No doubt about it: GPU processing and immediate feedback were crucial. It's essential to be aware that what we're doing is exactly what we see, without having to wait hours to generate an event and end up with half an image that doesn't match anything we want. That real-time feedback is indispensable.

This was right at the start - the first technological turning point we had - when we bought software that allowed us to make real-time visualisations with a graphics card. Today we have a cabinet full of graphics cards that allow us to render in real-time.

Then came the virtual area and the goggles. That was another important milestone because it completed what we had already developed: a total virtualisation of space. The goggles allowed us to literally enter that virtual space and communicate the completed project in a fully immersive way. We have our own software that works with the goggles, and we can use it in different offices — Lisbon, Porto, Los Angeles, New York, wherever. Just upload an image remotely, and whoever has the goggles sees the project in real-time. We are all in the same space, talking about the same object, as if we were together - but virtually. Sometimes we even have Zoom meetings, each pointing "to the left," "to the right," and we're all seeing exactly the same space. That tool became fundamental for us. At first, it was all based on gaming goggles. Now we're trying to replace that equipment because the new models don't allow exactly what we want. They still work well, but they no longer exist, so we're developing alternative solutions, which are already on the way.

More recently, there was another landmark change: the use of drones. That was a tool that gave us immense possibilities - from scanning surveys to photogrammetry and even using LiDAR on mobile phones. Anything that involves capturing reality became possible with these technologies. And of course, artificial intelligence. I have no doubt it's already one of the main tools we use - whether to produce software, answer emails, think, support processes, or even when we feel alone developing an idea. We even used it in the article we wrote for the Architects' Journal last year. Do you remember?

DS: Yes, the March one, I received it.

LM: In that article, we were talking about AI when almost nobody was discussing it. At the time, little to nothing was known or published about it, but the impact was already clear. The evolution is exponential. I have no doubts: either you learn to deal with this tool, or you risk falling behind. Not in the sense of not working anymore — but because AI will reduce the need for human intervention to a point where only those who master the technology will be needed. It's really a radical change — much more than the steam engine, the combustion engine, or even CAD. Do you remember those photos with hundreds of draftsmen lying down to draw plans? Then CAD came, and a single operator did the work of all of them. AI goes beyond that. That's why we really have to study it, use it, and implement it. And that's what we're doing: integrating the tool into our own skills.

DS – Q3.2: How is digital fabrication currently used in your practice?

LM: There are projects that push towards new technologies. We need to fully develop and understand them when something new emerges. We have to study it and see how to integrate it into our work. Currently, there isn't a direct and consequent relationship in the sense of saying: 1825 works because

it prints a plastic part. It doesn't work like that, not so directly. But there are projects we have developed, especially with Space Collector and with 1825, that were only possible because we did 3D printing. It's the result of the creative process. For example, something very particular, but that makes perfect sense… do you remember that machine that was hanging in the museum? Maybe a tiny train - about this size - but for me, it was fundamental.

DS: Yes.

LM: That small piece was connected to the cable, and the cable was fully embedded - with two clamps - hidden. And only by looking at the cable did you understand the piece. That piece was designed by us precisely to solve that problem. Where do you move it? How does it work? I could have taken a wire and bent it, but it wouldn't have the same elegance. That particular piece can only be made within this prototyping logic, where we study parts, things… where construction is part of thinking. For example, this is a piece we developed a few years ago. But these pieces are not born from a production need, but from a need for research, for formal exploration, for critique. We are developing a research process about how various parts are built.

DS – Q3.3: What are the main lessons learned that you could share with other offices considering exploring digital fabrication?

LM: I think we can talk about two main points. The first is already underway, and the second is consolidating.

The first is the Space Collector initiative, which started integrating our know-how about computers into the architecture office. We created a small workshop to assemble high-performance computers, specifically designed for architects.

It's very common to see architects buying generic computers, with gaming specs, for example, at MediaMarkt. But those machines are not optimised for the kind of work we do. What we do is design custom computers, with the right parts for each purpose. Although some parts are common - like the graphics card, which can be the same as in a gaming computer - the selection and configuration are completely different. Our know-how has been used to define, for example, how to save files, how to make backups, how to work remotely. All this technical and infrastructural knowledge was requested and is being implemented in our office.

DS: So, from an efficiency point of view, the system is really well aligned.

LM: Second point. Have you heard of Four Days? We are part of the pilot group, in fact, one of 40 integrating the pilot project - even more experimental. This project has been so interesting that, last week, they came to interview us to understand how it's evolving and how we managed to make such radical changes in how we look at quality of life. Because, ultimately, if we want quality of life, we have to work with quality. And for that, we need people who like to work with quality. To have people like

that, it's essential to create an environment where that's possible. That balance is increasingly necessary. We've been using this model for nine months now, and the results are extremely satisfying.

DS: So, you see that as a clear path for the future?

LM: Yes, for me it's obvious. It may not have a big impact on society in general yet, but it already has a huge impact on the people who work with me. And that's already a first step. It's what I can do - share the experience and show the benefits. Share how to reduce hours without reducing responsibility. We reduced the presence time in the office but not the responsibility. We work four days a week, with a 32-hour week. The working hours were reduced from 40 to 36, but in practice, we work 32. Overtime is put into an hour bank, which the team can use autonomously to manage work peaks or training. The Academy Project, which already existed, is also part of this. We organise six trainings a year, internal and external, with specialists from various areas - from photography to programming. It's a continuous investment in new tools, both for us and for those who want to participate. This is the contact point between the office and the university. Maybe because we are architects. Or maybe because, as my grandfather used to say, we have to create our own tools.

I see 35 as one of those tools. And designing a tool isn't just choosing a good computer — it's also creating the best possible work system. That includes having the best people, people who like working with us, who like being well, who work for something worthwhile.

DS: If we work with passion and intensity, the tiredness is different.

LM: Yes. It's like the Portuguese saying: "Who runs for pleasure never gets tired." Or the Japanese proverb: "If you find a job you love, you'll never work again."

Even so, the time we dedicate to our work is also the time we dedicate to ourselves, our family, our way of being in the world. If I want my employees to know how to critique an image, I have to allow them to read books, watch movies, go for a walk, to the beach, to the forest… to live. Only then can we have the best imagination possible.

DS: Because creativity needs nourishment.

LM: And that nourishment is serious - made of good vitamins and time.

What we implemented, in essence, was more responsibility. The team is responsible for its time, organises itself to meet tasks. We didn't reduce the work, just the presence time. And that's done efficiently. More efficient machines, more efficient software, and us also working better. We can work fewer hours and give better responses. It's a big ambition, but I see it clearly: I can't imagine going back to working six days a week. It's very different to think about work even when you're outside than to be physically all day in an office. So far, we haven't had any delays, any failed deliveries. We've managed to maintain a weekly average below 36 hours, with excellent productivity. For me, that's building the machine. The office is not just where you design the sofa or place a light. It's the

organisation machine behind it. It's how the work is structured, how the workflow is defined, what software is used, how the team communicates. All of this is part of the lesson we can share.

DS – Q3.4: What have been the key technological developments that facilitated the use of digital fabrication in your practice?

LM: I think there's a clear process here. Even though BIM is still not, for me, a fully effective language - it still has a lot to evolve - there is, however, an interaction that is already structured from the beginning of the process, between us and the architectural sector. The architectural team sends the drawing, we update the model and return the BIM visualisation. That's the point: that's why we say it's BIM 4. We can see what others don't see.

Although there's still a lot of confusion. BIM, usually, is not easy to navigate. There's little software - although there is some that allows quick previews, with fast renderings. They're heading in that direction. Some transitions aren't very beautiful yet, but they're effective. You can work and understand what needs to be done. And that's already an advance. When we enter the process, we can give extremely quick feedback. And basically, we provide that scale upgrade, which is what is usually missing. Because any BIM that is really rigorous works on a 1:100 scale. When it's very good, it goes down to 1:20. But it doesn't go much beyond that. We can reach the ideal scale. We've drawn at one millimetre.

DS – Q3.5: How has the integration of digital tools affected collaboration within the office and with other stakeholders?

LM: Normally, BIM is a horrible thing. Almost always it's very poorly done.

DS: Even more now that it will become mandatory...

LM: Yes, and the problem is that those who design often don't know how to optimise the models. For us, it ends up being more efficient to redraw or remodel everything from scratch. BIM can be useful in the technical part, but it rarely has the right definition for what we really need. Look, I'll give you an example that was terrible. We already have many years of experience, and once we had to do a competition for a hospital. I thought it wasn't necessary to worry - we already had everything ready, it was just sending the BIM.

But when they finally delivered the model to us… it was a nightmare. We were only able to work with it thanks to our programmer, who is incredibly competent. We managed to open the model to present to the director… and what we found were boxes, boxes, and more boxes - with the minimum useful information, but extremely heavy. There were doorknobs with millions of polygons! They had included all the placeholder boxes inside the walls, with all the screws and even small fittings. The model was technically perfect, to the point that the staircase could be 3D printed… But it was completely

impractical. Hundreds and hundreds of elements hidden in the walls - that no one sees, and I don't even know if they were ever accounted for.

And that's the problem: those who design often don't have enough training or a global vision of what BIM is for. Of course, when we receive a well-structured BIM, it can be an excellent base. It allows us to quickly understand the space and make changes much more efficiently, especially in the details that really matter - like baseboards, fins, or everything that a material requires on a real scale. BIM rarely manages to represent reality as it should. And when it does, it brings everything: toilet models, handles, designer chairs… it all becomes unbearably heavy and impossible to work with.

PART IV: FUTURE

DS – Q4.1: How do you see the future of digital fabrication in architecture?

LM: I see the future of these tools in architecture in a positive way.

But it's a delicate process, especially when it comes to artificial intelligence.

The risk, for me, is the extreme ease of presenting anything - something that may even look good but is not exactly what we want. For example, we can write a prompt asking for a beautiful building, and the software returns images of beautiful buildings. But it's not the building we imagined. It's not what we want. Still, those images can become moments of selection and reflection. I know there are clients who don't like working with us precisely because we face problems head-on. We demand that reality matches the project - and not that the project is something adapted to reality. My concern is that this type of "shortcut" may escape the project - that conscious loop between what I want and what I do might be lost.

It stops being an open discussion within a team of professionals. That's why I believe this needs to be controlled in every sense - not just in the image or the plan. It's going to be a process. I don't think our work will disappear easily.

But yes, it can change some steps, accelerate certain stages - and that's what I hope technology can offer in the future, whether in a year, two, or even a hundred. If we think about the last 50 years, it's important to reflect on the leap that was made:

There were no computers - or only the most basic ones.

There were no mobile phones.

There was no internet.

There was no ecological awareness like today. And there were no early signs of critical thinking in architecture that were starting to emerge. Therefore, the leap we're taking now may be even more exponential. Of course, there will be serious problems for society. And I have no doubt that our

validation as architects will be a critical issue: both for what is being designed now and for what will be designed in the future.

This isn't an issue that arose with AI overnight. Integrating these tools into the process requires study, proximity, and commitment. It's not just about agility or quality. It's part of a future movement that must start now. If not now, when? That raises the question: What will the architect of the future be like? What kind of needs will they have? I hope there will still be a strong root in knowledge. That we don't lose the perspective of discussing architecture made with bricks, with sweat - and not just with machines and buttons. That architecture doesn't become just a catalogue where you order an apartment as if it were at McDonald's. Because there are multiple functions that these tools will enable - and already are enabling.

I remember when I was in university, 20 or more years ago, trying to imagine the future. At that time, it was the peak of the "archistars." Working at Koolhaas or Zaha Hadid was the goal. There were about ten offices in the world that polarized global taste - and there were ten types of architecture.

Everyone wanted to go to those centres. But around us, the reality was terribly sad. It was construction, not architecture. The difference was clear:

Solving a problem in the worst possible way or not. Architecture, for me, is that:

A creature that lives between costs and benefits and tries to give the best possible solution within the best possible economy. That's the great architectural challenge. If Difusa's work contributes to that, then it's to train enough architects and professionals so that all construction - both current and future - is done with satisfaction. The time of the archistars as the centre of the world may already have passed.

But that doesn't mean references have disappeared. They still exist.

The important thing is to know that, even with simplicity, it's possible to do well. And that's still a concrete vision of the future. I believe that for this to happen, we increasingly need architects with critical awareness and technical capability. I see the architect not as an isolated figure, but as part of a coherent, multidisciplinary team. Offices working in networks, in synergy, across various specialties. The architect alone, in their room, doing architecture autonomously… I think that's disappearing.

The future is open dialogue between many stakeholders. Technologies are inevitable. These structures can only be made with people. And I still hear - and somewhat strangely - comments that maybe computers aren't that useful, or that hand drawing was better. Or that AutoCAD is just a representation tool.

But no. These tools are an integral part of the process. And their conscious use is what will define the architecture of the future.

DS – Q4.2: What are your expectations or plans for expanding the use of digital tools in your office?

LM: Our path has never been about adopting tools just because they exist — it has always been about discovering what really transforms the way we design and communicate. So, expanding the use of digital tools is not about adding "more software" or "more machines," but about making them work together as one coherent system.

We already have a fully digital workflow, but we want to push it further into real-time, collaborative environments. That means developing our own plugins and scripts, building machines tailored to our needs, and integrating artificial intelligence not as a "trend," but as a real assistant — something that supports creativity, decision-making, and precision. We're also experimenting with more immersive experiences, like virtual and augmented reality, so clients and partners can "walk" through a project and interact with it before it exists.

The focus is on efficiency without losing quality. Fewer hours spent on repetitive tasks, more time for thinking, for design, for life itself. It's like building the perfect tool for each job, like my grandfather used to say: "The craftsman makes the tool, and the tool makes the craftsman." For us, the future is to keep making those tools — physical, digital, even organisational — so we can design better, work better, and live better.

DS – Q4.3: How do you think your approach to digital fabrication compares with that of other offices?

LM: Our office, for example, is remotely controlled. We have voice interface to turn lights on and off. It's so digital that it's even architecturally digitalised.

We take the software control issue to the limit: being able to turn lights on and off, control everyday tasks, all through an app, voice, or software.

For me, that's not the future. It's the present. And it's not just out of passion - although it is - but above all because it's useful, it makes sense. You save time. You can do other things. The four-day project comes and goes, but it's important. It aligns with this need to better manage time. If we can optimise time and better manage the work schedule, we become more efficient. We use tools that save us time, and that time we can dedicate to other things that are also necessary: baking bread, taking a walk, dreaming, being with friends. We do all this so we don't end up being tied only to technology. That's what digital is.

DS: And how do other offices work?

LM: It's hard to say. I have a lot of experience, we've collaborated with many offices - from the most conservative to the most contemporary. Everyone uses computers. Today, there's no one doing technical drawings by hand. Of course, many still make models and hand drawings - sketches - but that doesn't replace software or artificial intelligence. Making a model or a sketch is a tool for clarifying the inner idea. We can use several tools at the same time.

DS: And do you work like that?

LM: Yes. In our way of working, we often have four people collaborating simultaneously: we have an idea, and we can see it, discuss it, talk about it, and represent it at the same time. That requires a lot of technology, a lot of effort, several people. But the sketch, even though it is essential, is very quick and efficient to fix an idea. Then, with technology, we refine it, discovering more information. From drones to pens, everything in the office is a digital instrument. And we use them all as needed. I don't know if this answers the question exactly...

DS: Yes, there are no right or wrong tools. There are tools necessary for each function, for each goal, for each situation.

LM: Exactly. You cook. To beat an egg, you use a fork. You could even use a knife, but if you have that whisk, it's much faster and more efficient. It's the right tool, but it's only for that. You don't serve meat with it, nor use it to eat. It's only for beating eggs. The kitchen robot does everything, but you have to change the blade. Sometimes, with a simple tool, you reach the goal - but it takes three times as long. Because the result is better, more refined. Choosing the right tool is a luxury, but it also has to do with professionalism. With intelligence and adaptability, you can survive in the forest with just a knife. But, with the right tool, you can do whatever you want. We have a tool - I don't have it here now, but you already know it - it's like a small tube. You place it on an object, and it captures the exact RGB colour.

DS: Oh, I know. In pen format, right?

LM: Yes. It indicates the exact colour, how the colour is composed. It's like a mini chromatic scanner. You put it in your pocket, touch it to a wall, and it tells you the colour. You can immediately digitize the colour - precisely and accurately. Its only function is to measure colour.

DS: Either you need it, or you don't.

LM: Exactly. You can try to find something close on a colour palette, but this kind of tool allows you to have the most realistic colour possible - it's not "more or less," it's that one. Now I'm thinking: imagine doing a project attached to an existing building. That building may have been painted with RAL 1090, but over time it aged, faded - the colour is already different. We deal a lot with that: tiles, decorations, mouldings... capturing, recovering, digitizing that information and bringing it into the digital world is essential to create new information. These contact points between digital and real are fundamental. That's why we try to use all the tools that are useful for the work we do.

DS – Q4.4: How would you compare the adoption of digital fabrication in architecture in Portugal with other countries?

LM: Actually, we always have, let's say, a mirror… in the end, we work with someone who gives us information. There are architects who have to do an analysis - and everyone who works with us shares a certain way of thinking, a certain autonomy. But it's very different case by case. Even the software itself, a CAD, for example, depends on how it's organised. Nothing is standardised. The basic

organisation - layers, everything - is still very open. And, in a way, that's good. Because it's not so standardised, it allows drawing to be worked more freely, with each one's own sensitivity.

But when it comes to passing information… you realise that not everyone uses the tools with awareness of what they're doing. They adapt old ways of working to contemporary instruments. They draw as if they were still at a drafting table: thin, grey, protected lines. If you have the digital label, great. But if you don't have a model, you're left only with lines. Without materials, only patterns. That shows a certain transposition of needs. There are those who are much more integrated with technology - using point counts, layers, metadata, everything. And there are others who are simpler in their use. But honestly, I'd say that everyone we work with - maybe because they work with us - already understands the usefulness of this. Sometimes they need a little extra support, but they integrate well. They understand that what we do adds value to the project. It's a qualification, it enhances the work. It helps deliver the project with more rigor, more clarity.

Of course, there are two or three offices where you still feel resistance - not because they're younger or older - but maybe due to a certain modesty or even a desire to seem "non-technological." Everyone chooses what to "eat," so to speak. I've had such situations. Someone with a more concise, more focused life, who didn't tell me how to do the drawing, but fully understood the need for adaptation. In a young office, for example, there may be someone who wants to work based on graphite because they believe that's how you learn. And I understand that. After all, Palladio didn't need a computer to do what he did. The computer is just a new pen. But that new pen allows you to do faster and different things.

If we look at Palladio's production, or even architects from the 1940s and 50s, they also produced a lot, and with great quality. They had large offices with many people. I don't know how they managed to pay so many people! But they produced great drawings, great works. They weren't less rigorous because of that. The Seagram Building was made by hand. With many drawings. It's possible. And it's fantastic. This isn't about erasing that world or saying digital is better. But today, digital is as fundamental as a whisk in the kitchen. If you don't have a whisk, you're an amateur. Same with the computer: if you don't have one in the office, you end up working by hand, like Peter Märkli. Which is fabulous, of course - he works in front of trees with charcoal on paper - but then he has an office behind that digitizes everything, draws, and delivers.

DS: In other words, it's not a substitute. It's a process. And there's no right or wrong way. The goal is always the same, the paths just change.

LM: Yes, I don't think one is more effective than the other. And effectiveness in architecture has to be well thought out. Because if we're only talking about quantity and speed… well, the Chinese build hospitals in three weeks. It's impressive. But is that the goal? Speed doesn't mean quality. For us, the goal is always the highest possible quality. If we're fast, it's because we research more than others to

find the right solution. We do a lot of trial and error to find the right path, and that excess of trial and error is what leads us to superior quality. We confront different paths, investigate more. It's a difficult path, but possible. And it improves the final result. Improve our feedback as much as possible. Not to rush, but to find a better solution in the same time.

DS – Q4.5: What emerging trends in digital fabrication do you find promising or interesting for architectural practice? We've been talking a lot about artificial intelligence. From what I've noticed, compared to other offices, I think you already have something very well established… I'm referring, for example, to the use of virtual reality goggles, which for you is already part of everyday life and is fully integrated into your work methodology. For other offices, this technology is either not yet known, or, even if it is, it's not being implemented. In your opinion, do you think VR could be one of the technologies with the greatest potential for adoption in architectural practice?

LM: VR is undoubtedly a very relevant topic. Currently, one of the biggest obstacles is that, to get a quality result, a lot of work is needed. It's still not an easy, quick, or cheap solution. Of course, there are simpler alternatives - SketchUp, for example, already exports directly - but the feedback is still weak. Many times, the effect doesn't compensate for putting two plastic boxes on your eyes.

Despite that, virtual reality is a very powerful tool. It still requires a lot of care and knowledge to be used well - you need to know what you're doing.

DS: But from your point of view, it allows a qualitative leap in communication and spatial understanding, right?

LM: Without a doubt. With VR, we can enter the real scale of the project - design, experiment, analyse, and imagine architecture in its own dimension. It's the first time in the history of architecture that we have access to that kind of experience in a relatively accessible way. Of course, equipment and tools are needed… but the possibility is within our reach. It's something concrete — we can use it every day. It's not complicated or impossible. I'd say the only comparable thing, with similar weight, are the Renaissance models of chapels, basilicas, like those of Saint Peter's and surroundings.

They were made of solid wood, often in reduced scale but large enough so that the Pope or the client could "enter" with their head into the model and visualize the space, imagine the construction — it was a way to seduce them to finance the work. We have to communicate with the client, with other architects… Communicating space, taking an idea from our head and making it understandable to others, is essential for the project to happen. The architect is one of the few artists who has to communicate their ideas before making them real. A visual artist, for example, works alone — they have their budget, execute their vision, and that's it. The architect doesn't. They have a structural priority: form has to serve need.

DS: And in terms of image? How was that communication done?

LM: We have the example of Shulman. He wasn't just a photographer - he pointed, framed, built the image with intention. Architectural photography at the time was mainly used in women's magazines - not to sell architecture, but to sell lifestyle, to create desire. The magazines were usually printed in black and white, but the women's ones, sometimes, in colour. Many times, we see identical photos - the same scene, one in colour and one in black and white - because they were aimed at different audiences. One with more or fewer pillows, with sofas in slightly different positions. There was a more architectural version, intended for the specialised publication, and another more decorative, intended for the female audience. But the main point is this: everything responds to a need. Without need, there is no solution. The entire process — whether models, VR, or photography - is always a response to a concrete need.

DS – Q4.6: What kind of support or resources do you believe could accelerate the adoption of digital fabrication in architecture?

LM: There's no secret. It's just… like I said before: If you don't need it, you don't learn it. If you don't use it, you don't discover it. If you're comfortable with your way of being, you don't change. You continue. If you've always done things one way and want to keep doing them like that, and you have no reason to change, then you don't change. Technology is only implemented and used by those who consider it necessary. There are very few "technological speculators," those who constantly change their TV, always looking for the newest, biggest model. But if you're comfortable with your TV, you only replace it when it breaks. You buy a new washing machine when the old one stops working - at the end of its life. In architecture, the scenario is different. You can't let technology "die." You can't use the same computer for twenty years, technologically it might even be possible, but for our profession, no. But, at the same time, it's like a wave. We have to always be at the top of that wave. If you're not up there, if you get too comfortable with the technology you have, you quickly fall behind - and you don't even notice. That's why continuous investment in new technology also has a psychological weight.

We create a very high ecological tension. Normally, everything we stop using is reused for other purposes.

DS: It's used differently…

LM: Exactly. It's never wasted. It's sold, rented, lent - there's always a new system to keep the cycle going. We have a maximum performance need, but our equipment still works perfectly and can be used in different contexts by other people. That's why investing in high technology, at the top of what exists, is necessary only when maximum speed, maximum performance is required. Otherwise, you need to ensure an ecological, economic return that justifies the value of the investment. It doesn't make sense for the equipment you bought to be worth less than what you would buy now. There's a

basic economic and strategic need: prevent your equipment from becoming completely outdated or idle. Now, if it's just to access the internet, a ten-year-old computer still works. More or less… nowadays, websites are much heavier.

DS: Yes, but if you have access, it works. Just slower.

LM: It's slower, but it works. And, in the end, that's it: function, need, are the elements that drive any kind of evolution - whether digital, sexual, or whatever. Without need, without a point of imbalance, there's no mutation.

ANNEX B – INTERVIEW TRANSCRIPT

Atelier Peninsular

The desire to create an interdisciplinary structure where architecture is a critical tool for understanding and cultural transformation led architects, landscape architects, and an anthropologist to found Atelier Peninsular. Based in Lisbon, the office brings together professionals trained in Lisbon and Milan, with experience in cities such as Dessau, Berlin, Copenhagen, London, Paris, Rotterdam, Berkeley, and Manchester. These experiences enable practices that synthesize different scales and programmatic and pragmatic approaches. The office is distinguished by applying holistic and subversive processes within the logics and rules imposed on the landscape and urban and social fabrics.

Interview conducted via ZOOM on 08/04/2024.

PART I: INTRODUCTION AND MOTIVATION

Daniela Silva (DS) - Q1.1: When and why did your office start incorporating digital tools into architectural practice? What was the initial catalyst?

Emanuel Diogo (ED): I might have a slightly different perspective from yours on what "digital tools" are. We like these technologies, yes, but we don't use them 100% yet. We are actually going through a transitional phase. Currently, we are seven people in the office, and we are implementing Revit as the basis of our work. The entire team, including ourselves, is in training, and we have the support of a person specialised in BIM, who is helping us define the internal protocol, structure the base template, and create a more solid system to move forward. Besides that, we have also started exploring 3D printing - we mainly use the printer when we feel that a model needs more detail to support decision-making. It has been a gradual process, but we have been making that effort. Our main goal, by the end of the year, is for the whole team to be working in Revit. From there, we want to take full advantage of the tool's potential: not only to improve our productivity and consistency in project development but also to facilitate integration with other technologies we want to explore, such as virtual reality. At the moment, we are still working with several tools at the same time - part in 2D, part in Rhino, then we move on to another software - and that makes the process time-consuming, fragmented, and often demotivating. Time is a precious resource, especially in a small office like ours, where human and financial resources are limited. We believe that adopting Revit will be crucial not only to improve our internal processes but also to reach a more specific type of client with whom we want to work in the

medium term. If we can't make this transition smoothly in the next two or three years, I truly believe we will lose competitiveness.

DS: So, just to clarify: in the case of Revit and the BIM methodology, did you start the implementation this year or already last year?

ED: Yes, the decision was made about a year and a half, maybe two years ago. I had never worked directly with BIM before - I used Revit, but never in a structured BIM system. However, when I worked outside of Portugal, I had contact with that kind of organisation and understood its value. Only now, this year, with some financial leverage, were we able to really invest in training the team and have someone help us implement the system more stably.

We want the system to be well set up because that person might leave one day, and the process has to continue. So yes, the decision to move forward was made some time ago, but only now have we been able to take the effective step to integrate these tools in a structured way in our office.

DS – Q1.2: What were the main motivations for adopting these technologies? Was it a response to digital evolution, or were there other reasons?

ED: The main motivations for adopting these technologies were, above all, the need to be more competitive - both commercially and in the quality and efficiency of project production and decision-making. For example, we had a project where we didn't yet know how to work in Revit, but even with a basic 3D model, we immediately noticed the positive impact. Just being able to make decisions in plan, see sections and elevations in real-time, and understand spatial transitions… That brought a much higher level of information and control.

DS: So, you feel you can have more control over the project.

ED: Exactly. And it's not just control - we can present with more quality and criteria, without leaving so many decisions to chance. When working in AutoCAD, which is basically an "infinite page," producing drawings takes a lot of time. And that often leads to delaying decisions that later end up compromising the project.

In the case of a housing building we were developing, we realised that we had made mistakes when drawing the facades - precisely because we hadn't modelled it in 3D. We went back, asked someone to make a Revit model for us, and in two or three days, we made decisions that substantially improved the project.

This transition is also linked to ambition and emerging opportunities. Our work has a strong commercial search component, and since our network is small, we need to be competitive - and that implies investing in process digitization. In addition, this digital capability attracts another type of client. If everything goes well, maybe two years from now we will already be able to present a virtual reality projection of a project still under construction.

DS: Which greatly facilitates client communication, right?

ED: Yes, completely. Communication is fundamental. Even experienced clients, such as investors, cannot easily abstract when looking at a plan or a section. 3D visualisation helps a lot in that sense.

On the other hand, I also had contact with these tools outside Portugal. I lived and worked abroad for several years, and I remember that already in 2012, 2013, 2014, Revit and other BIM platforms were in high demand. When I returned to Portugal in 2017, I realised that it was still starting here, with some delay. But I don't think it's for lack of will - I think the problem is lack of means. The transition to a tool like Revit requires more than buying software: it requires preparation, training, process systematization, financial investment - and all that is difficult for a micro-company like ours. Our willingness to migrate to Revit took time to materialize precisely due to lack of resources. We needed to gain some experience, consolidate the office base, before we could invest in training, hire someone, and only then start implementing the system.

DS: There is also an issue of access to financing, right?

ED: Yes. Here in Portugal, everything came out of our pocket. It is very difficult to access grants or support because many programs are aimed at technology-based companies. Architecture offices are often marginalized, as if they were not "digital" companies.

DS: This is something other offices also identify - the high implementation costs and the lack of specific support for the sector.

ED: Exactly. It's not just the cost of the software, it's also the training, process adaptation, hiring someone to guide us. I'm not a BIM manager and I don't want to be - I want to continue being an architect. I'm lucky that my girlfriend is a BIM manager and understands the process. There's a mismatch between political intentions and business reality. There's a lot of talk about digitizing companies, supporting startups, but many small offices like ours are left out of that support.

What we advocate is not free money - but access to investment, support that allows us to structure the office, and then step by step return that investment with work and results.

DS: So, the point is not to marginalize small offices in the digital transformation process.

ED: Exactly. Because honestly, when we look at the requirements of those applications, we immediately see that we don't meet even 20 or 30% of them. We do what we can with the resources we have, little by little and patching things together, but ideally, we would have real support. I'll give you an example: I worked in an office in France where the State already required the transition to BIM for public works. The company had the capacity to hire someone to lead that transition, and the State funded training for the entire team in ARCHICAD. A trainer came to the company, and all employees were trained. There's a different dynamic, a different understanding of its importance - they understand that it's essential for competitiveness, not only in the country but also abroad. So yes, the

main motivation was to be more competitive. Of course, 2D is still faster for drawing and thinking - and I'm still used to it - but I know that those tasks are being done by other people, with other skills.

DS – Q1.3: Can you describe a project where the adoption of digital technology was crucial to its success?

ED: Yes, there was one project where digital technology played a crucial role. It was a residential building with about 90 apartments, approximately 7,000 square metres of built area. In the initial phase, we started by modelling the entire building in Revit, with the support of someone who, although not very experienced, helped us make some important decisions. The "skeleton" of the building was defined in that model. However, that person had to leave the project. And that's when we learned an important lesson: working with Revit can be very interesting, but it only works well if there's a structure in place - with protocols, templates, and a team that knows exactly what it's doing. That was when, with some financial support, we decided to invest in internal training, selecting a collaborator who was enthusiastic about the tool to lead the process with us.

DS: But in that initial phase, there was a setback, right?

ED: Yes, exactly. That investment happened during the preliminary design phase, but that collaborator ended up leaving almost at the end of that stage. Since we were working against time, we had to go back to 2D to be able to deliver the project on time.

Even so, there were difficulties with licensing. We had doubts about our level of control, even with the models made, and some decisions remained unresolved. That's when another person joined us and helped resume the Revit model, going back to 3D work. That return to the three-dimensional model was essential, especially for the final decisions about facades, volumetry, and transitions between elements, such as from the gable to the main facade. It took some time to get the model functioning well, but the truth is that decisions began to be made with much more precision and speed. The difference was remarkable. Later, during a competition, even though we were still working in 2D, we kept discussing how to solve the roof, the top floor, and when we received the 3D model from the rendering team, we managed to unlock the process. They designed the model and navigated through the project with us. That allowed us to clearly visualize how decisions would materialize - how the facade rhythm would look, the materials, the coherence between elements.

There was one decision I made at that moment - still during the competition - that stayed in the project until the end, despite all the changes and nuances that came later. And that decision made sense until the end. Therefore, this three-dimensional visualisation capacity, even if virtual, was decisive. It's not comparable to drawing in 2D, especially when it comes to facades. Personally, I find it easier to work with plan drawings, maybe because I like them more, but when we move into three dimensions and work with two scales simultaneously, everything changes. That transition helped us immensely, both

in this housing project and in the competition that took place simultaneously. And we quickly noticed similarities in the process because both projects were based on the same principles - and digital technology was, without a doubt, central to this journey.

DS – Q1.4: Was there any model or example (national or international) that inspired your transition to using digital tools?

ED: Honestly, I don't think there was one specific model. I've always had a natural interest in these areas. Since I was a kid, I liked computers and everything related to standardised systems. I even wanted to create computer games - so that curiosity always kept me alert to the digital world. But I wasn't always able to dedicate as much time as I wanted. I wish I had more time to learn Revit, deepen my skills in 3D programs, and practice digitalisation more. I've insisted on that a lot in the office - we're three partners - but I recognise it's still a trial-and-error path. Today you try one thing, tomorrow another. I keep researching, testing, experimenting.

For me, rather than following a concrete example, it's about staying alert to trends and understanding what's happening. And if it's something that has always interested you, that impulse eventually arises naturally.

DS: In the end, that also reflects your background, doesn't it?

ED: Yes. When I was in university, nobody used Rhino - but I was already exploring it. And that ended up being an advantage. When I went to work abroad, for example, in London, it was very easy to get a job because, in other cultures, the use of these tools is already much more ingrained. In our training in Portugal, the foundation is more design-centred, whereas abroad, the focus is much more constructive. The work is always three-dimensional, with a strong connection between form and execution.

I was involved in a large project in 2015, perhaps the biggest I participated in, with around 60 to 70 thousand square metres of construction. And even then, we used virtual reality in presentations. Developers would come, put on the headset, and see the project immersively. That eliminated almost all doubts - there was no room for "maybe" or "I don't understand what you mean." There was immediate empathy with the project; it was direct and effective communication.

DS: A universal language, basically.

ED: Yes. And you notice it right away in the teams. I remember working with a guy from the United States who did everything in Rhino - 2D, 3D, execution images, renderings - all with a touchpad, without even using a mouse or keyboard. He had an impressive production speed. I didn't have that work culture and couldn't keep up. And then I realised it's not just talent, but training and constant practice. Then there's that idea: "Oh, the Portuguese abroad are good." And they are, of course. But in some cultures, the lack of technical and digital preparation makes entry much more difficult. There's a lack

of using digital tools as an extension of design thinking. When I came across that, I thought: this guy is a machine. He didn't solve technical issues, but he could resolve the project - communicate the idea clearly, reach the client, present with strength. I also worked with many Spaniards - it was curious because they had a very solid technical background.

DS: Yes, their schooling is very technical.

ED: Very. But the interesting thing was seeing how those two worlds balanced: on one side, conceptual quickness and idea definition; on the other, technical execution capability. We were talking about someone digitally sketching by hand, solving spatial problems while simultaneously creating 3D images, renderings, digital models - all in sequence, with impressive agility. That's when I clearly understood why those teams win large-scale projects. It's a different level of demand and preparation.

DS – Q1.5: What were the main perceived benefits that motivated the adoption of digital tools?

ED: The main benefit was the ability to make decisions faster and more clearly. Digital tools, especially BIM, allow for a more integrated project management - from modelling to measurement schedules, including visual communication. We are still learning, but the truth is that the gain in efficiency is huge. Doing everything manually, between AutoCAD and Excel, is slow and unproductive. Well-implemented BIM reduces resources, time, and errors - which allows us to think about projects on another scale and with another type of client.

Also, there's a new generation entering the market already with this motivation and openness: they want to work with these tools, want to experiment, test, propose -even when there are mistakes.

DS: In our office, we feel the same. The difficulty in finding available and qualified contractors is growing.

ED: Yes, and that's linked to something bigger: traditional construction is wearing out. There are no longer specialised craftsmen like before. Master builders, carpenters for formwork, that technical know-how is disappearing. It will become a niche - accessible only to an elite. That's why digitalisation is inevitable. And it's also essential to make construction more attractive to new generations, who don't want to work "in the mud."

I saw it up close in a factory in the north, already with digitalised modular production. It was a clean, technological environment, with young architects and engineers working directly on construction components. That is the future that can bring young people back to construction. Now, the challenge is structural. There is a lack of articulation between industry, offices, and training. If in 2026 projects are required to be delivered in BIM, who is prepared? How can that transition be made realistically? The truth is that only with digital production can we link all phases of a project, from design to construction. But in Portugal, we are still far behind - even compared to Spain.

What is missing? A strong construction industry. If it existed, these tools would already be integrated into the process. In countries like Germany, France, or the Netherlands, the industry invests in architecture, collaborates with offices, and drives innovation. Here, we are still waiting for something to change. But inevitably, it will have to happen.

PART II: BARRIERS AND CHALLENGES

DS – Q2.1: What were the main barriers you faced in implementing digital fabrication technologies?

ED: The main barrier has undoubtedly been cost - both the initial investment in tools and the fees associated with their application, for example, in BIM projects. We have proposed such solutions to institutional clients, with financial capacity, but even so, we hear that "there is no need." There is a very conservative culture resistant to change, where savings are often made in areas that, in the context of a 12 or 15 million investment, make no sense to cut.

In addition, the industry is very fragmented. Some work with one software, others with another, and there is no common basis or legal requirement to standardize processes. That creates collaboration obstacles. We also feel a lack of strategic vision from many decision-makers. The thinking is still small-scale. There is little understanding that investing in digital tools generates real returns in the second or third phase of the project - especially when working with professional teams capable of anticipating and solving problems on-site.

DS: And there is still structural resistance to change. Even when technology is available, there is a lack of interest, a lack of understanding of its practical impact.

ED: I believe the change will come with the arrival of foreign clients, used to another speed of work, another culture of investment and technical requirements. That will force the market to react. Either companies adapt, or they disappear. Unfortunately, we still live very much in that "good and cheap" logic, which in the end is not good - it's just cheap.

DS – Q2.2: Are there any local policies or regulations that facilitated or hindered the adoption of digital fabrication in your practice?

ED: We don't feel there are clear policies that facilitate digital fabrication adoption. What stands out most is the lack of structure - there is no alignment between institutions, industry, and academic training.

DS: Yes, perhaps now, with the new Construction Code coming into force and with the regulations related to BIM, there may be some change. From 2026, it seems it will be mandatory to deliver projects in BIM or at least in a collaborative network format.

ED: But even so, I wonder: how will a City Council—apart from Lisbon and Porto—have the capacity to follow that? Many public institutions are not prepared. At the same time, professionals also need to build capacity. This is not just a matter of technology. And it's frustrating to see how only now BIM is starting to be talked about as if it's something new when abroad it's been used for 10 or 15 years. There is a lack of structured training.

I know of a Dutch program where students do internships from their second year and work in digital environments from the start. Here, even specialised programs—like BIM master's degrees—end up being inaccessible for those who don't meet certain requirements, like five years of experience. That blocks access for those motivated to enter the market with new skills. Also, I notice schools have very unequal training. Those from technology-focused institutions are better prepared. But many architects graduate with no real contact with digital fabrication or project management tools. And that is reflected in practice.

We are implementing a project management system based on data and algorithms. It allows us to know who is doing what, with which tool, how long it takes... it's essential but forces us to completely rethink how we work. It's a risky leap. For a while, you feel like you are losing control; you must step out of your comfort zone. But it's necessary. The problem is this transition is not accompanied by coherent public policies. There is no integrated strategy between academia, industry, and the State. Without that, small offices are left on their own trying to adapt, and that creates anxiety. But it is inevitable. The only way is to start with small projects, test, learn, and grow from there.

DS – Q2.3: How has client perception influenced or affected the implementation of digital tools in your practice?

ED: Most still see the architect as someone who "makes the drawings" - a very reductive view of our work. Few clients recognise our value in all project phases, from preliminary studies to construction supervision and construction decisions. Even fewer understand that investing in tools like BIM can drastically improve project quality and building management, saving time and resources. Working with foreign clients, for example, shows us that cultural difference: there is openness, a predisposition to understand the return on investment.

DS – Q2.4: Was there ever a case where technological or financial barriers prevented the implementation of digital tools in a project?

ED: The biggest barrier we faced was clearly financial, not technological. Internally, we have the ability to adapt and a culture of continuous training - in fact, we set up our own systems and invested in Revit training since 2018. However, this transition requires much more than installing software. You need to

create protocols, templates, methodologies, ensure continuity even with staff turnover - and all that requires investment and time.

For a small structure like ours in Portugal, that kind of transition means creating a financial cushion to invest safely. For example, there is a lack of credit mechanisms or innovation support - I'm not talking about subsidies but something that facilitates this step. We are preparing for a stage where, even before moving forward with the full project, we want to know what the ideal structure is and which national industry can respond to that need. And if it doesn't exist here, we are willing to look for solutions in other countries.

For that to happen, it takes much more than architects' will. The construction industry needs to evolve, and everyone involved - technicians, municipalities, developers - must follow that path. Without it, it will be difficult to respond to today's housing scale challenges.

PART III: EVOLUTION AND CURRENT IMPLEMENTATION

DS – Q3.1: Do you identify any historical milestone that you consider pivotal in the evolution of digital fabrication in architecture?

ED: It's precisely in real-time decision-making that we identify an important milestone. Many times, in the traditional process, we postpone certain decisions until the end, and then there is no time to make them with due reflection because too much time was lost drawing plans, sections, or repeating processes.

When you have the ability to visualize proposals in multiple dimensions and from different perspectives - whether graphically or descriptively - it becomes fundamental. All that information can be communicated quickly and clearly, which greatly facilitates decision-making. Unlike 2D drawing, as in AutoCAD, where information often doesn't communicate anything by itself - they're just lines - with digital fabrication, the information is richer and more integrated. This allows for a more complete understanding of the project and more effective decision-making from the start.

DS – Q3.2: How is digital fabrication currently used in your practice? Do you use 3D printing only to make models?

ED: Yes, but I think it's more than that, it's an example of what I was saying. Just to give you a small example: we obviously produce the main parts, like the facade, in cardboard. But all the more complex elements (like stairs, rails, window frames) we make those with 3D printing. For example, this staircase: we wouldn't have known exactly what it would look like if we hadn't made a 3D model several times and tested it. Only then did we realise: "Okay, this is what we want." It was essential because it's very

difficult to do this any other way. Undoubtedly, this process helped us a lot to understand how the pieces fit and connect. It's a small example but quite illustrative.

DS: So, I can say that, in your case, you use digital fabrication as support in the project development process, to test solutions?

ED: Exactly. It's another element in the project decision process—to think, reflect. Of course, we also try to make the final result well-presented, to show the client. That's where the communication part comes in, but that's a secondary stage. The main goal of that little machine is not that—it's, above all, a design tool.

DS – Q3.3: What are the main lessons learned that you could share with other offices considering exploring digital fabrication?

ED: I think, more than sharing lessons, I wish someone had taught us a few things. We've lost so much time learning on our own... I feel that many offices are in exactly the same position: all trying to figure out how to do it, without a common basis. And that makes everything harder. When there is communication and dialogue, everything changes. Without it, it's complicated to know whether we are doing it right or wrong.

So, maybe it would make sense to create a space, a forum, for example, where people in the field could exchange ideas. Maybe even involve the Order of Architects, to give some more formal support. Something that offered training or at least some guidelines. Because sometimes in training, it's not so much what the instructor says that matters, but what you learn among the trainees themselves, when they share experiences. Without a doubt, it's that exchange that makes the difference.

DS – Q3.4: What have been the key technological developments that facilitated the use of digital fabrication in your practice?

ED: Honestly, I wish I had more time, more time to really invest in 3D printing, and I'd also like to have two or three more machines. Only then could I understand what it's like to produce multiple parts simultaneously and how that could better inform the design. Having only one machine isn't enough: production isn't scalable, and the printing pace is quite slow. To produce, for example, an entire facade with detail and precision, as we want, you need to have several machines working at the same time.

That capacity would allow for better-informed decisions, in useful time. It's a matter of resources and scale. Maybe, by the end of this year or the beginning of the next, we'll be able to acquire another, faster machine that helps more with production. I'd really like, for example, to see a full-scale 1:1 model made with digital printing.

When I visited a factory near Braga, I was amazed by the potential. I was still at the beginning of my experience with these technologies, but that impressed me. It was a very significant moment. There

are already companies working in that direction. One has already built parts of a house in 3D printing. However, I feel that often that knowledge stays too closed within an academic bubble. There are many things developed that don't reach practice. But it's also true that there's a lack of dynamics between academia and industry.

And it's not just about technology. It's about the role of the architect in society. Digital tools are not, by themselves, the salvation of the profession, but they are part of a new universe that changes the language and perception of what it means to be an architect. They allow us to negotiate better, state our ideas more clearly, and occupy a more relevant place in decisions about territory, infrastructure, and resources. The architect doesn't have to control everything but must be present.

Our work has been devalued in Portugal, partly because of us, our professional and academic culture. The 2008 crisis weakened the profession even more, institutionalizing precariousness.

DS – Q3.5: How has the integration of digital tools affected collaboration within the office and with other stakeholders?

ED: The integration of digital tools had a very positive impact on collaboration within the office. A good example was when we were all gathered around a screen, analysing the digital model of the mock-up. That allowed us to make decisions together, in an informed and comparative way. The digital model clearly demonstrated the options and clarified doubts, the questions that arose were about definitions, not about going back because something hadn't been thought through. There was a feeling that we were taking a step forward, that decisions were being well made and supported. That helped consolidate the project, or at least that stage of the process, and move forward with more confidence.

PART IV: FUTURE

DS – Q4.1: How do you see the future of digital fabrication in architecture?

ED: As we were saying earlier, if you resist change, you simply won't be able to keep up, with either the market or the profession. It's not possible. Only those who really want to continue evolving will be able to follow this path. Companies must evolve, and the architectural business ecosystem too.

It's partly our fault if we don't evolve. We have to take responsibility and make decisions. It's not about controlling every aspect of implementation, but about understanding the changes needed and coordinating the right people for that transformation. It's more about management and coordination than assuming all the technical or creative processes alone. Someone will handle that, of course. The essential thing is that we want to speed things up, transform, keep up with trends and demands happening abroad.

I truly believe that soon we will see a change in attitude in companies in our field. We are heading toward greater professionalism and stronger skills for everyone involved. And that includes not only fair wages and proper working conditions but also real investment: time, money, and energy. To attract and retain people (because companies are made of people) it's not enough to offer good pay. The work has to be engaging. The change has to be appealing.

Nowadays, those entering the market want more than financial stability. They want to feel relevant. They want to know they are contributing to something that evolves, adapts, and brings challenges. I talk to many young professionals, and for them, it's essential to see that the companies where they work have this ability to renew, transform, and follow new trends, like digitalisation, for example. That wasn't taught in our education, but it's unavoidable today.

That's precisely why we decided to move forward with all this training in the office, to motivate the team. They completely understood that this takes time, that it can't be implemented overnight. They already know what our vision is. We appointed someone to lead this transition, and she accepted immediately. She's 25, her name is Ana. And the fact that she feels valued, that she sees her work making an impact in a field she likes, makes all the difference.

The knowledge she is gaining will naturally spread to everyone. I don't have to do that work directly, the important thing is to let it happen, to create space for others to do it. And we all grow from that.

Now, those who resist these changes… will face many difficulties. There are still offices stuck in other times, other generations. And that makes everything harder.

DS – Q4.2: What are your expectations or plans for expanding the use of digital tools in your office?

ED: Ideally, by the end of the year, we want to fully implement BIM. That's really the next phase. It was my personal decision - to make that happen. Each one is moving forward with certain parts, but we're all aligned on that goal: by the end of the year, we want BIM fully implemented. Then there's also the desire that, next year, we'll be able to invest in another tool, maybe something more focused on 3D production, which is a more immediate need.

It's not just about installing software - there's a whole process involved. This connects to the issue of transitioning between design and construction. I still feel there is a "gap" there that I don't yet know exactly how to fill. I need to better research how to do that preview and control work of what will actually be executed on-site.

I'd like us to be able to add more value to our work - not just financially, but also in terms of the technical and conceptual value we bring to the project. There's also another important dimension: process and project management. We're trying to understand how we're going to integrate those tools in that phase too, more related to coordination and management.

The idea is not to be constantly producing but to know how to look at what is being produced, understand what data those tools give us, and how that data helps us make decisions. Later, maybe in three or four years, we'll be able to more critically understand the real financial impact of this digital transition - the return, the management gains, and how that affects the office's financial health.

DS – Q4.3: How do you think your approach to digital fabrication compares with that of other offices?
ED: We don't really know. Not even regarding the offices closest to us. It's funny because... I won't name the person, because I don't think I should, but it's someone very close to us - and he's a great architect. He still works a lot with drawing, mainly in 2D, but when he has bigger projects, he collaborates with someone who has already worked with us here in the office. That person works in Revit, and he loves it! And even though he's much older than us, he ends up being more advanced than us in that sense - he clearly understands the value of the tool. And we've seen that reflected in his work. When we look at what he's doing, we realise: "Okay, we really have to follow that path." Because if he, at 65, is doing it, then we also have to do it.

DS – Q4.4: How would you compare the adoption of digital fabrication in architecture in Portugal with other countries?
ED: We're way behind; there's no point even thinking much about it.

DS – Q4.5: What emerging trends in digital fabrication do you find promising or interesting for architectural practice?
ED: Regarding emerging trends in digital fabrication, I think Twinmotion is an interesting tool. I'm somewhat familiar with what it involves, although I don't yet know to what extent it's being implemented in our area - in architecture specifically. From what I know, there are some studies more focused on sports, where such simulations are used to define strategies.

Now, how that could be implemented in construction, in architecture... I don't know yet. But I believe that yes, somehow it could become part of our practice's future. However, I think the transition from Twinmotion to architecture isn't that straightforward. It's quite difficult. It requires a lot of work and resources. And you also need well-trained professionals capable of mastering multiple tools simultaneously. Because we're not just talking about Twinmotion, but also artificial intelligence and other emerging technologies.

DS – Q4.6: What kind of support or resources do you believe could accelerate the adoption of digital fabrication in architecture?

ED: Opening up support funds would be essential. For example, a line of credit through banks, co-financed or initially supported - and then we would repay that amount - but without being penalized with brutal interest rates. It would also be important to streamline these processes and, later, to have an evaluation: what was done with that money, how it was implemented, whether it really had an impact.

That evaluation shouldn't be only from our side but also from those who facilitated or financed the investment. It's essential to know if it was indeed a good investment.

But attention: this has to be directed at microenterprises. It can't always be the same big companies benefiting. It's necessary to support micro and small companies, which represent the vast majority of the sector in Portugal. Only then can these companies take the leap, become competitive, value their work, and improve their conditions.

We keep repeating these ideas because nothing concrete is done yet. I believe - I don't have the exact data, but I believe - that 95% to 98% of the business fabric in our field is made up of micro-companies. Companies with three, four, five, eight, ten employees, which can't get out of this situation because they don't have the financial capacity to invest.

It's not that all of them need to grow at the same rate, but they need support to scale. The most important tool we have today is precisely this: being here, in front of a computer, and being able to add value to our work with these technologies. And these are the tools that allow us to be competitive in other markets - not limited to the national market.

Because just as foreign architects are building in Portugal, why shouldn't we be building abroad? For example, like we talked about Gulbenkian: you enter a market like the Middle East, Asia, or even Europe, and you see companies from all over the world working remotely, producing architecture, doing network collaborations. They are huge work networks. And we here are still very limited. How many Portuguese companies are really working abroad? One, two?

If we really want to export our services - and that is essential for our economy, because we are a country of services and tourism - then we must empower those who are really working. And, in this sector, micro-companies are doing heroic work, constantly juggling to stay afloat.

ANNEX C – INTERVIEW TRANSCRIPT

CVDB Arquitectos

The architectural office CVDB Arquitectos was founded by Cristina Veríssimo and Diogo Burnay in 1999. The company's activities encompass various fields of architecture, including urban projects, the rehabilitation and construction of new buildings, the remodelling of interior spaces, and temporary structures. The professional practice of the office is based on architectural research where each project is understood as a field of experimentation open to all participants in the process, viewing architecture as part of a broad physical, social, and cultural context.

Interview conducted via ZOOM on 04/03/2024 and 11/03/2024.

PART I: INTRODUCTION AND MOTIVATION

Daniela Silva (DS) - Q1.1: When and why did your office start incorporating digital tools into architectural practice? What was the initial catalyst?

Cristina Veríssimo (CV): So, it was about six or seven years ago, I think. This whole BIM thing started to appear, right? We are also in the academic field, so these things also reach us faster. So, I'd say it came almost through academia, if you will. That would be the correct answer. But then what we did was start asking friends who were somehow already beginning to use these kinds of tools. So, our approach with them was to try to understand the advantages of these methods and these transformations, what this could bring to the office. I confess that the people who worked with us at the time were not… the most receptive. You know what I mean? Our collaborators did not want to change much in the method we were using. And I'll explain why. Because, right at the beginning of the office's first decade, we basically transformed AUTOCAD into a rather complex instrument. And at the same time, with huge advantages. It was all about layers, layer management, if you will, which made all the floors interconnected. So, it was almost an ARCHICAD adapted to AUTOCAD. And this method had many repercussions because even our former collaborators continued using this method. And not only that, our engineers, for example, started adapting to it. The builders on site also adapted. We would give them the files and all these things, and they started using the same system as us. Since this method was quite revolutionary at the time - because someone in our office set it up, he was a "brain" in these things - this made people a bit reluctant to change systems. So, what happened? Over time, we began to realise we couldn't continue this way and started adapting to more three-dimensional

tools, both Revit and Rhino. And this gave us other possibilities. So, to answer your question, it started through academia, but indeed it met some reluctance from our workers.

DS – Q1.2: What were the main motivations for adopting these technologies? Was it a response to digital evolution, or were there other reasons?

CV: Look, it was also a bit circumstantial, because above all, the great usefulness of these new tools was 3D visualisation. And not just 3D visualisation, but also the ability these programs had to cut, to make cuts from different places. So, an ease, let's say, in understanding the project. Up until then, we used a lot of physical models. Physical models were very much the tool. Also, because I had come from Zaha Hadid, you see? Zaha Hadid didn't have, if you will, computers when I joined. What we did was models; we cut the models into pieces and made sections, you know? Yes, yes, yes. At the beginning, I think the model was our tool because I had already worked with much more complex things, and we managed to do them with models. Then people started using computers, and things became more efficient, I would say. This idea made… Oh, and then we also had transitions to various offices, where space was reduced. And then 3D modelling was not only already difficult to find someone willing to do, because in the office it was mostly me doing the physical models. And when we moved to Canada, it was even harder. I didn't have as much time to dedicate to a model, you know? So, it made things a little harder. And so, 3D became almost day-to-day. The people we started hiring knew how; so even if the older staff didn't know, there was always someone who did. And, let me tell you, perhaps because of that, we started doing slightly more complex projects. Because, "hey, let's curve this, let's try that," and suddenly it looked great...

DS: And you had faster feedback...

CV: Completely! As for our clients, yes, it was useful, but clients continued to physically request models. And sometimes it's even easier to have a model at a city hall for a competition we won than a projection. Or even a video or 3D images, because the model is displayed at city hall, and they prefer that. Or because the client has the little house and says, "look, I'd like to better understand how this and that works," and we made the model and everything else. So, what am I saying? That until then, we already had communication tools. 3D obviously allowed other things. Plus, we started doing 3D models, 3D printing, right. So, physical models made by computers. Suddenly, we thought, "well, this actually might have advantages." And so, we started using it, because it made things easier, as you say, it saved time and, in reality, combined several things because the physical model still appeared.

DS: So, it didn't replace; it complemented.

CV: It complemented, exactly.

DS – Q1.3: Can you describe a project where the adoption of digital technology was crucial to its success?

CV: Yes, this last project, the Supreme Court of Mozambique. In Maputo, it's all based on curves. That project uses a lot of digital tools. Now, I can tell you something curious: when this goes to Mozambique, those three-dimensional tools, forget it.

DS: Yes, it's another language, there has to be a transition.

CV: Exactly. PDFs, drawings they can read, because there might be one or another person on site who uses it, but it's rare, and then you pass it to the foremen and workers.

DS: So that's the barrier, isn't it?

CV: Completely. We even sent it to carpenters and locksmiths because we thought they might have these tools, right? And everything is digitized.

DS – Q1.4: Was there any model or example (national or international) that inspired your transition to using digital tools?

CV: We talked to several friends. One of them is Francisco Teixeira Bastos, who is from Técnico. He's from BIM, digital tools. I went several times to his office, including when he used the model in his office; I went there to visit them. I basically tried to learn as much as possible. However, there's something funny, which is that new people arrive and are more used to using different kinds of programs, whether it's Rhino or Revit. The Mozambique Court project allowed something we did, which today we obviously regret, which was having 20+ architects working and we said, "OK, we'll coordinate," but we let the tools dictate, and we wanted them to work in groups. At some point, coordinating various types of programs created problems.

DS: OK, I see. At the beginning, it might have been easier because each person worked with the tools they were most comfortable with, but later in the project, it complicated things.

CV: Exactly, it complicated things. So, what does that mean? That right now we're in a limbo because we're starting to want to impose Revit, for example, which we didn't do until then. But suddenly, we're saying, no, let's just use one tool because this was a disaster, you know? Here in Canada, basically everything is done with ARCHICAD. In Portugal, ARCHICAD is not something that's widely used, you know? Anyway, we need to establish a rule because, depending on our work requests, we also need to…

DS: …be flexible.

CV: Of course. We have to be flexible with what's asked of us. I already gave you the Mozambique example, now I give you the Canada example, but these are different tools, different types of work, etc. Now, one thing is clear to us: for decades - and our office is over 20 years old - we've always had fantastic quantity surveyors. People we are on a first-name basis with, practically part of the office.

And lately, not only do we have to measure the work ourselves in the office, but when we don't want to measure and want someone very responsible to do it, we run into serious problems. And I emphasize the word serious here. People no longer have the teams they used to, teams that supported us are now doing other things; there's a major difficulty in the measurement area, which, if we were completely on BIM, maybe wouldn't even be an issue, you know? And we're not fully in BIM because we have a mix of things.

DS – Q1.5: What were the main perceived benefits that motivated the adoption of digital tools?

CV: Well, that's one, isn't it? Measurements and all those things being, let's say…

DS: More optimised, right?

CV: Yes. If you come here to Canada, where we are, there's one thing I think makes an enormous difference, which is that every worker has an iPad. They turn on their iPad and show or record what you want on the spot. So, no printed drawings. The other day, I visited a huge construction site, a convention centre, and I was amazed and said, "So, where are the physical drawings? Locked in a room?" The physical drawings were locked in a safe, like a precious item for them, but on a day-to-day basis, everyone had their iPad and recorded things.

DS: To view the project, to take notes.

CV: Now, here's the problem: and it's very noticeable on these Canadian sites - imagine situations of lack of coordination that sometimes even BIM can't resolve because it's so millimetre-precise, you know? Imagine electrical cabling crossing over others, and the ceiling is too low to fit it all. They only look at their own drawing. So, I was on that site and said, "So, you're installing the electrical wiring here. Do you know where the sprinklers go, where the HVAC goes?" "Oh no, I have no idea." Very discreetly, you realise there were coordination problems, and suddenly a ceiling had to be lowered in another area. That shouldn't happen. The integration of things isn't done well. They say it's three-dimensional, but the truth is that when you get to the site, there are always little things that weren't foreseen because the formwork sagged or something ended up lower than planned. It's a disaster, you know? And that still happens.

PART II: BARRIERS AND CHALLENGES

DS – Q2.1: What were the main barriers you faced in implementing digital fabrication technologies?

We just talking about the Maputo project, where you had to, in part, step back because they don't have BIM, and now you were mentioning the coordination issue, which isn't that straightforward. Can you identify other challenges or difficulties? There was the team's resistance, right?

CV: Yes, there are other challenges. Because it's not just about digital tools, but also artificial intelligence. The other day, a very famous architect visited us. He's Canadian; I don't know if you know him, but anyway, very interesting. He said to me, "This is going to be fantastic. Because we're already adapting to artificial intelligence, and we'll stop doing architectural details because AI will do them." I was completely shocked. Because, listen, in our practice, architectural details still matter, because a detail is not just a technical detail; it's a philosophical, spatial detail, etc.

DS: Exactly, it's nuance, project nuance.

CV: No, I don't think they're just nuances. It's like I tell my students: you zoom into a project, and if the project doesn't hold up, something is wrong. If you don't gain quality as you look closer, there's an issue. But in this case, that architect sees the detail as just a technical detail, you know?

DS: Right, like a necessary evil.

CV: Exactly. And for that, AI is probably great because if it doesn't leak, the program itself defines how not to leak, you see?

DS: Right, exactly. It solves technical issues but not sensitivity, creativity issues.

CV: Poetic ones, if you like. There are exceptions, people with that sensitivity, but I still believe Portugal, at least in schools, has that sensitivity. I still try to teach it as a professor, but it's diluted. We'll end up with buildings that, in terms of performance, are functional, but don't make us feel the space quality that some details can give to a building. When you have an architect saying that construction details are given to an intern, that says it all. Because that person has the AI tools and is not interested in passing on knowledge, nor in understanding what I gain from a human presence in a particular detail; they just want an operator - and often, the least qualified person in the office.

DS: I think it's like saying, "I only do the conceptual part, and the details go to the contractor because they have experience." They do have experience and won't let water in, but they don't have the architect's sensitivity.

CV: Exactly! You only don't give it to the contractor because they know they need to give a budget to the client and guarantee certain quality standards. The Mozambique Court has been a curious experience because we have certain construction areas that are very developed, like CNC machines. The stone flooring, which is all curved, has a metric, but then there are finishing situations, as you can imagine, that are not easy. And the person installing the flooring isn't worried because they have CNC cutting all the pieces exactly as I want. Which is great!

Then there are other things that are common, and they can't handle them, you see? Basic craftsmanship skills are disappearing. Building formwork requires skill, and if it were all done by computer and more technologically, it would be easier. In reality, that's not happening, and there are improvised solutions. Of course, what we want is the final result, and they're trying to make the concrete look good, but those formworks are a huge amount of work because they don't have CNC...

DS: It's unnecessary effort.

CV: Completely unnecessary. And they don't even realise that, you know? Maybe because labour is cheaper in Mozambique, I don't know, but it's scary because you look at those formworks, three boards nailed together unnecessarily… totally unnecessary.

DS – Q2.2: Are there any local policies or regulations that facilitated or hindered the adoption of digital fabrication in your practice?

CV: No, I don't know of any, it doesn't seem like it. I don't think that's an issue; if there are problems, they're not major ones. Now, there's this issue of project approval in City Halls.

DS: Yes, yes, which has been simplified, right.

CV: Well, the simplification is relative because, to me, it seems more like passing on responsibility. I've already had two or three meetings with two or three different city halls, some more agile, trying to understand this, and others less agile. But it's still too early to say how this will evolve. I'm a bit reluctant.

DS: It's still very fresh.

CV: It's still very new, you see? But in terms of software, programs, no. What seems to me is that we depend mostly on who we get as new collaborators and what they know so we can adapt them. Right now, we're hiring some new collaborators, and we're a bit confused because some only know one tool, others know something else, and I'm choosing people based on their skills, based on what they already bring. So, our dilemma is: what do we do? Do we train people inside the office and spend a lot of time teaching them REVIT or whatever, or do we hire people with those skills and teach them other things? My difficulty, right now with the increasing adoption of digital tools, is mostly at that level.

DS – Q2.3: How has client perception influenced or affected the implementation of digital tools in your practice?

CV: They're not even aware of the possibilities or differences, you know? I think the client still only cares about the result. Now, we already use BIM in many cases, yes. And the client doesn't even know. They're not even concerned about what we use or don't use. However, it also depends on the scale: in small and medium-sized projects, we don't see that concern from the client. But in large projects, yes, we feel it, both from the client's request and as a necessity.

DS: So, it depends on the scale of the project because they're different things.

CV: They're not only different things but also influence how we work and how the entire team works.

DS: Yes, and the team you work with also influences it a lot.

CV: Ah, completely.

DS – Q2.4: Was there ever a case where technological or financial barriers prevented the implementation of digital tools in a project? You mentioned the collaborators' issue earlier.

CV: Yes, but that has to do with training.

DS: Right, not the project implementation itself.

CV: No. Although you realise there's something interesting: when we're in a very early phase - and this is something we've debated with senior staff - when we're trying to understand what the project is, initially, so it's more conceptual, BIM is a barrier for me. Because we're asking for too much information at a stage that's still very creative, very abstract.

DS: Too much information for an early, creative, abstract phase…

CV: Absolutely, Daniela. So sometimes I say, "Look, it's better to just sketch than to input into something where we know that out of these three or four solutions, maybe only one even has a chance," you know? And that sometimes is an obstacle because I sit with a collaborator and say, "Hey, you're already defining the handle and this and that - do we even want this solution? Is it worth it?" And then they've spent so much time giving attributes to the computer that, in the end, they look at me and say, "Yes, maybe this isn't the best solution after all."

DS: Yes, yes, yes. So, there's an obstacle there, yes. In the initial conceptual part, yes. I understand because I worked with BIM for four years, and I think it's not the program for conceptual, abstract, study phases at all, because it requires walls, doors…

CV: Exactly, tons of things - thicknesses, finishes… Sometimes people just say, "Well, colour it blue, we know it's going to be some material, we just don't know which one yet, but that one over there colour it red because we know that won't be the same material," you know?

CV: It's like what Zaha Hadid used to say, "I just want it to be this colour," and we knew that didn't mean a specific material.

PART III: EVOLUTION AND CURRENT IMPLEMENTATION

DS – Q3.1: Do you identify any historical milestone that you consider pivotal in the evolution of digital fabrication in architecture?

CV: Yes. We always need to keep the context in mind. Globally, these tools have already entered the market, and there's no doubt that, for example, in Europe - the UK, Germany, Belgium - they're being used effectively. But here in Canada, there's this duality: in very large projects, every worker has their own iPad - an enormous cost, you see? - but in small projects, they just pick up a pencil. In Portugal, for example, I must say something: after the "Parque Escolar" program, I thought there was going to

be a digital peak, and it was exactly the opposite. That shows how much depends on local context. I feel there's a big gap: most companies don't have qualified workers like before. I bring drawings to the site and spend part of the meeting explaining what's on them because people don't understand.

DS: They need detailed reading and don't realise it's all integrated.

CV: Exactly. You see? It's a step backward. Suddenly, when I go to site meetings, there are questions, and I say, "Look, it's in the drawings," but they don't know how to read them.

DS: Exactly. There's that barrier.

CV: Completely. Many times, the workers executing the project don't even have the proper tools or experience. Of course, not all of them. Our projects have this quality, this attribute (let's call it that): we go back to the essence of things. I'll give an example: the Braamcamp Freire project, which is entirely designed with a metric related to construction materials, because the cement block was the finish. And one day I got to the site, and there was a young guy starting one of those walls, and I asked if he knew if the wall was supposed to be there - he didn't even have drawings with him. And he answered, "Oh, architect, I already know. I know that one of these walls is 15 cement blocks laid together, and then there's a door." Meaning, he understood the project DNA and was already doing it. And he was absolutely right.

DS: He took time first to look at the drawings.

CV: And then he started executing. If he learned how to do one, the others are all the same. Some architects don't understand that. But he, who was building it, did. And that's what matters!

DS – Q3.2: How is digital fabrication currently used in your practice?

CV: We're using BIM in parts of projects; we're not managing to adapt BIM to an entire project yet. However, in smaller projects, with smaller teams, we can. For example, imagine a house. We can adapt BIM, but maybe it's not financially the most efficient project for BIM.

DS: Yes, but maybe for you it's also a tool to discover, to train collaborators, and to outline methodologies.

CV: Exactly. You got it. Ideally, I'm still waiting for a tool that will replace BIM. I think BIM overcomplicates certain things. So, I'd be waiting for a second generation of BIM to move forward. But I think it's kind of inevitable. Basic things, like even finding a quantity surveyor, don't exist anymore. If it's not in BIM, you can't find anyone to measure the project. And if only for basic things like that - which is a bit silly, but it's true. Another thing we're trying to adapt is how information is passed between collaborators; often we have issues understanding how information flows. Sometimes attributes change, and no one knows how it happened, and this can have major consequences. There need to be reference notes saying, "I changed this thickness or did that."

So, there are coordination things that deserve improvement, even if it's just a command saying, "modified on this date by this person…"

DS: To track what's...

CV: Exactly, the information, what was changed.

DS: But this is for BIM. And digital fabrication, in your case, is it only used for model materialization?

CV: Basically, yes.

DS: So, you always end up working in 3D, with BIM in a digital environment and the model through digital fabrication becoming physical.

CV: Now there are many more possibilities with CNC, for example. If you have a lot of curves in a project, no problem, because CNC does what you want and all differently if necessary… there's an expectation of digital prefabrication on the contractor's side that until now wasn't available to us. It's really interesting.

DS: Yes, you can see the immense opportunities and possibilities.

CV: Completely. It's a relief for creative freedom.

DS – Q3.3: What are the main lessons learned that you could share with other offices considering exploring digital fabrication?

CV: We are going through a hybrid phase. Our projects have not yet found the necessary receptiveness from clients to be fully implemented, as happened, for example, with the Mozambique Supreme Court. This leads us to believe that, at the moment, we have more to learn than to teach. An episode I experienced in Canada illustrates this challenge well. I observed that the workers on site used iPads to control their tasks, which is a technological advance. However, when I asked an electrician what height the suspended ceiling would be at, he didn't know. He said to me: "I only know I have to bring power to this light fitting at height X and then I'll put in the lamp at the end." I was perplexed because that's a basic detail. His concern was only with the visible part of his task, the lamp. This situation made me think: what if things don't work 100%? What if not everything is perfectly aligned? Each professional seems focused only on their task, without an understanding of the overall project, functioning a bit "going with the flow."

The big lesson we take from this is that technology alone is not enough. There must be a culture of integrated project design.

There is an interesting story about Siza Vieira's Bairro da Malagueira, shared by José Pinto Duarte, which shows how Siza himself recognised that a computer could extrapolate more possibilities in seconds than he could think of in his head. This proves that even great masters see the advantage of digital tools. However, the Canadian example shows what happens when, in practice, each person does their part without communication: architecture suffers. Therefore, the main conclusion is this: BIM is

an excellent tool, but its advantage drastically diminishes if each participant doesn't understand the project as a whole. We have learned that we need to continuously train our team and strengthen communication so that everyone has the full vision. If there is something other offices should share, it is this: working in BIM requires a mindset change, where everyone sees the whole project and not just their specialty. And that is a transition we ourselves are still making.

DS – Q3.4: What have been the key technological developments that facilitated the use of digital fabrication in your practice?

CV: Actually, maybe I'll go a bit back. For example, an important evolution was having a colleague of ours bring the first computer into the office and deliver information to VECTORWORKS so they could develop new versions. It was almost like placing him in Zaha Hadid's office to teach things, learn others, and respond to their requests. He helped develop new resources.

DS: Vectorworks was an early stage that allowed the evolution to BIM.

CV: Exactly. So, from then on, when this colleague brought in the computer, our life became easier. But before him, we were working without computers. Today, I feel we are bolder in designing more organic and complex architectural solutions, which we didn't do before. For example, the shape of our cinema theatre was one of the first we did without computers - it was a challenge. Today we do that almost effortlessly. One thing has changed: it made communication with the construction site easier. When we go to Mozambique, for example, we see that carpenters and metalworkers have CNC machines. So, when we give them a drawing, they can cut pieces immediately.

DS: Exactly, there's that ease, whereas in some situations, there are barriers, but on the other hand, it facilitates things.

CV: In Portugal, many companies don't have that capacity. This shows how technology has facilitated evolution: it allowed us to be more complex formally and sped up collaboration. Although there are still friction points, like contractors asking for separate drawings, overall digital tools have already integrated into the process - at least in large offices - and that technological transition has helped a lot.

DS – Q3.5: How has the integration of digital tools affected collaboration within the office and with other stakeholders?

CV: Within the team, one of our senior architects ended up providing internal training: he held workshops with colleagues, explaining Revit and Rhino. With that, the whole team gradually adapted to using these tools. From the office's side, we now offer full support: we have licenses for both (Revit and Rhino) and share resources so younger staff can learn quickly. This helped align the team, although there are still hybrid collaborations because there isn't yet total consensus on the best tool, so we

allow both. As for construction sites, that collaboration is still evolving. So far, we haven't found many contractors capable of working directly with the integrated digital model. Many prefer PDFs or separated layers. I even saw contractors separating all layers and refusing to use the model. Only one tried to use the integrated model but ended up isolated because others insisted on working with PDFs. It's frustrating, but we are learning: maybe we don't yet have the right partners, or maybe it just hasn't happened in the local market yet.

DS: We are still in the middle of this adaptation, which delays full collaboration, but I have no doubt that, over time, construction teams will also adapt, as happened in the past.

CV: For now, integration has greatly facilitated internal alignment in the office, but in construction, the process still needs to mature.

PART IV: FUTURE

DS – Q4.1: How do you see the future of digital fabrication in architecture?

CV: Look, I don't know if this criticism I'm going to make is about the software itself or about the consequences of this type of approach, you know? More and more, I see offices interested in simplifying processes and delegating part of the work, sometimes even human resources, to technology. For example, I met a Canadian architect couple who already asked about artificial intelligence: they believe that, in the future, AI will handle most architectural details. To me, that's scary: architectural details are more than just technical details; they are poetic and spatial details. If we let AI deal only with technical details, we risk losing spatial quality. Perhaps it's inevitable that technology will advance, but I hope architects continue to value that creative sensitivity.

DS: It would distort the profession, wouldn't it?

CV: Exactly! The future of these tools is inevitable - we will increasingly use BIM and digital fabrication, but the challenge will be to maintain the human vision of the project amid automation.

DS: I'm personally in favour of implementing digital tools, for example, artificial intelligence. I think it has immense potential. But I think the danger is excessive use: if we use these tools to perform a series of automatic tasks, of course, it saves time and resources! However, we can't let these tools replace our own sensitivity, experience, and perspective.

CV: Completely. And it's not just about being easy; it's also much cheaper for the office.

DS – Q4.2: What are your expectations or plans for expanding the use of digital tools in your office?

CV: At the moment, our full adoption of BIM depends on project scale. If a large-scale job comes up, then yes, we'll go for it because we already understand the advantages. For smaller or medium-sized projects, I'm still not sure. I'd say we're in a slow transition phase.

DS: Because the investment is also significant.

CV: Exactly, very significant. That's why we're "half-mast," waiting for a specific project to materialize. If that happens, we'll have to seriously think about the transition. Otherwise, if we continue with medium and small projects like we've had this year, we might postpone that decision a bit longer.

DS – Q4.3: How do you think your approach to digital fabrication compares with that of other offices?

CV: We've been saying our approach is always hybrid. And there was a moment, for example, in the Mozambique Court project, when we made an important decision: we didn't want to expand internally, even though we were working with almost 30 architects on that project. Instead of increasing the team inside our own office, we chose to rely on former collaborators and distribute the work across several offices. Essentially, we created a collaboration network. The big advantage of this model is that we had a collective brain in the cloud. Since we had all worked together before, integration was super smooth. In total, three or four offices were involved, and in the end, there were five. Why did this work so well? Because, even though some offices were larger than others, everyone brought knowledge they had gained from our office. Interestingly, they took those methodologies into their own practices. This made the workflow between the almost 30 people involved very simple.

Now, why am I saying this? Because if we change our operating methods too much, we can't repeat this model. And since we now deal with newer offices, former collaborators who have set up smaller practices, it's harder to apply this technological approach. Some don't need it; others don't have the financial capacity to implement it. These are things to consider. On our side, I can say we set an example. There was a phase when we developed such a complex and intricate AutoCAD methodology that it was basically an ARCHICAD inside AutoCAD. The results were great. That created know-how that spread. Just yesterday, we had a conversation with a former collaborator we might work with again. We asked him: "So, and the drawings? How are you working now?" And he replied: "It's all the same, we're using the same thing." He left the office four years ago but is still using the tools and methods we developed here.

DS: They're being used and make sense.

CV: Exactly. This just shows how easily we could implement this network logic. In the case of the Mozambique Court, we could have doubled the office's size, from 12 to almost 30 people. But since we don't always have that volume of projects, it would be hard to scale back afterward. So, this network worked very well—and still works. The hybrid model still serves us. Of course, this doesn't mean we won't adopt BIM in certain projects. In fact, we've already had difficulties, like I told you, for example, in finding people to measure projects. Quantity surveyors have practically disappeared. And we've detected important errors in those processes because they're no longer at the precision level we need.

DS: Yes, it's almost like extinction.

CV: Exactly. It's something to consider and a conversation we need to have. In our network model, these issues aren't easy to manage. And then there are also competitions we do with other offices—not always former collaborators—and there we need to maintain rules, coordinate well, and avoid cacophony. But so far, no one we've worked with is 100% on BIM. No one.

DS: These transitions always take time, don't they?

CV: And it's not very sustainable for an office to make that jump… on faith.

DS – Q4.4: How would you compare the adoption of digital fabrication in architecture in Portugal with other countries?

CV: Compared to Canada, I think we're more behind. Whereas compared to Mozambique, we're obviously ahead.

DS: Yes, they're completely opposite contexts, aren't they?

CV: Completely different. In Canada, for example—as I already mentioned—the approach is different. Their schooling works differently. When that architect said that, from now on, drawings would be done by interns, that shows how details are approached there. For Canadians, with rare exceptions, architectural details are treated as a technical, almost bureaucratic process. It's curious because, for us, that level of detail is also design. It's part of creation. But there, no. They understand the poetic side of architecture only in the conceptual phase. Then, the technical part is "just dispatching details."

DS: I think it's a pragmatic response.

CV: Yes, completely. But if you look at some buildings in Canada, at first glance, they look fine. You look at the whole and it works. But if you zoom in, look at the details… it doesn't hold up. It's funny to see that. For example, Rem Koolhaas was extremely grateful to Jorge and Teresa Novaes for the construction preparation and details our office did for Casa da Música. There were details Koolhaas himself had never thought of. When you enter Casa da Música, there are little details where you think, "Wait, who did this?" And when I asked Teresa, she replied: "It was us, our office." That shows it depends a lot on schools, you see? What each school values in architecture. Ours still has that culture that detail is part of the project. It's an extension of architectural thought. Now, that's being lost a bit, but it still exists. In other parts of the world, like Canada, no. The technical component is separate from the creative component.

DS – Q4.5: What emerging trends in digital fabrication do you find promising or interesting for architectural practice?

CV: Look, artificial intelligence, for me, could represent a new step. I see advantages - I also see many disadvantages - but I want to be optimistic and focus on what it can bring positively. I'm very intrigued

and curious. I want to understand how it works better. I think fear only arises when we don't know the tool. And right now, I still don't fully know it. But I want to learn it better. And then use that tool freely - with my free will - to decide: "This I want, this I don't want." That attracts me. Artificial intelligence attracts me. So, I believe that sooner or later, architecture will integrate it. I have no doubt about that.

DS – Q4.6: What kind of support or resources do you believe could accelerate the adoption of digital fabrication in architecture?

CV: Well, on one hand, I think it's great that training with these tools is already being introduced in schools. It's a fantastic tool, and I'm starting to notice that students already come in with some skills. Every day I get résumés, and I think: "Wow, they already know these tools." That support is being given by schools, and that seems excellent to me. In addition, many take their own initiative to learn. Here in our school, for example, there's a student working on a somewhat complex project. I asked her: "But do you know how to use Rhino and Revit?" And she replied: "No." And I thought: "Oops, this won't be easy." Three weeks later, she was already working with it. I said to her: "But you're already using these tools?" And she said: "Yes, yes, I took an intensive course and now I can manage." And since she uses them every day, she gained fluency.

DS: She made a huge leap.

CV: A huge leap in three weeks! What she can already do is incredible. Even if she only learned it for that specific project, it's impressive. Now, what seems to me is that these tools require much more powerful computers - and that, for us, is a constant challenge. We're always updating and improving our hardware.

DS: And then the programs are also expensive...

CV: Of course. Every company that can license these programs naturally wants to make a profit. The licenses are expensive - very expensive, I'd say. Perhaps that's why contractors, for example, don't invest as much as architects. And where could this improve? No doubt, reducing the cost of licenses would help immensely.

ANNEX D – INTERVIEW TRANSCRIPT

FAHR 021.3

Founded in 2012, FAHR 021.3® is an internationally awarded creative and experimental office that operates at the intersection of Art and Architecture. Named after the German word "Erfahrung" (experience), FAHR 021.3 functions as a lab office, developing conceptual strategies characterized by unexpectedness, contradiction, and decontextualization. Known for their formal and provocative approach, notable projects include Hairchitecture, São João Structure, Metamorfose, Eclipse, Nappe, and Nook. In 2018, they presented the Serralves Pavilion at the Venice Biennale, and in 2019, they were selected for the 40 under 40 European Design Award. FAHR also founded the collective HODOS in 2014 to enhance walking routes with art and architecture. They coordinated Desencaminharte'18 in 2018 and 2019, promoting cultural and natural heritage through artistic creativity in Alto Minho, Portugal.

Interview conducted via ZOOM on 05/07/2024.

PART I: INTRODUCTION AND MOTIVATION

Daniela Silva (DS) - Q1.1: When and why did your office start incorporating digital tools into architectural practice? What was the initial catalyst?

Filipa Almeida (FA): In fact, when I graduated from university was the first time I came into contact with digital tools like Rhino. That happened during an Erasmus period in Berlin. At the time, I didn't fully embrace the possibilities of these tools, but I recognised they were great for exploring ideas. I saw them as a great complement to traditional work. When I returned to Portugal to do my final thesis, I met Hugo in a Rhino workshop - it was also his first time with the program. We both realised that we had a positive first experience with that tool at that stage of our training. We didn't want to depend solely on technology, but we understood it was an added value: it could speed up processes and allow us to experiment with new ways of rethinking projects. After my thesis, I worked in Germany, where using these tools was common. I learned to use other programs beyond the one I knew and realised that digitally modelling forms was already routine in that office. So, when we founded FAR in 2012, using digital tools was already part of our daily routine. Of course, we still start every project on paper - we never jump straight to the computer without prior ideas - but there is always an immediate connection to transfer those ideas to digital to quickly experiment. In a way, the computer became for

us almost like a pencil, a tool to draw ideas. Moreover, we still make many physical models; 3D helps develop paper or cardboard models quickly when we want to test something.

DS – Q1.2: What were the main motivations for adopting these technologies? Was it a response to digital evolution, or were there other reasons?

Hugo Reis (HR): It wasn't really an "oh, everyone is using this now, so we have to use it too" kind of thing. It was more natural. We had already come into contact with these tools at university and later through professional experiences abroad. We quickly realised they could speed up processes, help us experiment with new ideas, and communicate better with teams and clients.

FA: Yes, exactly. For us, digital tools were never an end in themselves, but rather a complement to manual work. We still start with sketches on paper and build physical models, but we began to see the computer almost like a pencil - just another tool to quickly draw ideas and test them in a different way.

DS – Q1.3: Can you describe a project where the adoption of digital technology was crucial to its success?

HR: No specific project was determined solely by digital technology; all the work could have been done without it, although it would have taken much longer. These tools give us great support to quickly materialize ideas and even ensure execution itself. We often develop complex formal geometries in our projects, and it becomes difficult for a local builder to understand 3D modelling without translating it into very clear 2D drawings.

FA: We use these tools to simplify communication, ensuring complex details are well explained.

DS – Q1.4: Was there any model or example (national or international) that inspired your transition to using digital tools?

FA: No, there wasn't really a specific office or name that made us think, "this is the path we should take."

HR: It was more about our direct contact with these tools throughout our journey, in contexts where they were already naturally in use. That showed us we could adopt them without fear, in a very organic way, without following any particular model.

DS – Q1.5: What were the main perceived benefits that motivated the adoption of digital tools?

HR: Digital tools allowed us to quickly reach higher levels of complexity in projects. They also helped us immediately translate very complex projects to clients and for construction. For example, we can quickly illustrate and demonstrate complex forms, which optimises dialogue with other teams

involved. These tools improved project communication and accelerated the implementation of more sophisticated ideas, turning processes that previously took a lot of time into agile and clear solutions.

PART II: BARRIERS AND CHALLENGES

DS – Q2.1: What were the main barriers you faced in implementing digital fabrication technologies?

HR: The barriers were mainly technical and cultural. The biggest challenge was the relationship with the local construction industry. Many traditional companies and professionals were not prepared to work directly with advanced digital files. For example, it is common to find older contractors or carpenters who cannot read 3D files, which always requires us to "translate" them into well-defined 2D drawings. Also, suppliers often have different processes and machines, which requires extra coordination work.

FA: In Portugal, in particular, there is rarely investment from the sector in equipment or training for this. We noticed the same issue in projects abroad, such as NAPPE in Taiwan: many creative people, but the local industry doesn't keep up. The main barrier is getting builders, metalworkers, and engineers to keep up with digital tools, creating compatible processes. Without this alignment, every project requires greater manual effort to make everything fit.

DS – Q2.2: Are there any local policies or regulations that facilitated or hindered the adoption of digital fabrication in your practice?

HR: Hugo: We are starting to see some institutional intent to promote digital project delivery. It is still incipient, but it is growing. Some of these initiatives seem interesting, but many are still just intentions, not fully consolidated plans. Maybe we are not that far behind, but it is important to understand that some of these measures can actually be exclusionary. For example, when we are not allowed to deliver a hand-drawn piece or when we are required to use specific formats, it becomes limiting. I understand that there is a desire to organise and standardize, and I even understand this need, but certain policies end up being prohibitive - or, to put it more softly, conditioning. They define exactly how things must be done and delivered, and that can become a problem. We had a concrete case in Porto City Hall, where they only accepted one type of PDF generated through AutoCAD. Well, we don't use that program. At the time, this created a real obstacle. Later, they corrected the situation, and today it is already possible to submit with other software, which shows some openness. But, fundamentally, what happens is that policies are launched, software adapts, and along the way some get left behind. This process can create barriers - dangerous, even biased - because they exclude tools with other dimensions or alternative approaches.

DS: The problem is when those requirements stop being recommendations and become obligations. Then, yes, they become real barriers.

FA: But it is also natural to move toward some standardisation of submissions. It makes sense, actually. When we talk about these things, I immediately think of initiatives like Simplex, which already defines what formats we should use. Even if we don't do much conventional architecture, occasionally we come across these requirements. And we will have to adapt.

HR: Yes, but there are cases where there is simply no adequate BIM solution. We had, for example, a concrete intervention with curved forms, and no engineer had software capable of directly calculating it. Since the project also didn't have a huge budget to allow for an in-depth initial study or multiple iterations with several teams, it wasn't feasible. One engineer ended up buying specific software just to calculate that structure. It turned out to be useful in the end, but it was a forced leap.

DS – Q2.3: How has client perception influenced or affected the implementation of digital tools in your practice?

FA: I think what matters most to clients, in the end, is being able to visualize what they are going to get. Because often it is hard to imagine the final result. And I get it, it's normal. So, when we can communicate the idea with images that are already close to what it might be, that helps a lot.

HR: Yes, no doubt. It improves project communication and helps sell ideas better.

FA: At least it allows them to have some awareness of the process, to understand why a certain decision was made. Sometimes it's more about the story we tell, the project's journey, than the technical detail - like "we arrived at this line" or "this is a surface."

HR: But at the same time, there can be constraints. It depends a lot on the client, of course. Digital visualisations, like renderings, don't show everything - the material, the space, the passage of time, the wear of things. All of that is missing in a 3D image. It goes into so much detail, almost like in a cinematic logic. And that can lead the client to think, "but this wasn't exactly what I wanted." Sometimes the question is whether the space looks that way because it's grey, or white, or full of wooden slats, or because the sun shines in a spot where, in reality, it rains almost all the time. And clients are critical of that.

DS: And, on the other hand, that also raises other issues, doesn't it? It maybe even takes away some room for imagination.

HR: Exactly. Because there are clients who don't even know how to read plans but trust them. The plan is there, drawn, and that's it. But when they see a very realistic image, then they have an opinion, they question it.

DS: But have you noticed, since you founded the office until now, that clients have changed in that respect? I don't mean the same client, but different clients who show up. Are they more aware of the

tools available? Or is it indifferent to them whether the project is done in AutoCAD, by hand, in Rhino...?

HR: I think how it's done doesn't matter much to them. But, in the logic of selling the project, that does matter a lot. And yes, they are much more aware of what can be done with these tools.

FA: Yes, our clients tend to value digital tools to the extent that they improve communication. They want to understand what will be built. 3D and renderings help in this sense - they make everything clearer and build trust. But they can also be limiting. They make the project very "closed," with little room for other interpretations or to imagine alternatives.

DS – Q2.4: Was there ever a case where technological or financial barriers prevented the implementation of digital tools in a project?

FA: As far as we know, there has been no project where a technological or financial barrier completely prevented the use of digital tools. We already have the necessary software, and even if a client has budget constraints, we usually find a way to apply digital tools to the key parts of the project. Ultimately, if some resource is lacking, the work is done in a more traditional way in certain details, but that has never forced us to completely abandon technology when it was useful.

PART III: EVOLUTION AND CURRENT IMPLEMENTATION

DS – Q3.1: Do you identify any historical milestone that you consider pivotal in the evolution of digital fabrication in architecture?

HR: Identifying a historical milestone in the evolution of digital fabrication in architecture? I would say yes, especially with Frank Gehry's project. I think I mentioned this before, didn't I? He was, without a doubt, a pivotal figure in this context.

FA: Yes, he proved it was possible to apply digital processes on a large scale.

HR: Exactly. It was a turning point. From that moment, many began to explore the potential of these digital tools. The construction industry itself had to adapt. Of course, there had already been earlier experiments, even manual parametric processes, but Gehry managed to prove the viability of these methods in a global and meaningful way.

FA: But even before that, there were already people thinking along these lines, right? For example, Buckminster Fuller, who did manual experiments with complex geometries - true parametric processes, even without computers.

HR: Yes, exactly. And even Gaudí, with those out-of-the-box models, already had an almost computational logic.

FA: And we can't forget the impact of other areas, like aeronautics, where these methods started being explored before entering architecture.

HR: Yes, those industries helped pave the way. Gehry himself admits that - he borrowed processes from other fields. And those who study the subject also recognise that path.

FA: But it was with him that parametric architecture reached the mainstream.

HR: No doubt. It was an important transition. From there, many tried to follow the same path. Even though there were earlier investigations, he took the risk, elevated architecture to another level, and made it clear that digital fabrication was possible.

FA: It is also important to understand that using digital tools is not directly tied to the formal complexity of projects.

HR: Exactly. Sometimes there is that confusion. Not everything formally complex is the result of digital, and not all digital leads to complexity. The important thing is to understand that parametric thinking existed long before computers - digital just opened new possibilities for execution.

DS – Q3.2: How is digital fabrication currently used in your practice?

HR: In our practice, we use digital fabrication tools mainly at the prototyping stage. They are often used to test solutions, both for us and for the contractor, so that they can better understand how to master the machine itself.

FA: Yes, for example, in the Loop project, we made digital formwork to create a prototype. That was already at a more advanced stage, after the design phase, just before on-site execution. We use these tools in a punctual way because, in reality, there is always a budget limitation.

HR: Even so, we have had cases where we mixed several approaches. Sometimes, we split tasks among different teams: one that prepares digital models, especially of curved forms, and another that manually executes the simpler parts. That joint work is essential when one team alone can't execute everything.

DS: That's interesting - to see how teams complement each other.

HR: Yes, exactly. The Loop project is a good example. Although it has an apparently simple geometry - it's a circle - its execution in concrete required another level of complexity. The inner structure was made manually, and then we had to resort to moulds. And moulds, under those conditions, are a different challenge. It's not like making a wall or a concrete slab. It's a closed mould, outdoors, without laboratory control.

FA: And there aren't many moulds in the world at that scale.

HR: Yes. We ended up creating a huge wooden structure into which all the concrete was poured… and we prayed it wouldn't burst everywhere. No one had done something exactly of that nature at our scale.

DS: And that required many teams, right?

HR: Absolutely. We had a team specialised in curved forms, another for simpler shapes made manually, steel workers to bend the rebar, and engineers monitoring the concrete's behaviour. Because, even with perfect formwork, concrete is a chemical material and always reacts unpredictably.

FA: It was a process full of obstacles but super rewarding.

DS: I can imagine. The piece looks very simple, but you can tell the execution has much more complexity than what is seen.

FA: Yes, no simplicity at all. Someone from the outside might think it's easy, but challenge any architect to execute it… they'll get there, but the path is tortuous. But it's worth it. And it's important to say: our process doesn't work in a linear logic, where you finish the design, send it to a producer, and they execute it exactly as is. It's not: "oh, we'll do it like this, like this, and it's done." No. These are very specific, customised pieces.

DS: And they require constant supervision, right?

HR: They require total proximity, in everything. For us, digital fabrication does not replace manual know-how - it complements it. We use these tools to test details, validate solutions, make parts of the project feasible, such as CNC moulds or module tests. But construction still heavily depends on artisanal knowledge.

DS – Q3.3: What are the main lessons learned that you could share with other offices considering exploring digital fabrication?

HR: Yes… I even hesitate to say "lessons" because it sounds like we are 80 years old or have a 60-year career.

DS: I'm asking this because, as an observer, I've always seen your office as very experimental. I never felt like you had a fixed formula that you apply to all projects. On the contrary, it always seems like each project is a new investigation.

HR: That's it. If we had a recipe for everything or started repeating projects, even two or three times, I think it would stop being fun. The challenge would disappear.

FA: We'd lose our motivation. What drives us is this openness to the new, the possibility of thinking about each project uniquely.

HR: And that's where the main lesson we've learned from using digital fabrication comes in: don't let the tool dictate the project. The architect, the creative, has to maintain a critical attitude. They must question the tool and, even more, try to surpass it.

FA: Yes, you can't fall into the ease of letting the tool give the result by itself. Because if it's just that - if there's no clear intention, deep thought, awareness of what you're doing - the result may be aesthetically appealing but will be superficial and empty.

HR: And today there is a dangerous trend. Many architecture projects are "sold" in images - renders, videos, immersive experiences - but these visual universes are often built from ready-made models, blocks downloaded from platforms. And that creates an imaginary world that isn't real. People don't live that way. It doesn't correspond to everyday life.

FA: And much is lost in that process. Spontaneity, detail, the building of a more authentic thought are lost.

HR: Exactly. There is a whole market around that - imagery, real estate, accelerated production. And those who make themselves available to produce within these logics risk leaving out what is essential.

FA: So, for us, the recommendation is simple: experiment, use digital tools, yes - but with depth, with critical awareness. Not as an end, but as a complement to the design process.

HR: Technology can't be the starting point just because it's new or impressive. If someone is printing giant houses just because the technology allows it, it's important to ask: does it make sense? Does it meet a real need?

FA: In short, the tool can enhance design but shouldn't replace it. You always need to be thinking, questioning.

HR: Yes, at the end of the day, it's this: just have critical thinking. That's everything.

DS – Q3.4: What have been the key technological developments that facilitated the use of digital fabrication in your practice?

HR: Interestingly, we didn't feel there was one big "technological revolution" that changed the way we work overnight. What we did was use existing tools, like CNC moulds or digital formworks, in a very focused way - mainly during prototyping phases.

FA: Yes, for us, digital fabrication is just another complement. We use it when it makes sense, to test solutions or validate complex details, but always with a strong manual component present. In the end, the real step forward was being able to combine these digital tools with traditional know-how, and that's what opened up new possibilities for us.

DS – Q3.5: How has the integration of digital tools affected collaboration within the office and with other stakeholders?

HR: I think integrating digital tools influences a lot, mainly because it gives us more time for what's essential: talking to people. But, in fact, we don't feel major blockages because of it. The people who come to work with us are not chosen for their mastery of a specific software like Rhino or AutoCAD. What we look for are broader skills, which go far beyond the digital tool. Tools are indeed excellent complements but do not determine the process. In our daily routine, we realise that not all projects require this type of approach. And when they don't, there's little use having someone who masters

Grasshopper end-to-end - because they might not even use it. That's why we value versatility, adaptability, and that same logic also applies to how we relate to construction partners. Each project has different requirements. Today, I might send one type of technical file, but tomorrow I might be on-site cutting wood with someone, testing solutions, making a prototype. And from there, the process naturally takes shape.

PART IV: FUTURE

DS – Q4.1: How do you see the future of digital fabrication in architecture?

FA: Well, this question is inevitably speculative. Everything we can share comes very much from our experience and perception. Not long ago, someone asked me: "Aren't you afraid of losing work because of artificial intelligence or all these new technologies?" And yes, it's true that digital tools and technology, in general, are evolving very fast, accelerating all processes. Of course, we will have to adapt. There are things we never imagined when we started studying architecture that are now reality. And there will certainly be others, yet to come, with significant impact. But what I think is really essential is that we can't lose the human side. That conscious thinking, that intention behind every decision, is what makes one project truly different from another. Even if an algorithm can generate diverse solutions, will it be able to communicate what a group of people wants to convey? I don't know… Maybe one day yes, maybe it will become so refined that it's indistinguishable from human work - but we are still far from that.

HR: I agree. I honestly think we are still very far from that scenario. Currently, digital processes are still entirely operated by us. They still depend on our command, our interpretation. Maybe, over time, these tools will begin to anticipate our choices - start noticing patterns: "Ah, Hugo, Filipa, or Daniela usually react like this, so I'll propose this." In our case, for example, we value error, failure, uncertainty throughout the process. And that's often where the project gains strength. That creative mess, that unexpected detour, is something no digital tool can replicate. So yes, tools will evolve, become more and more useful, especially in specific phases. But I think we are still far from replacing the human factor - especially at the moment of creation. Perhaps the construction sector will keep up more directly with this evolution, as other industries already do consistently. And we can learn a lot from them.

FA: Yes, but even there... In our recent project MATRIZ 45, where we questioned precisely the relationship between art and industry, we had a very clear example of that. We worked with Navarra, a company that extrudes aluminium. Their work is highly technical, with an obsession for perfection. But, if it were just the machine extruding profiles without the human hand constantly intervening and correcting, errors would be inevitable. There's a permanent effort for the result to be impeccable - and

that only happens because there is always collaboration between machine precision and human sensitivity. I don't think we will ever live only with machines, nor can machines live without us. There is mutual dependence, almost as if they shared the same soul.

HR: Exactly. And that's where the transformation lies. The real progress comes from failures - when something goes wrong and we are forced to find a solution. Error forces us to think differently. Sometimes you don't have an immediate answer, so you look for an alternative. That wandering, that trial-and-error process, will continue to exist - and will always keep us at the forefront.

DS: And often, from those errors, new ideas are born, right? Sometimes, only by seeing something fail do we realise there is an opportunity to create something new.

HR: No doubt. That happens to us daily.

FA: We love that part. Sometimes we even say: "Shall we see where the error is?" - because we know that's where the creative potential lies.

DS – Q4.2: What are your expectations or plans for expanding the use of digital tools in your office?

HR: Our approach is always critical. The use of digital tools must be directly related to the scope of each project, not to the tool itself. In other words, we're not interested in using augmented reality or virtual reality glasses just to show we have that technology or to impress with visualisations. For us, and maybe Filipa sees this slightly differently, it's much more interesting to develop a project that questions the tool itself: what it is, what it can be, what it represents socially, economically, culturally. It's that critical reflection that drives us - what is behind the process, not what is merely produced by the tool. We're not interested in following the logic like: "Oh, now I have this technology, so I'm going to do this." For example: "I'm going to print houses because now I have a giant house printer." The question we ask is: does it make sense? Does your reality demand that? There are cases where the idea of printing houses is sold as a way to solve housing problems in Africa. But there are so many urgent structural problems in that context that I don't think 3D printing houses is the immediate or appropriate solution. Yes, building houses makes sense. Printing houses? I don't see why. Most of the time, that kind of technology is neither efficient nor sustainable in the context in which it is applied. And it creates an illusion that these tools are always at the forefront - technological, economic, social - as if they were universal solutions. But we believe that whenever there is a "good recipe," there are also side effects. And maybe it's in those side effects that our real interest lies - more than in the immediate solution or the promise of the tool.

DS – Q4.3: How do you think your approach to digital fabrication compares with that of other offices?

FA: I think each office uses digital tools according to their own interests and priorities.

HR: Yes, I see many offices using these tools mostly in the communication component - in the way they present projects.

FA: In visualisation, exactly.

HR: But there are also offices already exploring these tools beyond communication - for efficiency, sustainability, how buildings will behave over time, how materials react, how they can be optimised. Even so, I would say that most still use them more to communicate, to show, to visually frame the project. And in some cases, I even notice a kind of fixation, almost an obsession with these technologies. There's a certain fascination that often ends up consuming time and energy that could be better applied to rethinking the project itself.

FA: Yes, maybe this trend will intensify even more in the future… and, who knows, maybe we are the ones who are wrong.

HR: It could be. Today there are already systems that tell you: "Here are 50,000 possible ways to build this five-story building." And you just have to specify the material. You say "wood," and it narrows down to 20,000 options. Then you choose "metal stairs," and you're down to 100 options. And so, you refine it. You still make the final decision, but the entire process up to that point is automated. I think we're heading there. I don't know if it's good or bad, but it's a real possibility - and it's worth paying attention to.

DS – Q4.4: How would you compare the adoption of digital fabrication in architecture in Portugal with other countries?

HR: We can only speak from our direct experience, of course. We don't know all contexts, so it's hard to make absolute comparisons. If we think, for example, about countries like Iceland, Switzerland, Stuttgart, or Lausanne, we see that the main drivers of digital technologies applied to architecture are often universities. And these are universities very open to technological experimentation. If we compare that with, say, a university in South Africa - which may even have the same type of laboratories or equipment - the priorities may be different, and that completely changes the scenario. From our experience, looking at the European panorama, I'd say the big obstacle isn't so much in the offices, which are agile and quite capable of adapting to new technologies, but rather in the industry. The Portuguese industry is, in fact, very backward. It will still take quite some time to catch up with processes that are already common in countries like Germany, the Netherlands, Belgium, or Switzerland. I'll give an example: in Switzerland, they can move entire buildings - 100-metre palaces - 50 metres to the side with precision. That simply doesn't happen here in Portugal. But, interestingly, the engineers and architects doing that work are often Portuguese. So, the problem isn't the people but the industrial system and the context in which they operate. Regarding the East, I can talk about China, Macau, and Taiwan. Our experience was that, despite having great creative potential, the

industry also doesn't keep up. I'd say they are still slightly ahead of the Portuguese average, though. A concrete example: we were at a university in Macau with a robotics lab equipped with two robotic arms. We worked directly with those robots, questioning their functioning: what they do, how they operate, how they fail. We even experimented with them: we put a brush in the robot's "hand," let it drip ink, explored the limits. But in the end, what we noticed was that the students didn't show much interest. The robots were there - the equipment existed - but there was no human engagement. And maybe that shows something interesting: people don't see an immediate impact on their daily life, on their practice.

It might even be a sign of critical awareness. Maybe they don't engage precisely because they don't see a real purpose for using the technology in that context. In short, yes, there are big differences between countries - not only technologically but especially in how industry, academia, and professionals position themselves regarding digital tools.

DS – Q4.5: What emerging trends in digital fabrication do you find promising or interesting for architectural practice?

FA: So far, we haven't identified a concrete trend that seems immediately revolutionary. We haven't seen a specific tool we should point out as "the big novelty." However, we highlight that developments in artificial intelligence and data analysis have great potential. For example, imagining software that simulates multiple future scenarios or explores possibilities is promising. We haven't yet seen any technology applied to digital fabrication that gives clear answers, but we believe the future lies in this integration of AI and data analysis. If we create tools capable of modelling different scenarios in a project, that could be a very interesting advancement.

DS – Q4.6: What kind of support or resources do you believe could accelerate the adoption of digital fabrication in architecture?

HR: The main support, in our view, would be in training and capacity building. We see a huge gap in the knowledge of the industry itself: carpenters, assemblers, and even engineers are often not familiar with new tools. So, investing in courses, workshops, or hands-on training programmes for these professionals would be crucial. If builders learn to work with digital software and methods, everyone can evolve together. In other words, resources aimed at training those who execute the project would have a great impact. This would allow everyone to speak the same "digital language" on the construction site. Additionally, initiatives that promote knowledge exchange between architects and other sectors (engineering, industry) would help disseminate knowledge.

ANNEX E – INTERVIEW TRANSCRIPT

Konceptness

Konceptness is an urban design and planning office focused on the client's goals and the impact each project can have on society.

Interview conducted via ZOOM, on 01/26/2024.

PART I: INTRODUCTION AND MOTIVATION

Daniela Silva (DS) - Q1.1: When and why did your office start incorporating digital tools into architectural practice? What was the initial catalyst?

Susan Cabeceiras (SC): Yes. Well, BIM emerged at KONCEPTNESS in 2018, when I explored Canada as a market for our expansion, because I'm Canadian-Portuguese. So, I went to explore Toronto, which is where we plan to open an office, and I realised that between 2018 and 2019 all the offices were working in BIM. So, after this analysis, I realised that if you're behind, you won't even get into the market. I packed my bags, came back to the office and said, "Okay, let's figure out how to implement this, what the costs are." And really, it's a work in progress - whenever a new person joins, it takes two years of training. It's been constant, but we're not going back. And now, within Women in BIM and the whole implementation, and a lot of evangelization… I've had architects treat me badly because I came to a meeting and said, "Why isn't this in BIM? It's much more useful for the client," and the answer was, "You don't know what you're talking about." And I shrink away. We still have many architects with this mindset (the client is mine, I know best), and I'm just suggesting new tools. In Portugal, unfortunately, we still have a backward culture; many offices still work on the drafting table, without BIM, and those offices will close in the next five years - I have no doubt.

DS: Exactly. They're not keeping up with the natural evolution, especially since it's also an optimisation tool. That's very interesting.

SC: Yes, I say BIM allows us to think about the project; AUTOCAD makes us draftspeople - nobody can think about the project because everyone's drawing lines. I prefer to use the tool in favour of the quality of the work rather than being a slave to the tool. We shouldn't be slaves to technology, but we should explore tools efficiently.

DS – Q1.2: What were the main motivations for adopting these technologies? Was it a response to digital evolution, or were there other reasons?

SC: When I went to Canada and realised that all the offices were already working in BIM, I understood that if we wanted to compete in that market - or even understand where the profession was heading - we had to act fast. It wasn't just about digital evolution; it was a necessity. If we didn't adapt, we'd be left behind. So yes, it was about evolution, but more than that, it was strategic - about positioning ourselves to be part of the future of architecture and not stuck in the past.

DS – Q1.3: Can you describe a project where the adoption of digital technology was crucial to its success?

SC: We have several. We're in the third phase of the Somaí project, which is a cannabis project in Carregado, and if it hadn't been done in BIM - receiving HVAC drawings in BIM and everything else - the construction might still be ongoing. It was a project done in a year that was work in progress - we were designing while construction was happening - and really, the fact that we used BIM was crucial. We had gaps due to a lack of electricians in Portugal, but HVAC evolved a lot because European suppliers work in BIM, and we received many elements from them. There was a major project three years before implementing BIM where we could've saved a lot of money, time, and stress from small construction changes that could've been detected through clash detection and BIM verification. So, I have no doubt: I can go anywhere and talk about BIM and its advantages, both in construction and design, for the client as a whole. However, the client later forgets; for example, if they see a change in 10 minutes, they think they should only pay for 10 minutes, but switching from AutoCAD to Revit represents €10,000 to €12,000 in post-work. So, we have to explain to the client that beyond the training, the tools are much more expensive, but in the end, the client doesn't bear that cost - they only get the benefit. We've always borne that cost ourselves.

DS: Yes, because it's not about the time it takes to do the task, but the time it took me to get to the point where it only takes 10 minutes. It's very different.

SC: Exactly, that's it.

DS – Q1.4: Was there any model or example (national or international) that inspired your transition to using digital tools?

SC: No, no. If we really wanted to open an office in Canada, we needed a team there - our goal was to do services here and deliver them there, so to have a team doing that. There's a project there, but I'm not hiring locally; the competitive advantage between Portugal and Canada is doing the projects here. BIM allows this because it's collaborative: a technician in Canada and another in Portugal can edit the same model at the same time, which is not possible with AutoCAD. I started talking to technicians there about why they use Revit and not another tool: 90% of the suppliers there told me they use Revit, so I chose Revit, even though it's more expensive. We're now managing a project where the designer only

does architecture in Archicad - it makes sense for someone who only does architecture, but there's a compatibility problem with IFC file versions. We're still in transition: we do a lot of design, but we're also moving into project management. BIM 360 facilitates compatibility. In general, we'll see a big split in the market between those who understand the technology and those who don't. For example, a surveyor once told me: "Forget it, I do 2D. If you don't want that, find someone else. I won't evolve." We're going to buy a Matterport machine to do point cloud surveys - I won't waste time chasing surveyors anymore. Technology is on our side. We're really heading toward automating more processes; for example, on Monday I have a meeting with a supplier because this will reduce labour on site - one person does the job of three, because the point cloud goes straight into REVIT, much easier to verify.

DS: Just as a side note, I'm not currently working with BIM at the office I collaborate with, but I worked with Revit five years ago. And five years ago, it was very difficult to find HVAC technicians working in BIM. I'm happy that things have evolved and that they're starting to appear…

SC: It's still not everyone. Look, Daniela, I can say we started offering BIM and Revit training because there was no one, so we had to train our team and sell the training to see if anyone else would start the evangelization. I can say that last year we didn't sell any training, because people, besides wanting everything online, are all waiting for something to happen, because people are more afraid and have far less economic capacity than they had in 2019.

So, since there was no legislation requiring BIM or Revit, all the campaigns we did - we spent a lot of money saying "come take the training" - I had to pick up the phone and say, listen, I'm doing evangelization that's good for people, and I still had to chase people to sign up. Then I gave up; I don't know if I'll do it this year because it's exhausting telling people, look, this is good for you, and people still… I always say this: I compare BIM to the transition from hand-drafting with Chinese ink to AutoCAD - we're in the same era. Anyone still using AutoCAD and not evolving to BIM will fall behind.

DS: It's the same transition.

SC: It's the same - it's the same leap we're making. So, people have to understand this, it's like everything: either you realise you need to take the leap, or you say, "I'm of a certain age and I don't want to evolve anymore." Okay, then make room for those who do know and want to evolve. Because when I'm 80, I won't want to evolve either, I'll say, "There's the team, let them do it, the family's there, they'll carry it on." I get it now - we just can't say it's crap, like I've been told and even attacked - literally in front of clients - aggressively, like, "Shut up, you're saying something stupid." That is unacceptable to me, and that's why I only say good things about BIM in all conferences, etc.

DS: Yes, because it's one thing to say "I recognise it but don't want to implement it by choice," and another thing to say "it's useless, it doesn't work, it's a waste."

SC: Exactly, those are two different things. Two different worlds, yes.

DS – Q1.5: What were the main perceived benefits that motivated the adoption of digital tools?

SC: Time savings, quality of service, and coordination. BIM allows us to think about the project - unlike AutoCAD, where you're just drawing lines. With BIM, we're technicians, not draftspeople, and that changes everything. It helps with finding the best solutions, improves collaboration, and reduces construction time - what would take a year can take six months if everyone's aligned. It also filters the type of professional we work with. Those who embrace BIM are people who want to evolve and do better. For me, that's one of the greatest benefits: surrounding ourselves with people who care about quality and progress.

PART II: BARRIERS AND CHALLENGES

DS – Q2.1: What were the main barriers you faced in implementing digital fabrication technologies?

SC: Workforce and implementation cost - which is huge, ten times that of AutoCAD - because we had to change servers, change computers, buy software, renew licenses every year. It's a cost that sometimes isn't recouped. So, it's always about the lack of workforce and high tool costs. Another challenge: client reception and their comparisons. Clients still don't know how to distinguish a BIM team from a 2D one, and those who work in 2D are always cheaper. So many clients don't value the maturity and quality a BIM team brings - they prefer the cheaper option. That's the third negative factor we face.

DS – Q2.2: Are there any local policies or regulations that facilitated or hindered the adoption of digital fabrication in your practice?

SC: Absolutely. I have to take a BIM project and convert it to AutoCAD to submit it to the city council, creating layers - I spend two or three days doing draftsman's work to deliver the project. We've implemented BIM in architecture since 2018, and every time we deliver a project, we have to reverse the process, clicking on lines and naming layers. It's a complete waste of time. So, I no longer insist on it being mandatory; we know legislation is expected in 2030, but they should at least allow BIM submissions. Even without requiring it - the obligation doesn't yet exist. Today in Portugal, BIM is still taboo; there's no national standard. We're very behind. In Spain, it's been mandatory for two years already. There's always this investment gap - it's expensive, and people avoid what they don't understand. So, we're stuck in this limbo.

DS: Yes, and I also think sustainability suffers a bit from the same thing - used as a buzzword. "We invested in sustainability," but when you look closely: where is it? "Oh no, we just added the word because it's trendy."

SC: Look, I just got a call from a supplier with German materials for a lab I'm implementing with a client in Porto. When I answer, I'll say: why not choose our products? Because it comes from Germany? We have a supplier in Maia, Portugal - 10 minutes from the site. This is about ecological footprint and sustainability. People, until they internalize this and realise sustainability isn't just a pretty word… Nowadays, many companies don't even want to use the word anymore because it's been overused.
DS: Because it's become… overdone. And I think BIM is sometimes used that way too - by municipalities, for example.
SC: It's marketing.

DS – Q2.3: How has client perception influenced or affected the implementation of digital tools in your practice?
SC: At the moment, when we work with investment fund clients, they look for BIM. But five years ago, it made no difference to them. Small or individual clients don't care whether it's BIM or Revit - they just want the job done. I've always seen this as an investment in the future. For example, I did a fire safety course in 2009 and only got returns 10 years later during COVID. I invested in it while everyone said it was a waste. It's the same with BIM - a long-term investment. In Portugal, cycles are 10–15 years, and BIM will only bear fruit from 2028–2030. Last year and this year we've seen some gains because now I don't accept projects sent to me in AutoCAD. If they arrive like that, I tell the client I'll need four times the hours to do the same drawing - I have to manually do everything in 3D. The client is surprised by the cost, but if we didn't have the BIM platform already integrated, marrying everything in 2D would fail - it's happened to us. If we had everything in BIM, we wouldn't be evangelizing anymore - we'd just be charging a normal service. I think in one or two more years we'll start to see returns on the BIM investment.

DS – Q2.4: Was there ever a case where technological or financial barriers prevented the implementation of digital tools in a project?
SC: No, but sometimes it delays things. For example, when COVID hit, everything stopped overnight, and within a month we had trained the whole team in BIM. We used the fact that people were at home to continue Konceptness - we all learned what BIM is. Many people joined the team without knowing what BIM was, and now it's the colleagues themselves explaining to newcomers that we work in BIM - it's no longer just top-down. In terms of postponed or lost projects, there wasn't a case where we lost out because of a barrier - sometimes we even lose projects because we use BIM, since we're more expensive at first. But that's part of being innovative.
DS: It's part of competing.

SC: When you start innovating, you feel the sting at first. But later, the market naturally filters itself: those who want tech hire you and move on; those who don't stay in 2D.

PART III: EVOLUTION AND CURRENT IMPLEMENTATION

DS – Q3.1: Do you identify any historical milestone that you consider pivotal in the evolution of digital fabrication in architecture?

SC: Well, there were several. Airplanes and ships have used BIM for over 25 years. Boeing was a classic case - they had project managers who only handled supplier coordination and purchasing through BIM. If you were a supplier, you had to deliver the BIM model. I think there are several such historical milestones scattered around. Today, it's more about managing people and finances that forces us into BIM - for example, Casais, where tight deadlines require manufacturing in BIM. Also, because we're among the last in Europe to implement BIM - that's enough, right? There's no single milestone in Portugal, but many things have pushed the sector forward.

DS – Q3.2: How is digital fabrication currently used in your practice?

SC: Right now, we're not fabricating directly, but we're preparing for that. We're about to get a Matterport machine to do point cloud surveys. That's a big step because it allows us to bypass external surveyors who don't want to evolve and still work in 2D. With the point cloud going directly into Revit, everything becomes faster to verify and model. It's already changing the way we approach site analysis and modelling - it's part of automating processes, removing manual work and gaining precision.

DS – Q3.3: What are the main lessons learned that you could share with other offices considering exploring digital fabrication?

SC: I had a major lesson early on: the first thing I did was look for a trainer, and that didn't work. The first thing you need is support to plan the implementation, not just train on the tool. Initially, we had a trainer who only wanted to sell his courses. I talked to him about software, but I didn't learn anything about what BIM really was. I ended up going to the Portuguese Order of Architects to take training with Start BIM, and a year later they became our consultants. They still support us today in implementing BIM. If we'd done it all alone, it would've been possible, but having a team with over 15 years of implementation experience and modelling was a huge leap. I made a false start, wasted money, and got nothing - but then we adjusted. My lesson is: don't look for software first. First understand what BIM is and what tools exist. Choose the right tool for you. Konceptness uses REVIT because we do architecture, engineering, and project management. REVIT has almost everything. If we did only architecture, we'd use ARCHICAD. I was oriented toward ARCHICAD myself but realised it

wasn't great for all engineering. With REVIT, sometimes you can't even tell whether it's an architect or an engineer using the model - everyone uses the same file. It's a much more integrated tool.

DS: Yes, small companies keep emerging and innovating. That works. And Autodesk has been growing, yes.

SC: Autodesk grows because it's always inventing and buying out competitors. Each one goes where innovation happens or where they fund researchers. Either way, the biggest challenge is not picking software blindly but sitting with someone knowledgeable and planning the whole process. You forecast how and when it'll happen, and then you get training. First you choose the right tool; then you choose the training team and make a phased plan. Don't do all the training at once. Do modules: Revit 1, then maturity, then Revit 2, and so on. Don't be afraid to lose some staff along the way - you'll lose 20 to 30%, that's normal. We lost people and trained new ones again. The important thing isn't avoiding turnover - it's having a strategy and support from those who've already done it.

DS – Q3.4: What have been the key technological developments that facilitated the use of digital fabrication in your practice?

SC: Definitely the ability to integrate point clouds directly into Revit - that's huge. The Matterport device is a big step for us in that direction. Also, BIM 360 has helped a lot with coordination and compatibility, especially when working with teams in different locations. These tools allow one person to do the work of three, and that's what's pushing us forward. It's not just about drawing anymore - it's about managing data, optimising time, and getting closer to automation.

DS – Q3.5: How has the integration of digital tools affected collaboration within the office and with other stakeholders?

SC: Right now, BIM even impacts invoicing, because the codes and the way files are saved affect everything. Within the office, we've already implemented BIM for architecture, but we still receive AutoCAD files from other designers or consultants. There's not yet a 100% Revit-only workflow. We get AutoCAD files and evaluate whether it's worth converting them to Revit. For now, "total BIM" isn't possible in the Portuguese market, because many clients still work in 2D - it's like saying "I only drive electric cars now" when most cars are still gas-powered. Just as there are still gas stations and electric chargers, we still get AutoCAD files. Sometimes we take on work from other teams that started in AutoCAD and have to decide: do we stay in 2D or model it in 3D?

For example, an older colleague gave us elevations and plans in CAD that weren't up to date with the factories the client currently has. I said, "Okay, send me the drawings, but we're going to have to convert this all to Revit." The client thought that would take a week, but modelling from scratch takes longer - and clients aren't prepared to wait. That's another challenge: the time curve before you reach

efficiency. BIM changed internal collaboration - everyone has to work on the same model, but we still deal with a lot of "2D legacy." That brings planning and time pressure, because we're not all 100% aligned yet, and the client needs to understand that initial delay.

DS: Right, you have to manage that expectation.

SC: And sometimes you sit with the client and have nothing to show yet. We sometimes have to open Revit and say, "Look, we're building - the model is being built." This was something Joaquim from StartBIM taught me - you have to manage the client's expectations during the model-building stage. In every situation, we have to choose whether to work in CAD or Revit. We've had situations where we worked in both just to meet a deadline - say, we had to deliver a layout in a week. Creating a model would take three weeks, so we had someone doing the layout in CAD because the client sent the drawing, and we were doing the industrial layout in CAD. But simultaneously, the other team was developing the BIM model because I knew the client would need to contract other parts too. If it's just a layout, we use AutoCAD. We always have to be flexible with time - we need to weigh the return on investment in time. Once we've done the Revit model, everything from that client will be faster.

PART IV: FUTURE

DS – Q4.1: How do you see the future of digital fabrication in architecture?

SC: In Singapore, they don't even talk about BIM anymore - they're already beyond that. I often talk with Frederico (a mentor of ours in Singapore), and he told me that over there, BIM is already passé and they're onto the next stage. For us, the future of BIM is to keep using and exploring the tool as much as possible. We're still far from using it at 100% - us, Portuguese, not even close. I believe that with the emergence of artificial intelligence in the next 10–15 years, we'll have new tools to adapt to, but we're still not using BIM to its full potential. What's important is to make the most of what we already have, train teams, and build maturity, knowing new technologies are coming. I hope something new emerges in the next 10–15 years - and we'll have to adapt again.

DS – Q4.2: What are your expectations or plans for expanding the use of digital tools in your office?

SC: We already have all of architecture implemented in BIM and continue with regular training for new team members. The plan is to include all engineering disciplines within 2 to 3 years. We've already begun strengthening internal project management, and that will also be integrated into BIM. So, we have a 2-year plan to consolidate architecture and project management in BIM, then another 2 to 3 years to implement it across engineering. I believe that, if everything goes well, in 2 to 3 years the process will be fully consolidated in the office. If something unexpected like another lockdown happens, it might take longer, but our goal is full implementation within that time frame.

DS – Q4.3: How do you think your approach to digital fabrication compares with that of other offices?

SC: When we started talking about BIM at KONCEPTNESS, starting around 2019–2020, there were 3 or 4 big companies (Quadrante, Saravia, etc.) working in BIM - but we're talking about €10, €20, €30 million projects. We were always seen as a micro/small company with a forward-thinking vision. I remember having big conversations with Cláudia Antunes from Start BIM - she said, "You're always a success story." Autodesk also invites us to speak regularly, because when they talk to small offices - up to 20 people, like us - many say, "Ah, BIM is too expensive, not worth it, I only do small projects, just houses." I replied, "You'll spend just as much time doing houses in 2D." I told them, although it's hard for many, "It's worth it for the future." It's hard to validate the immediate gain from that investment, but we can see the difference in the service we provide to the client.

Also, we filter the kind of clients we want to have: in the future, more clients will seek out BIM teams, even if today they don't know the difference. Last year, we had requests for final plans in BIM - many still think that's only relevant after construction, but I explain it makes sense to use the technology from the design phase. Our competitive advantage as an office lies in the differentiated service and willingness to lead this change, even if the value isn't immediately understood today. We had requests last year for BIM "as-builts," and I'd say, "Mr. Contractor, as-builts are done during construction, not after it's built. I don't know where the pipes are; I don't know what's hidden." So now we'll have this machine that can go to the site every month and scan everything.

DS – Q4.4: How would you compare the adoption of digital fabrication in architecture in Portugal with other countries?

SC: Other countries have been doing this for over 10 years - in Canada, in Finland, in the Nordic countries. We are the last country in Europe to seriously implement BIM. Almost every northern European country has had regulations in place for years. Finland was the pioneer in regulating BIM, then came other countries, and we're using the UK standards because we don't have our own legislation. We are very, very behind. We've lost a lot because of it - our construction sector (AEC) is underdeveloped compared to Europe, America, and Canada. When a foreign client (e.g., from the UK) arrives here, they're shocked to see we still show 2D plans. There's still a huge cultural shift to be made. We even had a design team using ARCHICAD that kept presenting plans, sections, and elevations - and I told them, "Show the model! Don't do that! The client doesn't understand plans, sections, and elevations."

The mindset takes time to change. That takes time. In countries outside Portugal, BIM is already part of professional and legislative daily life, while here we're still taking our first steps. For example, Autodesk has already won over many small offices, but we still need a national standard. In the end,

we're way behind several European and North American countries. We still have a long way to go and many internal and external clients to educate.

DS – Q4.5: What emerging trends in digital fabrication do you find promising or interesting for architectural practice?

SC: Good question. No, I think the big challenge is that some people will fall behind, and by 2030 we'll see what happens. There's a huge challenge here - whether the country is ready for this technologically. I'm a bit concerned that if we start uploading files to the platform and they're so heavy, the platform might crash. So, I think we still have a very long way to go before we get anywhere.

DS – Q4.6: What kind of support or resources do you believe could accelerate the adoption of digital fabrication in architecture?

SC: We had an interesting case where someone once said about CIFIT a few years ago: "Good thing I'm investing in BIM because we're going to get support." When we checked, there was no innovation funding, because it's software that already exists. We were simply training our team, and I thought we'd get back €8,000–€10,000 in return on the investment, and we didn't. I think if companies were rewarded - or if the government reduced taxes, or there was some certification or qualification that marked companies as innovative in this area - and got returns from it, it would be a great asset. If we're going to reach a point where it's mandatory, then maybe 10 years earlier we should start giving companies the conditions to adapt. But for us, it's always been our own investment. We never had any kind of support for this kind of implementation. We thought we would, but we didn't, and we haven't given up - we keep going. But I think if there were support in that sense, it would be helpful. Free training platforms would help - there are so many things. One of the things I think they must do is stop letting tenured professors say everything should be in 2D, because all students graduating from university don't even know what BIM is! This is surreal in the age we're living in. That, to me, is one of the biggest handicaps the government has: professors still say no. AutoCAD is already a problem - when you add 3D, it becomes a monster. No. We are way behind in architectural education in Portugal compared to the rest of Europe because of this - because we refuse to evolve. Universities are like healthcare and education - everything's a mess in Portugal. We don't invest in what we should - which is, ultimately, innovation.

ANNEX F – INTERVIEW TRANSCRIPT

Rebelo de Andrade

The Rebelo de Andrade atelier focuses on the design, development, and execution of architectural projects, balancing the diverse interests involved. It respects the client's wishes and public expectations while adhering to national and local regulations. The atelier values harmonious integration into the landscape, understanding and respecting its presence and form.

Interview conducted at the office on 01/21/2024.

PART I: INTRODUCTION AND MOTIVATION

Daniela Silva (DS) - Q1.1: When and why did your office start incorporating digital tools into architectural practice? What was the initial catalyst?

Tiago Rebelo de Andrade (TRA): I can say there were several moments. As you know, I have two companies - Subvert and Rebelo de Andrade. My father, as an architect and my business partner, was part of one of the first offices in Portugal to work with ArchiCAD. ArchiCAD was one of the first BIM platforms, but the office never really used it as a BIM tool - more as a 3D tool.

DS: Right.

TRA: That was at the very beginning, when I was still in school. Later, my father ended up using ArchiCAD only as a 2D tool. After graduating (I studied in Porto and Milan), I worked in London for a year. Interestingly, in London, I worked with MicroStation, which the Porto faculty also taught (instead of AutoCAD, which I thought was absurd!). After that experience in London, I returned to Lisbon. I had friends working abroad; for instance, Diogo Aguiar - we did the Pedras Salgadas competition with him - and João Jesus from LIKEarchitects, with whom we collaborated on a competition in 2011 (Triennale of Architecture, "A House in Luanda: Patio and Pavilion"), where we came in second place. They were already using tools like Rhino back then.

Around that time, we were in the midst of a financial crisis and money was scarce. My father had his architecture office, ARQUITRAÇO, which I later rebranded to RA. One of the first projects I worked on with him was Casa da Areia, around 2007 - a semi-buried house with lots of curves, integrated into the terrain. The only way we could develop it quickly and precisely was by using Rhino for modelling (starting from hand sketches by my father and me).

Working with family was complicated - we argued a lot because I was young and eager to try new things, while the office had a very traditional, family-oriented culture (for example, my aunt worked

there, and there was resistance to trying different tools). So, I felt it was important to follow my own path. I even did a post-grad in management at Nova and a design course to, for instance, build a new website for my father's company, which needed a fresh image. Around that time, I started envisioning my own office, Subvert, because I saw a gap in the market: there were very few companies combining design and architecture. That is, when designing a building - whether a residence or, as in our first Subvert project, a law office - we would also handle the branding, website, graphic identity, in addition to the architectural design of the space, all with a coherent standard.

So, we started Subvert. In our first major project (a nautical building), we hired Marta, who came from the Porto Faculty and already worked with BIM. Together, we started implementing ArchiCAD in the office. I also had a very commercial role in the company at the time, but I was also working in BIM.

DS: Right, since you had the post-grad...

TRA: With that extra training, if I sit down for a month to practice, I can work in BIM better than most people here.

DS: Sure, you bring that background with you.

TRA: Exactly. Nowadays, though, my work is more about hand drawing and concept creation. I often still do some form studies in Rhino myself. We're very collaborative in that aspect.

Since 2014, we've been working entirely in ArchiCAD at Subvert. My first office was on Rua da Rosa; my fathers was on Avenida João Crisóstomo. We eventually moved into a shared space on Rua da Prata - literally side by side - which marked the beginning of our closer collaboration. We moved into our current space about two years ago. A year ago, only three people here were working in BIM (me, Marta, and our colleague Rafa). Now we're almost 30 people, and only two don't work in BIM.

DS: In just a year? That's a huge leap!

TRA: We also had the luck of winning a few key projects during that time. (Luck plays a big role: we often compete for projects and clients choose based on price, unfortunately.) For example, we recently lost a hotel project because a competing office proposed fees four times lower than ours. Practices like that end up "killing" the market: small offices, often without software licenses, with lower fixed costs and no insurance... so they can drastically undercut prices. In any case, BIM helps us speed up processes. Sometimes we have an idea for a project and with BIM, it's easier to realise and visualize it in 3D quickly. I'll give you an example: we have a house in Melides (a residential project) that we developed in two months during the preliminary design phase, for licensing submission, because we used BIM. We didn't have to redo the project multiple times - we could see what we wanted (and didn't want) from the start - we immediately understood what was right or wrong in the model.

DS - Q2: What were the main motivations for adopting these technologies? Was it a response to digital evolution, or were there other reasons?

TRA: The main motivation was really to keep up with digital evolution. We like to always be at the forefront when it comes to technological innovation. In the past, those who used to draw by hand eventually moved to the computer - it's a natural progression.

DS: Exactly. For example, when I started architecture school, one of my professors forbade us from using AutoCAD in the first year; he said we had to draw everything by hand.

TRA: Yes, that was also the case at my school (Porto): in the first two years, we didn't touch computers, and I think that's important.

DS: So, we can develop control over drawing, right?

TRA: Precisely. When we drew by hand, we had to think before drawing each line. Nowadays, people draw on the computer often without thinking - and then there are more corrections needed. The computer also has the downside of the zoom: you focus on a detail and can lose sight of the whole project.

Whereas with hand drawing, you always keep a global perception. On the computer, if you're not careful, it's easy to lose that sense. Still, the traditional process of hand drawing, of developing visual sensitivity and attention to detail, is important even when working in BIM. Someone might master a digital tool and still not really know how to design or understand what's happening on site.

DS: True. I'll give you an example: recently, we had an Erasmus intern who thought Revit made everything "by magic." I explained: yes, it's fast, but you have to think about the space while modelling each wall. In AutoCAD, you're just drawing lines on a plane; in BIM, you're actually building something in three dimensions - you need to understand what you're doing in space. There's no point using the tool on autopilot.

TRA: We also had a colleague, Rafa, who was a great architect and very skilled with the software, but his BIM model was full of "construction cats" (errors and patches in the model). In other words, the architecture itself was very good, but the BIM project organisation left much to be desired. This shows that knowing the tool isn't enough - you have to think deeply about the project. More than the tool itself, what matters is the ability to think through the project. That awareness was a motivation: we knew that by adopting new technologies, we had to learn to use them critically, without losing the fundamentals of design. And that's what we did - always trying to balance digital evolution with the classical principles of architecture.

DS – Q1.3: Can you describe a project where the adoption of digital technology was crucial to its success?

TRA: Yes, the Nautical Building project was a textbook case. For instance, we consulted 14 contractors for that (large) project, and the variation between bids was minimal - the standard deviation was around 4%. That happened because the project was very well defined in BIM, with all

quantities and details clear, so it was hard for any contractor to claim errors or omissions in the specifications.

DS: So, everything was clear in terms of quantities and calculations - no surprises.

TRA: Exactly. That protected both the contractor and the client: each bidder priced the job based on a rigorous model. In the end, the owner chose the contractor who truly understood the project (not necessarily the cheapest, which often hides quality cuts or hidden costs).

Another aspect was that the construction meetings became much smoother. Usually, site meetings are tense and difficult, but with this BIM project, we developed a great working relationship with the builder (Alves Ribeiro) and the client. Site meetings were almost fun - we'd go in good spirits, not to argue, because there were virtually no interpretation conflicts.

DS: That's amazing - and very rare!

TRA: It really is. Even with Casa da Areia (finally under construction now after many years), we felt something similar: since the whole project is modelled in BIM, the client has already seen everything in 3D and knows exactly what they're getting. There's none of that mismatch between what the client imagined and what the architect drew; digital tools make communication much clearer.

DS: Exactly - and I imagine it's also easier for clients to visualize a project using BIM rather than just floor plans.

DS – Q1.4: Was there any model or example (national or international) that inspired your transition to using digital tools?

TRA: Honestly, we didn't follow any specific model - it was our own initiative and will. In fact, when we started (around 2012–2014), there were hardly any references here in Portugal. Offices working in BIM were rare, especially in Lisbon. In Porto, there was that architect from the Cruise Terminal project who claimed to be using BIM, but apart from that, there weren't many others to inspire us. The truth is our digital transition was internally driven - we saw it as the inevitable path and wanted to be proactive.

DS – Q1.5: What were the main perceived benefits that motivated the adoption of digital tools? Would you say it was mainly about process optimisation?

TRA: Absolutely, process optimisation. With digital tools, we can speed up phases and get a tighter grip on the project - that is, have a more holistic control of everything.

DS: Plus, everyone stays on the same level of information, right? It becomes easier to communicate the project to everyone involved.

TRA: Exactly - everyone on the team (and even externally) is on the same page with the model, which brings a lot of transparency. But mainly, it was efficiency: we make changes and run tests much

faster, avoid unnecessary rework, and anticipate problems before we're even on-site. That raised the quality and confidence in our projects, and that's what most motivated us to adopt these tools. We can say that today our processes are more coordinated, there's less room for error, and the client clearly understands what will be delivered. That combination of benefits - speed, control, and clarity - was decisive for us to fully embrace BIM and other digital technologies.

PART II: BARRIERS AND CHALLENGES

DS – Q2.1: What were the main barriers you faced in implementing digital fabrication technologies?

TRA: The biggest barrier we faced was human - related to team dynamics. In our field, there's a lot of turnovers in architecture offices - unfortunately, many architects end up leaving for other countries where they're paid better, and it's hard to retain them here. That means that, in the past, if someone developed an entire project in 2D and then left (or went on vacation), the next person would have great difficulty interpreting and continuing the work. A lot of information was stuck in the head of the person who drew it and wasn't clearly expressed in the drawings.

By implementing BIM, we were able to mitigate that problem. With a BIM model, all the project information is integrated and accessible; anyone new on the team can pick up the project and understand it quickly without losing information along the way.

DS: Exactly. So, if you need to allocate more resources halfway through the project, you can do it without breaking continuity.

TRA: Exactly - the Building Information Model retains everything. Today, if someone steps away, another person can pick up the work in the BIM model almost immediately. That was fundamental for us. It gives us more freedom and independence - we're no longer tied to a single collaborator or dependent on drawings scattered across dozens of 2D files. Of course, there was a period of adaptation and training - not everyone mastered these tools in the beginning, so we had to invest in that. But it was worth it: once we overcame the initial resistance and the learning curve, the team embraced the change. The main barrier was really cultural and personnel-related (changing work processes, training everyone, reorganising workflows). Once that was overcome, the benefits spoke for themselves.

DS – Q2.2: Are there any local policies or regulations that facilitated or hindered the adoption of digital fabrication in your practice?

TRA: Honestly, no - there are no local policies that help; rather, the opposite. There's still a lot of ignorance from the official entities. I'll give you an example: today we had a meeting at Grândola City Hall, and we had to show the 3D/BIM model so the planner could understand the project. On the floor

plan, she was interpreting everything wrong: it was a steep site, but since the 2D drawings didn't show that clearly, she thought the building had two superimposed floors, when in fact it followed the slope (one level was "buried," the other above). So, she was evaluating blindly, without understanding the spatial solution. Often, city technicians don't even visit the site and evaluate only on paper - and if the representation isn't crystal clear, they can reject a project simply due to lack of understanding. With the 3D model, we could show the project as a whole and clarify: we just had to rotate the model and make a few sections, and she immediately understood. That avoided a rejection based on a misunderstanding.

So, if anything, digital tools have been helping us educate the regulatory entities themselves about the projects. But direct institutional support for adopting digital fabrication? No, it doesn't exist. In general, there are still no regulations requiring BIM or digital fabrication here, but things are evolving.

DS: In London, for instance, it's already mandatory to submit projects in BIM to city halls, right? Here in Portugal, we're starting to see a light at the end of the tunnel. Even so, I still notice a lot of resistance from some offices: they say "oh, everyone talks about it, but it never goes anywhere."

TRA: I heard architect Pedro Campos Costa say at a conference that these difficulties are real. I think, deep down, it's fear - and that's understandable. My own father, at first, was afraid of losing control over the project by using new tools. Many Portuguese architects also have a certain ego and resist looking at architecture as a business (they're averse to those who approach it more pragmatically). But honestly, a balance needs to be found. Here, we try to maintain the artistic/authorship aspect, of course, but also see the office as a business - at the end of the day, we have to pay salaries and keep the lights on, right?

Unfortunately, some people remain stuck in the past and criticize the newer offices that are innovating. I think that's a mistake (sorry to be blunt). Siza Vieira or Souto de Moura also looked abroad for references and innovated by adapting ideas to our culture. Thanks to that openness, they made a mark and elevated Portuguese architecture. So, it doesn't make sense to demonize new technologies or approaches - there are many valid paths to good architecture, not just one "correct school." In short, the lack of clear guidelines and the conservatism in the field still hinder wider adoption. But I believe that, over time (and perhaps with legal requirements in the future), that will change. For now, we keep pushing forward on our own and showing results - and that ends up convincing even the sceptics.

DS – Q2.3: How has client perception influenced or affected the implementation of digital tools in your practice?

TRA: In general, clients didn't come to us asking "do it in BIM" or anything like that. Most clients just want the project done for X amount and don't care whether we use AutoCAD or BIM - their focus

is on the final result within budget. So, from our side, there's always been an important role in educating clients about the advantages of digital tools.

DS: Even today, you have to explain a lot to clients about what BIM is and what value it brings, right?

TRA: Yes, absolutely. Most clients initially don't understand the difference, but once they do, they end up loving it. We've had clients literally fall in love when they saw what we could do: for instance, showing the project with virtual reality goggles or navigating an interactive BIM model on a tablet - they're amazed to "walk through" the house before it exists. In those cases, the technology helps clients visualize and make decisions, and it builds much more confidence in the project. But there are also clients who remain indifferent - they just want the building done, that's it. With those, the challenge is getting them to value what digital modelling brings.

Often, we have to explain the value of our design fees. We say it like this: if a client doesn't have the money to pay for a good design, they probably don't have the money to build the project properly. When you break down the design cost into the total cost of the project, you realise it's just a small fraction - sometimes it costs less per square metre than the tile!

DS: "Cheaper than the tile," I love that comparison.

TRA: It's true! For example, in a project that costs, say, €2,500 per square metre, our fee, when divided, might come to €40, €50, €70 per square metre - which is nothing. And a good project can easily save €700 or €800 per square metre during construction, by reducing errors, omissions, and waste. So, investing in a well-thought-out and BIM-modelled project pays for itself. Plus, a BIM project helps avoid a lot of improvisation and renegotiation during construction, which usually causes delays and losses for everyone involved. Fortunately, we now have several clients who understand that value and are open to the conversation.

DS: It's great to see that some are open to being "enlightened" in these aspects.

TRA: Of course, not everyone - there are always those who only look at the short term. But I notice that, increasingly, when we show the concrete benefits (in time, money, or quality), clients are convinced. Nowadays we present virtually all projects in 3D models, with renderings, etc., because we know that not only does it help with approvals, it increases satisfaction. I'd say adopting digital tools was an internal decision for us, but it ended up shaping client expectations: many who went through the process with us now almost demand that level of clarity and realism in every project. So, by showing it in practice, we're also raising the bar for the average client - which, ultimately, pulls architecture as a whole upward.

DS – Q2.4: Was there ever a case where technological or financial barriers prevented the implementation of digital tools in a project?

TRA: Honestly, no. I can't remember a single case where we chose not to use our digital tools because of technical or financial limitations.

PART III: EVOLUTION AND CURRENT IMPLEMENTATION

DS – Q3.1: Do you identify any historical milestone that you consider pivotal in the evolution of digital fabrication in architecture?

TRA: Honestly, I don't think there's been one single, defining moment - but I think we're living through that moment now. Let me explain: in recent years, especially post-pandemic, certain conditions have reached a critical point that will force change. For example, the licensing processes have become so slow and bureaucratic (we have projects that take two or three years just to get licensed!) that it's unsustainable to continue with traditional methods. In my view, that will force a technological shift - probably a broader adoption of BIM and digital workflows to streamline and debureaucratise project approvals.

Also, the pandemic made a lot of people realise their homes lacked quality of life. Suddenly, there was a huge surge in renovations and improving housing (some even moved to the countryside looking for a different lifestyle). At the same time, we're facing a housing shortage in the market and pressure to build faster and more affordably. All these factors create an urgent need to optimise processes - and I believe digital fabrication (as well as collaborative remote work, etc.) will grow in response to that need.

Many times, new technologies in architecture are adopted out of market necessity: labour shortages, pressure to reduce costs and timelines, etc. (Think of solar panels or electric cars - they became viable more due to economic and resource pressure than pure ideology.)

DS: It's curious to see how many licensing processes are submitted to City Hall and just sit there.

TRA: Exactly, we had an architect here who took a sabbatical from Lisbon City Hall and said that every day he processed a licensing case, but by the end of the day, 20 more had landed on his desk. It's unimaginable! There's no way to keep up!

DS – Q3.2: How is digital fabrication currently used in your practice?

TRA: Right now, we integrate digital tools in practically every stage of the project. For example, we start a new project with a survey of the site or existing building, already in BIM. From there, we develop the project in a fully digital workflow - from concept to execution. At the office, we have digital fabrication equipment (a 3D printer, a CNC cutting machine) that we use for prototypes and models - which allows us to visualize and test spatial solutions in physical form quickly and affordably.

That said, one thing I avoid is becoming dependent on a single software or method. Some offices limit themselves to one tool, and that ends up overly influencing the outcome - I've seen cases where the architect only uses one modelling software, and all the projects end up with that "software look" (everything in curved organic shapes, or conversely, repetitive orthogonal boxes). I make a point of avoiding that trap. Here in the office, we use a variety of digital tools depending on the need: ArchiCAD/BIM for documentation and coordination, Rhino or others to explore complex or generative forms, rendering software for photorealistic visualisation, and so on. Tools exist to serve us - to help solve the project in the most effective way - not the other way around.

The goal is for technology to free us up to be more creative, not limit us. For example, if I need to go from point A to point B, I can walk or I can use a bike that gets me there faster and gives me time to explore other paths. In the same way, if a digital tool helps me reach a solution faster and test more design alternatives, I should use it. That really improves the quality of the outcome, because we can go through a much more intensive "trial and error" process: testing different forms, materials, etc., until we reach the best solution - almost like a scientific process, like a chef adjusting ingredients until the dish is perfect.

DS: I understand. And the more tools you master (or at least are familiar with), the more options you can generate, right?

TRA: Exactly. It's not about using technology for technology's sake, but expanding the range of possibilities. If I master four or five different tools (or have people on the team who do), I can explore a much wider variety of approaches for the project. That prevents us from getting stuck in a single way of thinking. It also makes us more competitive: nowadays, everyone has access to global references and information, and the market's expectations have risen. So, those who know how to make the most of the tools can produce better solutions in less time. In our office, for instance, we've invested heavily in 3D modelling and realistic rendering - our renderings are very faithful - because we know that communicates better with the client and sets us apart. In short, we use digital modelling and fabrication in our daily work, whether to design and document projects, visualize them, or even fabricate models and prototypes. Always with the philosophy that technology should serve our creative process (and not dictate the project's style).

DS – Q3.3: What are the main lessons learned that you could share with other offices considering exploring digital fabrication?

TRA: What we learned is that the hardest part isn't the software - it's the shift in mentality. Getting the team aligned, reorganising workflows, and making sure everyone works in the same way was key. Once that clicked, everything became more coordinated: we communicate better, distribute tasks more efficiently, and nothing gets lost along the way.

Another important lesson is not confusing tool mastery with good architecture. You can be great with software and still miss the point. You need to think about space, keep the big picture in mind, and not model on autopilot. We always try to combine digital tools with hand drawing and concept thinking - it keeps the project grounded.

And lastly, don't fall into the trap of becoming dependent on one tool. We adapt the tools to the project - sometimes it's ArchiCAD, sometimes Rhino, or a 3D printer. The goal is always the same: to use technology to help us think better and work better.

DS – Q3.4: What have been the key technological developments that facilitated the use of digital fabrication in your practice?

TRA: In terms of impact on our practice, I would highlight two things: first, the adoption of BIM software (in our case, ArchiCAD) - that revolutionized how we work internally. Second, the introduction of the 3D printer in the office - being able to quickly fabricate 3D models and prototypes was a huge leap.

From the client's perspective, interestingly, another technological development had a big impact: our investment in 3D visualisation and photorealistic rendering.

DS: Yes, the renders I've seen from you are incredibly realistic. It completely changes the client's perception when they see an image like that, right?

TRA: No doubt. Often, just using the "raw" BIM model, the client doesn't fully perceive the space. But when we present a realistic render, with materials and lighting, the project comes to life for them. We've even had cases where we showed a client a navigable BIM model first (those interactive models on a tablet) and then showed high-quality rendered images - and the client was so convinced that they immediately approved the project.

So, besides BIM and physical prototyping, I'd say the evolution of rendering software and even Virtual/Augmented Reality for presentations was crucial: it made communication with clients much easier and enabled faster, more confident decisions.

DS – Q3.5: How has the integration of digital tools affected collaboration within the office and with other stakeholders?

TRA: The integration of digital tools had a very positive impact on internal collaboration. As I mentioned, by working in BIM, everyone accesses and contributes to a single, up-to-date model. That practically eliminated those internal communication failures - the project is no longer "broken" into dozens of separate 2D files but has become a unified database. So, if one team member makes a change, everyone else sees it immediately; we gained a common language within the office. It became

much easier to distribute tasks across the team without risking information loss, which significantly increased our efficiency and group cohesion.

PART IV: FUTURE

DS – Q4.1: How do you see the future of digital fabrication in architecture?

TRA: I see digital fabrication playing an increasingly important role in construction. For example, we've already started using solutions like CLT (Cross Laminated Timber) structures in some projects - which, if you think about it, is almost like building a full-scale model, given the level of prefabrication and digital cutting involved. I believe the adoption of digital fabrication processes on site will happen mostly out of market necessity. There's a shortage of skilled labour in construction: nowadays, almost no one wants to be a carpenter or mason (younger generations are looking for other careers). So, to fill those gaps, we'll need to turn to automated processes, factory prefabrication, CNC-cut components, 3D printing of certain elements, and so on.

Of course, this also brings social challenges - people will complain that machines are "taking away" jobs. But you can't stop progress: it's an inevitable evolution.

DS: Yes, it's like what happened at toll booths with Via Verde - the humans were replaced by automatic systems.

TRA: Exactly. I believe something similar will gradually happen in construction. We'll mechanize and digitize certain tasks simply because there's no one left willing to do them manually. However, I don't think the creativity of the architect will be replaced. We're seeing the rise of artificial intelligence and advanced automation, but in our field, human intervention will continue to be crucial. No matter how much AI advances, I believe it will always be a support tool, not a full substitute for the architect - especially because clients often don't even know how to express exactly what they want; translating those desires into liveable spaces is a deeply human skill, inherent to the architect's sensitivity.

DS – Q4.2: What are your expectations or plans for expanding the use of digital tools in your office? You currently use digital fabrication for prototyping - do you imagine in the future using these tools to produce final pieces (finished building elements)?

TRA: Yes, definitely. That's actually the path we aim to follow in terms of quality: to be able to digitally fabricate certain building components, custom-made and precise, either in the office or in a factory, and then install them on site. Practically speaking, we want to make greater use of these machines. If today we use them for models, tomorrow we could use them for customised construction pieces. That not only raises the quality of what we deliver but also makes us more efficient.

DS: For example, instead of staying up late cutting a model by hand, you leave the 3D printer running overnight and the piece is ready in the morning, right?

TRA: Exactly! I gain quality of life and time to focus on what I really love and am good at (which is creating and designing), instead of spending hours on repetitive tasks that the machine does better.

DS – Q4.3: How do you think your approach to digital fabrication compares with that of other offices?

TRA: It's actually hard to compare - every office has its own pace and priorities. But I like to think that, in some ways, we're a bit ahead of the average in this regard. At least, we've been pioneers in some things: we were among the first in our circle to seriously implement BIM, invest in 3D printers, those kinds of things. On the other hand, we don't see this as a kind of "industrial secret" competition. Unfortunately, many offices in Portugal are very closed off and afraid to share knowledge, afraid of losing an edge. We try to go against that current: we keep an "open office" posture. We share what we do, we're not jealous if another office is more advanced - on the contrary, we want to learn from them. And we're also fine with being an example for others who are just starting out. I want other offices to even surpass us, so that we'll be encouraged to surpass them again - in a positive dynamic where everyone evolves.

DS: A kind of healthy peer competition, right?

TRA: Exactly. As I said at the beginning: we're all architects, and ideally, we push each other to be better. I gain nothing by hiding my methods - the success of a colleague doesn't prevent my own, and vice versa. Unfortunately, some still think otherwise.

DS: Once, we had a funny situation: a client told us she'd been approached by another office who said something like, "Are you really going to do the project with them? I have good contacts at Lisbon City Hall; with me, your project would be approved in no time..." Very classy, right?

TRA: That kind of approach, besides being unethical, leads nowhere - t's just hot air, because everyone makes promises, but in the end the project takes the same time to get approved. And worse, that mentality fragments the market: if every architect isolates themselves in their own little kingdom and tries to tear down the neighbour, soon no one's going anywhere. We prefer the opposite: to collaborate and exchange ideas.

DS – Q4.4: How would you compare the adoption of digital fabrication in architecture in Portugal with other countries?

TRA: I feel like they're further ahead abroad. Portugal was slower to embrace these tools. In many offices abroad (especially in Northern Europe), BIM and other digital technologies have been the standard for years, while here there's still reluctance and only now it's starting to become widespread.

But there are nuances. For example, I have an architect on my team who studied with me in Porto and worked in Switzerland, at one of the top offices there, and he told me they didn't use any BIM at all in that office!

DS – Q4.5: What emerging trends in digital fabrication do you find promising or interesting for architectural practice? (For example, artificial intelligence, drones, etc.)

TRA: We're paying close attention to all of that. We already use drones, for instance - it's something that's here to stay. Drones are great for topographic surveys, photogrammetry, site monitoring, and even for producing aerial presentation images.

But talking about more "futuristic" things: Artificial Intelligence (AI) is definitely a promising trend. Graphisoft (ArchiCAD's developer) recently released an experimental AI integration for generating rendered images. We tested it here at the office: our colleague Gonçalo installed a plugin that allows you to ask the AI for a certain render style for a BIM model. We tested it on a simple massing model - we typed instructions like "concrete and glass facade, late afternoon lighting" - and the AI automatically generated rendered images with those materials and lighting applied to our model. It was impressive because, instead of spending hours in 3ds Max assigning materials, positioning lights, and setting up cameras, we just typed what we wanted and got a visual result almost instantly. It's not perfect yet, of course, but you can see the potential.

Another trend is Virtual/Augmented Reality.

DS: Have you explored that?

TRA: We haven't adopted fully immersive Virtual Reality (VR) yet - we chose to invest first in other priorities, like setting up a render farm (a room with powerful computers) to speed up traditional renders. But we've experimented with Augmented Reality (AR) on site. For example, the other day we went to a plot with an iPad using an app linked to our BIM model, and we could "see" the projected building overlaid on the actual site through the camera - it was amazing! Seeing the full-scale building in its real location, before it exists physically... the whole construction team was excited.

DS: And you see potential in that for the future?

TRA: Definitely. These immersive technologies make it easier for everyone involved - clients, contractors - to understand the project because they can visualize exactly what will be built, in situ. It eliminates so many doubts and misunderstandings during the process.

And coming back to AI: I believe it will speed up many repetitive tasks (like generating images, optimising early layout ideas, maybe even suggesting solutions based on parameters). I don't think it will replace the architect - as I said, it's more likely that an architect who knows how to use AI will replace one who doesn't.

DS: No doubt - those who know how to take advantage will have the edge.

TRA: Exactly. These tools also tend to democratize the field. For instance, we have a very strong 3D visualisation department here, and that's a competitive advantage today. But imagine a small office that doesn't have in-house capability to produce high-quality renders - suddenly, with accessible AI, that office can generate great images of their projects without a dedicated specialist. Emerging technology can level the playing field: whoever adopts it early can get results that previously required a big investment.

We saw something similar a few years ago with social media: we were one of the first Portuguese offices to use Facebook to share projects, and it gave us huge exposure (we even won ArchDaily awards largely thanks to that online visibility). At the time, many established architects looked down on those platforms - hey thought it wasn't "serious." But then, when they themselves started getting recognition through them, their attitude changed.

So, technological trends first seem strange, then they become mainstream. I'd say today it's essential to stay on top of things like AI, AR/VR, automation in design and digital fabrication. Those who adopt these trends intelligently will definitely stand out - and at the same time make architecture more efficient and accessible. At the very least, we're keeping an eye on everything and ready to try whatever can bring value.

DS – Q4.6: What kind of support or resources do you believe could accelerate the adoption of digital fabrication in architecture?

TRA: I believe one of the biggest helps would be at the fiscal and policy level. Today, in Portugal, architecture is taxed like a luxury (23% VAT) - this makes projects more expensive for clients and limits the financial margin offices have to invest. If there were a VAT reduction for architectural services (perhaps aligning with cultural services, etc.), that alone would provide important relief and allow offices to invest more in innovation.

Also, the equipment and software we need (computers, BIM licenses, 3D printers, CNC machines, etc.) are extremely expensive and heavily taxed. Why not create tax incentives or funding lines for acquiring these technologies?

Abroad, architects charge proportionally much higher fees. In Switzerland or Germany, for example, they talk about fees around 10% of the construction cost (and that can go up to 15% or more if they include full project management), and those percentages apply to buildings that cost two or three times more than ours. That means foreign offices have far more resources to invest in digital tools than we do - and they often pay less tax on them. Here, we pay the same (or more) for software and hardware licenses, but with much lower fees - it's a tough equation. If the Portuguese government wants (as it seems) to require offices to invest in BIM and new technologies, then it should also create

the conditions for that: for example, tax reductions on equipment imports, subsidies or funding for training and software/hardware acquisition, etc.

DS: It's almost an unfair race, isn't it?

TRA: Exactly. Today, a small national office is even competing with foreign offices in some markets, and those outside competitors benefit from cheaper fuel, more accessible software, better-paid labour… they have huge advantages over us. Structural support is needed - a more business-oriented vision applied to architecture. I think that's often lacking, both from institutions and even from architects themselves here in Portugal. Recognizing that if we want innovation (BIM, digital fabrication, etc.), we need to provide the means for architects to invest in these tools. In short, measures like tax incentives, reduced technology taxes, modernization funding programs for offices - all of that could greatly accelerate the widespread adoption of digital fabrication in Portuguese architecture. And, I dare say, the return would be enormous in terms of productivity and quality in the sector. So, I hope that in the future, architecture is seen not just as an art form but also as an industry to be modernized with support and investment.

ANNEX G – INTERVIEW TRANSCRIPT

Saraiva + Associados

Saraiva + Associados, founded in 1996 in Lisbon by architect Miguel Saraiva, operates in the fields of Architecture, Urban Planning, and Interior Design. With a multidisciplinary approach and innovative solutions, the office stands out for its creativity and cultural diversity in its projects. Since 2004, S+A has been internationalized, operating in 08 countries across 4 continents, in close collaboration with the founding office. Globally recognised, S+A is frequently featured in the WA100 world architecture ranking, being the 87th largest architecture office in the world in 2021 and 10th in the sustainability ranking.

Interview conducted at the office on 07/05/2024.

PART I: INTRODUCTION AND MOTIVATION

Daniela Silva (DS) - Q1.1: When and why did your office start incorporating digital tools into architectural practice? What was the initial catalyst?

Luís Barros (LB): From the very beginning of the office, in the mid-1990s, we already adopted the available digital tools. For example, in 1996, architect Miguel Saraiva (founder of the office) and his partner, both very young at the time, started working with AutoCAD - which at that time was still quite rudimentary, but it was the most advanced tool available. In other words, the use of digital technologies has been in the office's DNA since its foundation because we always believed in the potential of these tools. The initial catalyst was largely the company's collaborative philosophy and the availability of these new tools that allowed work optimisation.

As the company grew, the need to optimise teamwork arose. We always had a very strong collaborative culture: everyone worked together in the same room, sharing tasks for each project. However, in the early 2000s, working in teams using only AutoCAD was…

DS: It was a challenge.

LB: Yes! Each architect was isolated on their computer, and sharing information meant exchanging files on floppy disks, which was slow and error-prone. That's why we decided to implement an internal network to connect all the office computers, allowing access to shared files and simultaneous work. This decision was pioneering and set us apart at the time because it gave much more fluidity to collective work. We also developed an internal project organisation methodology, ensuring everyone had access to updated information and that each person could contribute to a joint result. This

collaborative approach has always been a hallmark of ours - we even adjusted our physical workspace to keep teams united because we realised that separating people by rooms or floors reduced spontaneous idea exchange.

DS: Because even unconsciously, there ends up being a separation…

LB: Exactly. By keeping everyone close, knowledge exchange happened naturally and catalysed better results. Over time, we continued updating our technological tools to support this way of working. A major leap occurred around 2016 when we adopted BIM as part of our practice. At that time, the BIM tools we started using were still relatively basic for us, but there was a clear motivation for this change: we were competing in international projects, and many foreign clients and partners already required BIM projects. We even trained 90 people - the entire company - which took months. But it was necessary because of these international commitments. To remain competitive in the international market and meet a very high level of demand (complex projects, tight deadlines, and absolute precision requirements), we saw that we had to learn and incorporate BIM quickly. In other words, besides the internal motivation to improve collaboration, there was also an external factor – market and client pressure – that forced us to evolve. It ended up being positive: thanks to the international experience we gained at that time and our existing team-oriented work culture, we successfully integrated BIM into our working method. So, I would say that initially, we adopted digital tools to improve internal collaboration, and later, the adoption of BIM was driven by the need to keep up with market innovation and competitiveness, especially internationally.

DS – Q1.2: What were the main motivations for adopting these technologies? Was it a response to digital evolution, or were there other reasons?

LB: The adoption of digital technologies, and in particular BIM, initially arose as an internal response to the need to improve collaboration between teams. We always had a collaborative work culture, even before these tools became a market standard. In a way, when the industry began to value collaboration and CDEs, we already felt at home - we had been working that way for over 20 years. However, there was also a strong external motivation. To remain competitive in the international market and be able to respond to increasingly complex projects, with tight deadlines and a very high level of demand, we realised that we had to incorporate BIM quickly.

DS: In the beginning, it takes a lot of time…

LB: To implement, yes. And client pressure and the need to keep up with innovation ended up accelerating this process. International experience helped a lot because we were already exposed to that level of demand and had the right culture to integrate these tools into our work methods.

But not everything is simple. Implementing BIM also brought challenges. Being a large company with many teams, process systematization became inevitable. There is a constant need to structure,

to properly prepare projects, to get everyone on the same page, which means creating maps, schemes, schedules, plans - and all that takes valuable time, especially at the beginning of the process. They say BIM saves time, but that gain is only felt at the end. At the start, it's exactly the opposite. And this raises another issue: how to balance all this technical and procedural demand with the creative focus that architecture requires? The biggest challenge has been ensuring that this need for systematization does not negatively affect the creative process. Because, in the end, the architect still needs time to analyse, test, conceive – and that's where the true value of our work lies. So, I would say that adopting these technologies was indeed a response to digital evolution, but above all to a concrete demand from the market and our clients. It was a necessary adaptation, and despite the challenges, it turned out to be positive. Today, we feel we are in a more comfortable time – technology has evolved toward collaboration, and this aligns very well with our way of working.

DS – Q1.3: Can you describe a project where the adoption of digital technology was crucial to its success?

LB: It was what allowed us to win an international French BIM award in 2018. It was for a project we did for Vinci Consolucion, a hospital in Kazakhstan being built by this French construction company,

whose architecture was Portuguese – ours. The functional program, because it's a hospital, was very complex and created by an American. Structural engineering was done by a Polish company. Mechanical and electrical engineering by a Lebanese company highly specialised in these processes, and then there was a Polish lighting designer. A series of people from all over were involved in this project, except from Kazakhstan itself. The only company that had an office in Kazakhstan was ours, and we had been there for quite some time. So, how do you build something as complex as a hospital in BIM?

DS: With such a dispersed team.

LB: Exactly. So, we, together with Vinci, who at the time was testing the BIM 360 platform, did the work with Autodesk. And we were basically the ones who inaugurated the platform. We had access because they were using that tool. Moreover, Vinci has over 10,000 network licenses.

DS: That's another scale.

LB: A completely different scale. And Autodesk was really testing this. They had already had some versions and iterations that were more or less efficient.

DS: But it was really the trial by fire. And it was used.

LB: It was fully used at the time. It was a huge success. We met monthly in Astana with the entire team to discuss and solve problems. But everything else was done collaboratively online – this was in 2016.

DS: So, in the year you really started working with BIM, it was the first big project.

LB: The first serious project, because just opening Revit and playing around is not working with BIM.

DS: Exactly. That's my biggest struggle in the office where I work now – convincing people that knowing how to draw a wall and add some windows is not working in BIM.

LB: It's not. And then there's also the aspect of how to make this work from a business perspective, not just as an office exercise. We have responsibilities we need to fulfil and deliver.

DS: And respond to clients.

LB: Because of that. And how do you make all this happen, right? These international experiences really taught us how to do this properly and how to use these tools. I remember well the BEP for that hospital… It was an oncology hospital, an extremely complex project. And the BEP was absolutely exemplary. We still use it today as a reference for how a proper BEP should be done. Because it had everything. Absolutely everything. At that time, we collaborated with a French team - I remember the woman who led that work. I went to Paris several times, and we really had the opportunity to participate in creating the plan. And that was crucial because the stakeholders who were defining the BEP were the same ones who would execute it. That's how it should be: whoever will implement also participates in defining it. She based it on the Penn State University model, but then it evolved. It ended up being a super well-structured manual, where it was detailed exactly how information should be inserted by all disciplines. It wasn't just for one specialty, it was for all, so the system would work in an integrated way. And in the end, ideally, you press a button and get the expected result.

That was incredible. It was really in that project that we realised the true potential of the tool when used in its entirety. At that time, in Portugal, no one was doing anything even close. We didn't even know it wasn't being done. We went there, participated, and later even won an award.

Later, we participated in BIM conferences, like the one in 2019 - I think it was in Coimbra - promoted by PT-BIM. Professor Resende even told us: "Bring that project because it's interesting!" - and so we went and presented it.

Teresa, our BIM Manager at the time, was in charge of the presentation, and we ended up sharing it – I started it, she finished it. And there, at that moment, we realised: no one in Portugal until then had done that – the whole team working on the same platform, at the same time, in a truly collaborative way.

Nowadays, I think there's more awareness about this. People are starting to understand what working this way means. But there's still a bit of a gap. There are still those who don't want to pay for licenses, who use makeshift solutions… the industry still lacks some maturity.

But the truth is, it has already been done. It has been proven to be possible. And that's where everything started to change for us.

DS – Q1.4: Was there any model or example (national or international) that inspired your transition to using digital tools?

LB: When we started the transition to BIM, there were practically no reference models in Portugal we could follow. The truth is that we didn't rely on any other national office. We were already very exposed to what was being done abroad - we had daily contact with international partners and clients who already worked with BIM in advanced ways. That gave us more than enough input to know which way to go. We had many people abroad doing all of this, and we had direct, constant access to them. And here in Portugal, there simply wasn't that demand. The technical commission of 197, which should have been laying the foundations for BIM in Portugal, was still finding its footing. When finally, some minimally concrete results started to appear, we were already applying BIM in real-world projects. We had already evangelized clients, convinced suppliers - we were already convincing the whole chain to work on the same wavelength. It was an implementation done on our own, exploring and learning internally, based on the international experience we were accumulating. We didn't feel the need to seek inspiration within the country because best practices came from those collaborations abroad. And that made all the difference. When everyone is aligned – client, team, supplier – the process works completely differently. And we moved forward, always with the knowledge we were gaining abroad. When the national market started waking up to BIM, we had already paved the way.

DS: Yes, it's more fluid. And people also have to experiment to understand the benefit. There is a lot of resistance.

LB: There is because there's a lot of fear. Fear of obsolescence, of becoming obsolete.

DS – Q1.5: What were the main perceived benefits that motivated the adoption of digital tools?

LB: We still don't consider this finished. We're not yet satisfied. And this is always a process – the tools keep evolving, new plugins appear… people need to understand that it's not really perfect yet.

DS: It has limitations.

LB: Yes, it has limitations. Before coming here, I had a rather complicated meeting with a client who insisted on extracting waterproofing directly from the model. And I explained, saying it's prohibited in our office to model waterproofing because for it to come out correctly in a quantity take-off, it would require modelling all the falls, folds, and risers in detail. Therefore, quantifying that directly from the model should not be done. It must be done professionally by a cost estimator who knows how to relate horizontal surfaces.

But of course, using digital tools brought several benefits to our office. First of all, it forced us to structure and organise our work better, adopting more systematic and standardised processes – which in a company of our size is fundamental. BIM methodology, for instance, imposes a certain discipline:

it's necessary to define standards, procedures, and nomenclatures, which ultimately improves the organisation and rigor of the entire design process. For us, this was great because we already valued having everything well proceduralised (it's a reflection of not being just three people in an office, but dozens of architects working together). With digital tools, this systemic approach became even more necessary and ended up increasing the quality and consistency of the delivered work.

Besides internal organisation, digital tools significantly improved team collaboration and efficiency. Working in BIM, for example, all stakeholders…

DS: Share a single centralized model.

LB: Exactly, which means that architects, engineers, and other partners are always on the same page. This reduces rework and coordination errors, making the process more efficient. We noticed productivity gains especially in later project phases: although BIM requires more preparation at the beginning (modelling, parameterisation, etc.), it compensates by preventing problems during documentation and construction phases, saving time down the line. I would also highlight accuracy as a benefit: with digital models, we can extract quantities, detect inconsistencies, and run simulations with much higher precision than traditional processes, which increases project reliability.

PART II: BARRIERS AND CHALLENGES

DS – Q2.1: What were the main barriers you faced in implementing digital fabrication technologies?

LB: Implementing BIM and other digital tools on a large scale brought several challenges. The main barriers we faced were the high initial investment, the need to convince the market/clients of the value of BIM, and the shortage of already-trained professionals, which forced us to invest heavily in internal training.

So, barrier number one was the financial cost. Licensing software for dozens of workstations involves a very high investment. In our case, we're talking about around 90 BIM licenses (Revit, etc.), which is a huge expense for an architecture office, a field that naturally already has tight margins and relatively low fees. Incorporating these additional costs into the company's financial structure was difficult.

DS: How do you explain to the client that it will be more expensive because the project is in BIM?

LB: It's complicated to explain to a traditional architecture client that a BIM project may cost more (due to the added value it brings) because from their point of view, "it's just a project, why would I pay more?". So, there was significant financial pressure at the start, which we had to manage carefully. Even so, we decided to invest, aware that it was a strategic long-term bet.

The second barrier was cultural resistance and the lack of understanding of BIM's value by clients and other stakeholders. It was (and to some extent still is) necessary to put great effort into educating clients – explaining why working in BIM brings benefits and justifies the investment. Many clients

initially questioned: “But why should we pay more or change the process, just so you use these tools?” We had to spend a lot of energy raising awareness and convincing not only clients but also some partners about the advantages of the digital process (faster updates, better coordination, fewer errors, etc.). That “evangelization” work was quite demanding at the beginning. Fortunately, over time, some clients themselves began to see the benefits (for example, requesting clash detection or coordination, which BIM facilitates) – but at the start, convincing the ecosystem to embrace change was definitely a barrier.

It’s worth mentioning that internally, we also had to change mindsets: not all architects felt comfortable abandoning traditional methods, so there was also a change-management component within the team.

The third major difficulty was (and still is) finding human resources with the right skills. It’s not easy to recruit architects who are experienced in BIM (namely Revit) and, at the same time, have a solid traditional architectural background. We look for professionals who are good architects – with design vision and construction knowledge – and who master digital tools, and that combination is rare in the market.

We ended up concluding that we would have to train a lot of people internally. In fact, we made a huge training effort: we provided intensive BIM training to about 90 employees, in successive groups, over several months (around six months of continuous training). In other words, practically the entire company was trained to get on the “BIM boat.” It was a challenging logistical and financial process (during this period, productivity dropped because people were in training), but it was necessary. Even so, to this day, we still struggle with recruitment – the supply of competent BIM professionals does not fully meet demand.

So, managing and retaining specialised talent and, at the same time, raising the skill level of the rest of the team through continuous training has been (and still is) a major barrier.

DS – Q2.2: Are there any local policies or regulations that facilitated or hindered the adoption of digital fabrication in your practice?

LB: In general, local regulations and practices have not kept up with digital evolution at the same pace, which initially made BIM adoption more difficult. For example, in many cases, after developing a fully BIM project, we still have to deliver everything in traditional format (2D drawings, PDFs, DWFs) to meet the requirements of licensing authorities or specifications. That’s a contradiction – working on a digital model and then converting it into paper or outdated formats ends up wasting some of the efficiency gains.

Therefore, the lack of alignment of official entities with the BIM methodology was (and still is) a limiting factor for full implementation of these tools. That said, we are starting to see positive signs of change.

Some recent policies and local initiatives have been encouraging digitalisation in construction. We have noticed that certain public and private clients in Portugal now accept and even require BIM models in tenders or for project verification.

For example, in market consultation and construction preparation phases, some already use the digital model to extract quantities and detect conflicts, recognizing the benefits of the process. So, the mentality is gradually changing. There still isn't a fully standardised national BIM regulation (unlike countries like the UK, which have had mandatory BIM standards for years), but the topic is increasingly being discussed.

DS – Q2.3: How has client perception influenced or affected the implementation of digital tools in your practice?

LB: Honestly, client perception did not significantly affect our decision to implement digital tools.

DS: That's good, in my opinion.

LB: We moved forward because we believed in them, regardless of whether the client understood or not. In many cases, we were the ones pushing clients, not the other way around. In other words, adoption was driven by an internal strategy, not by external demands.

Of course, we had to, in parallel, educate and clarify some clients about the process (as I mentioned in the barriers, there was awareness work), but this need for explanation didn't hold us back – it only made us communicate better. I would even say that we are often more demanding than clients regarding BIM results. We see advantages and details that sometimes the client doesn't explicitly value, but we implement them anyway because we know they improve the project.

In general, clients ended up trusting our way of working. If the project was well done and delivered on time, they were happy – whether it was in CAD or BIM – so there was no active resistance on their part that compromised implementation. Some more technologically advanced clients supported the initiative, and those who didn't know BIM were pleased with the benefits when they noticed them (for example, fewer errors, better 3D visualisation, etc.).

So, the client reaction was not a direct obstacle; at most, we had to do some pedagogical work, but we managed to implement BIM in the office without major difficulties imposed by clients. Today, we see that many clients have already embraced the results (they appreciate the visualisations, improved coordination, etc.), but even at the beginning, their lack of understanding didn't stop us – we moved forward and proved the benefits in practice.

DS – Q2.4: Was there ever a case where technological or financial barriers prevented the implementation of digital tools in a project?

LB: Yes, it's very complicated. But we've had some victories over time. And of course, being the largest company in Portugal helps - sometimes we can use that to our advantage.

We had a specific case back then - and even until recently - where we didn't have specialty engineers who could work the way we wanted. We were developing the model, everything was working, and I said: "I can't do the structure! There has to be a structural model. There has to be a structural engineer working collaboratively on the platform so I can follow along, give feedback, say whether it's right or wrong, adjust."

But simply… there wasn't anyone. Now there is. Because we told some of those partners: either you get on board with us, or we'll have to look for solutions elsewhere. And that generated evolution – engineering companies started to realise they needed to develop that kind of expertise internally.

DS: To stay competitive as well, of course.

LB: Exactly. And those who embraced that, who built their own teams instead of outsourcing, are now on another level. There is clearly added value. We also apply some pressure: we push the client, the engineer, the subcontractor – all to make sure we can work in the full way we know works best.

But it's difficult for clients to accept spending more – even when the additional cost is negligible compared to the benefit achieved. The problem is that often clients don't even have the internal capability to benefit from that. Either they don't know, don't understand the value, or simply have other limitations.

DS: So, there are also other barriers on their side.

LB: Yes, and those are things we can't control. But we also have other clients who are very well informed, who won't even accept doing it any other way. They build their own control structures, the right teams – and then everything runs as it should.

PART III: EVOLUTION AND CURRENT IMPLEMENTATION

DS – Q3.1: Do you identify any historical milestone that you consider pivotal in the evolution of digital fabrication in architecture?

LB: I always go back to 2016, to that hospital project. Because, honestly, that was a real key moment. At that time, I simply couldn't find engineers - neither structural nor HVAC - who really knew how to work well in this new context. There just weren't any. And suddenly, we were in that "honey pot" – everyone involved, working on a collaborative platform, very well structured, very well organised. It just had to be taken advantage of. That moment marked a real difference. It was truly a turning point.

DS – Q3.2: How is digital fabrication currently used in your practice?

LB: Currently, we use digital tools intensively in practically all projects, but that doesn't mean BIM is blindly applied 100% of the time to everything. What we practice is the philosophy of "use the right tool for each task."

DS: Regardless of which one it is.

LB: Exactly. In other words, BIM (namely Revit) is a central tool in our workflow, but we don't force it to do absolutely everything if it's not efficient for a given purpose. For example, there are stages or types of projects where other applications may be faster or more appropriate – and then we use them without hesitation.

We are aware that BIM is not a "one size fits all." There are still tasks for which traditional BIM (like Revit) isn't ideal, and in those situations, we prefer to adopt another solution and later integrate the results. This actually results from a major evolution in our way of working: in the past, perhaps due to novelty, we tried to do everything inside the BIM platform; today we are much more mature and know how to combine tools. For example, if a certain calculation, drawing, or presentation works better in another tool (whether parametric modelling, GIS software, or even an automation script), we use it and then reconcile it with the BIM model. The important thing is to ensure the best result, not to be dogmatic about the tool.

DS – Q3.3: What are the main lessons learned that you could share with other offices considering exploring digital fabrication?

LB: Don't delay the decision out of fear, start knowing it will take time and effort, approach BIM as a paradigm shift in how you work, and be persistent, adjusting and learning continuously. That combination, in our view, is the path to successful implementation.

DS: There's no magic recipe.

LB: Exactly, it requires adaptation and courage. Essentially, understanding that it is a gradual process, seeing BIM as a new work methodology, not just software, and having a spirit of exploration.

DS – Q3.4: What have been the key technological developments that facilitated the use of digital fabrication in your practice?

LB: Honestly, there wasn't any external technology that suddenly made everything easy for us. On the contrary, what we realised is that to work well with BIM and digital tools, you have to invest a lot in infrastructure and technology yourself.

We had to create the conditions for these tools to work optimally in our context. For example, we built a central server and an extremely robust internal network, capable of supporting more than 100 people accessing models simultaneously. We also invested in high-performance computers for

architects because complex 3D models require a lot of processing power and memory. That was all essential – without proper machines, it doesn't matter if the software evolves.

DS: Rendering is very demanding.

LB: Exactly. Additionally, we paid special attention to system security and stability. Everything digital also brings risks (system crashes, data loss, cybersecurity), so we implemented backup solutions, redundant servers, firewalls – a series of measures to ensure the infrastructure doesn't fail, because today the entire production of the office depends on it. There was also the need to allocate people dedicated to technological support. Currently, we have team members who focus almost exclusively on maintaining and improving this digital ecosystem (from license management to daily technical support).

DS – Q3.5: How has the integration of digital tools affected collaboration within the office and with other stakeholders?

LB: The integration of digital tools significantly improved collaboration among architects (and also between architects and other specialties). Today we can work simultaneously on the same project in ways that were previously unimaginable. For example, with shared BIM models, multiple architects can develop different parts of the project at the same time, seeing in real time what their colleagues are doing. This creates a much more synchronized teamwork dynamic – everyone has access to the most up-to-date version of the project, which reduces mismatches and incompatibilities.

It also became much easier to collaborate with external engineers and consultants: we can integrate their information into the model and detect conflicts automatically, and vice versa, almost as if we were all in the same virtual room. This digital coordination sped up processes that previously required countless in-person meetings and email file exchanges. Now, many times, we solve problems collaboratively within the BIM platform itself, in real time.

Beyond BIM itself, we adopted complementary communication and management tools that reinforced collaboration. For example, we use corporate chat platforms, task/project management software, and online document-sharing environments. These tools keep the team connected even when not physically together. Today, it's perfectly possible for an architect in office A and another in office B to work as if they were side by side, thanks to videoconferencing, chat, and the shared cloud-based BIM model.

This was particularly important when we had remote work periods or teams distributed in different locations – productivity remained because the tools supported that remote collaboration.

However, we also learned that digital tools do not entirely replace human contact and face-to-face creative collaboration. We noticed that, if we're not careful, technology can lead each person to isolate themselves at their screen. That's why we make sure to continue encouraging face-to-face discussion,

brainstorming meetings, hand sketching together around a table – essentially, the human side of collaboration. Architecture is a profession heavily based on exchanging ideas, arguments, and counterarguments, and that requires open dialogue.

Digital tools facilitate the exchange of objective information, but they cannot (and we don't want them to) replace the inspiration that comes from spontaneous conversations between colleagues or the critical eye an architect gives to another's work while passing by their screen. We are aware that we cannot let the team lose that habit of direct interaction.

Interestingly, historically, we always worked all together in the same physical space because we believed in the strength of that interaction. At one point, due to growth, we had to split across two floors and immediately noticed communication worsened – things stopped "flowing" as well. Today, with all the collaborative tools, we can mitigate that distance (we are currently also on two floors and no one complains much because we use chat, video calls, etc. all the time). Still, we prefer to keep teams close and in frequent contact because we know certain ideas only arise in those corridor conversations or improvised sketches next to a colleague's computer.

PART IV: FUTURE

DS – Q4.1: How do you see the future of digital fabrication in architecture?

LB: Internally, we have been studying a lot in this direction. Since we have our own academy, we run a series of tests and experiments – some public and others not yet. Our goal is to anticipate what's coming, to understand what the digital "object" of the future will be.

We all know that Revit, as we know it, is doomed. Something else will come. In fact, there are already alternatives, but they haven't really taken hold yet. Right now, there's a certain noise around this natural evolution – with all the buzzwords about artificial intelligence, generative AI, etc. – and that makes it hard to see the clearest path.

If Revit had been evolving as it should, it would already have capabilities that it still doesn't have today. But since it belongs to a near-monopolistic company, evolution only happens when it makes sense to them in terms of cost per action. And we clearly feel that the tool needs to be much more fluid, closer to the architect's reality, and less like the logic of an IT technician. Nowadays, it almost takes a course just to integrate an Excel sheet with a model. That doesn't make sense.

DS: Yes, some tasks are desperate. Drawing annotation, for example, drains our time and energy absurdly.

LB: Exactly. An engineer changes one column and suddenly wall coding, texts, dimensions all break. I have projects with 500 or 600 drawings, and reviewing all that is like a "Where's Waldo" hunt. The tool is inefficient for what should already be possible with today's digital resources. That's why I believe

evolution has to go through automating repetitive tasks – those that are truly absurd in architectural practice.

DS: And which consume huge mental effort. At the end of the day, they leave us exhausted and away from the creative focus.

LB: Exactly. We need to free ourselves from those tasks so we can really focus on concept, creativity, program analysis, and client needs. And that's where generative AI comes in, which can be a powerful tool. We've been using, for example, Form, an Autodesk platform that was previously SpaceMaker, applied to urban design processes.

DS: I also tried it a bit, and it seemed quite intuitive to me.

LB: Yes, but it doesn't stand on its own. If someone knows nothing about urbanism, they can't work with it. You need to know what you're asking for. But once you know the rules, the tool quickly generates multiple options – which we can then analyse, critique, select, and even refine elsewhere.

That kind of "collaborativity," so to speak, is interesting: using the right tool at the right time, strategically. But the truth is that many people are still quite scared of these technologies. We recently had a talk at our academy about artificial intelligence, and what impressed me the most were the colleagues' questions. They were terrified.

DS: I saw it on Instagram, but I wasn't sure if it was open to the public.

LB: They're all open to the public. But what really matters is the attitude. Many people still see AI as a threat – "we're going to lose our jobs," "this will replace everything." And it's not like that.

DS: Yes, there's no point ignoring the elephant in the room. We need to recognise its potential. People might not want to use it, but they need to know it exists and what it can do.

LB: Exactly. The problem isn't being or not being tech-savvy – it's being afraid. Whoever is afraid is already outdated. Because AI can help in many tasks where we currently have limitations. We're talking about time, budget, deliverables. And all of that ends up limiting our creative process, which it shouldn't.

The ideal would be to test 300 solutions before finding the right one. But we don't have time or money. These tools can help us exactly there: to speed up testing processes, to generate options, to support decisions with more confidence.

DS: I clearly felt that when I interned in Japan. The shock was realizing that there, offices always presented three options to the client – unlike what often happens here in Portugal, where only one is presented.

LB: And that makes perfect sense. We also work that way with international clients. They don't want just one proposal. They want to see alternatives, understand pros and cons. And it's up to us to inform

them: “this option has this, that one has that, and we think this is the best.” But the choice is the clients.

DS: It’s a way of involving them in the process, of respecting them.

LB: And it avoids that “it’s like this because I said so” attitude, which is almost offensive. The future of digital fabrication, for me, is about that: automating what doesn’t make sense to do by hand, and giving space to what truly distinguishes our work – analysis, creativity, the ability to propose and justify relevant options for each case.

DS – Q4.2: What are your expectations or plans for expanding the use of digital tools in your office?

LB: Right now, what we are really doing – and it’s no secret – is taking the lead in what artificial intelligence in architecture means.

DS – Q4.3: How do you think your approach to digital fabrication compares with that of other offices?

LB: Well, the truth is that now, being more connected to management, I see things through a different lens. And, in practice, offices have costs, they have revenue, and they make some investment - but that’s where the “cake” comes from. And investing at the level that the latest digital tools demand… I don’t know if that’s within everyone’s reach.

In other words, I have serious doubts that our colleagues – the other offices – are investing enough to truly take advantage of these tools. Because there still isn’t really a ready-made, accessible “product” that you can just buy and use. There are one or two interesting solutions, yes, but most still require research, development, and, of course, investment by companies.

Then there are tools with very high costs. For example, using GPUs in the cloud, on Amazon, costs a fortune. Doing this professionally requires much more than it seems – it requires different infrastructure, different types of tools, and a well-structured internal organisation. And I don’t know if that’s happening everywhere.

DS: Yes, because it’s not just about investing – it’s about having the capacity to integrate these tools consistently.

LB: And I don’t know if everyone has that capacity. Or maybe they do – I could be wrong – but I don’t have that visibility. Regarding BIM organisation, for example, I think there’s been good progress… but I don’t know if it’s the right path. Because using these tools “properly” really requires a lot: organisation, systematisation, structure. And that, honestly, is hard to see widely implemented.

Just to give an idea: our annual turnover is double that of the second-largest office in Portugal. And our operating income – already reduced and clean – is higher than the total turnover of most other architecture offices in the country. That means we actually have some margin to invest. And even so, we have to limit ourselves. Because it’s all very expensive.

So, if our colleagues are investing and seriously implementing these digital tools – great. But I doubt that's happening on a broad scale. I still see a lot of that logic of "I'm doing this by myself" or "I know how to do it," but then there's no ecosystem around it.

DS: Yes, that makes everything harder.

LB: Exactly. That's what happened to us with engineers, for example. We knew how to work well with these tools, we came back to Portugal enthusiastic and ready to move forward… but then we were missing the partners. There was no one doing structures, HVAC, etc. That ecosystem – as it's now called – really has to exist. Everyone should be making this journey, at their own scale, in their own way. But honestly, I don't know if that's happening.

DS – Q4.4: How would you compare the adoption of digital fabrication in architecture in Portugal with other countries?

LB: Yes, for example, take Asia – over there, you simply don't hire anyone who doesn't know how to work in BIM. It doesn't exist. Some are more skilled, some less, but everyone knows it. And why? Because they're trained that way, from the ground up. Many come from British universities, where education is already much more advanced in this regard.

DS: Yes, London is playing in a completely different league.

LB: Exactly. Their league is different. There's a clear understanding that the digital model has information, and that information must be handled correctly. It's another level of evolution. And we, in Portugal, are not there yet. Abroad, work is already happening on another level.

But in my opinion – and this is a personal opinion – there's also the risk that with so much digitalisation, some quality in concept and design may be lost. That which is truly essential in the project.

So, it's not about being on one side or the other. I believe there has to be a balance. The problem is that we haven't found it yet. The international offices we work with, many of them with very well-established digital practices, have already achieved this marriage between manual conceptual work and digital work. And that shows they are at a much more advanced stage than us here in Portugal. Unfortunately, there is still a great lack of digital literacy in the sector.

Clients, for example, don't even know there is an IMPIC manual. When I send it as a PDF, they look at it and say: "Sorry, isn't this a bit outdated?" But I mean, how are these initiatives not better publicized? In the end, it's always someone isolated trying to push things forward.

DS – Q4.5: What emerging trends in digital fabrication do you find promising or interesting for architectural practice?

LB: I'd say one of the most relevant trends is what's being called artificial intelligence – although, for me, the more accurate term is machine learning.
Because, let's be clear, there's zero "intelligence" there. It's a statistical, purely mathematical model – let's not fool ourselves. But despite that, I think it has enormous potential, especially for those more mechanical, even mindless tasks where we still waste a lot of time. There are things that should already be automated, already implemented long ago. And that's where these technologies can really make a difference.

DS – Q4.6: What kind of support or resources do you believe could accelerate the adoption of digital fabrication in architecture?
LB: Perhaps the most important thing would be the general environment of the activity - having a common involvement, something everyone wants to discuss and contribute to.
That public entities would also actively participate, taking on their regulatory role. For example, that public procurement BIM manual… it should already be updated, communicated, and known by everyone. Especially those who hire - the developers. They should know that document.
DS: Yes, maybe not exactly a database, but at least some common reference point…
LB: Exactly, something transversal that truly moves the sector forward. And moreover, with the obligation to deliver projects in BIM starting in 2030, it seems like things are being imposed without real preparation. It's like: "it has to be done, okay, now get ready." But the truth is no one really knows how to prepare for it. Something has to happen. There has to be a movement to encourage this development - and that would be very positive. Because along with that comes everything else: new digital tools, platforms, automatic project submission, verification systems, everything. And that's interesting. Visualisation, for example - today there are tools that allow you to quickly see the model being created. But they're still slow, too demanding. They should be much more accessible. This whole process should be easier, lighter, more agile. That's what should be happening now.

ANNEX H – INTERVIEW TRANSCRIPT

SUMMARY

SUMMARY is an architecture practice based in the Science and Technology Park of University of Porto.

Seeking the balance between pragmatism and experimentalism, SUMMARY develops building systems assuming the optimisation of time and physical resources as the core theme of its practice.

Interview conducted via ZOOM on 01/15/2024.

PART I: INTRODUCTION AND MOTIVATION

Daniela Silva (DS) - Q1.1: When and why did your office start incorporating digital tools into architectural practice? What was the initial catalyst?

Samuel Gonçalves (SG): Well, I don't know what you mean by digital tools, because digital tools have existed since the creation of the office. Since 2015, for us, digital tools are a given – we can no longer work without them. I don't know if your question is more along the lines of not just digital tools, but perhaps digital fabrication.

DS: Yes, digital fabrication.

SG: Ah, that's the next step, right? Exactly. So… well, from the beginning we've worked a lot with modularity and prefabrication. So much of what we do – much of what we design – isn't directly built, but rather pieces that are later assembled on site, right? So, in a way, our architectural design is quite close to product design, right? Designing parts that have to comply with a set of production criteria. I can give you some very simple and easy-to-understand examples. For instance, some of our buildings are made with reinforced concrete panels. For production reasons, one of the panel's dimensions cannot exceed 3 metres. We can have large panels – 10, 11 metres long – but in one direction they can't exceed 3 metres. This is a production limitation, so to speak.

DS: But also, a transportation issue, right?

SG: Yes, transportation too, but that's another matter where we can stretch the limits a bit. But at this level, it's a production limitation tied to transport, but also to the characteristics of the production line, the concrete beds, etc., the moulds. So, these are limitations we can parameterise, right? The more organised this information is, the better.

Another example: we're currently working a lot with metal prefabrication. The complexity in terms of fitting, the connections between various elements, is much higher than with concrete

prefabrication. When we think of concrete prefabrication, we think in terms of mass. We know there's a lot of steel inside, but we don't design for that – it's negligible. All we need to know is: okay, what thickness of concrete do we need? Then you can put as much steel inside as you like. As long as they give us that information, we work with the thickness and don't know what's inside. But with metal prefabrication, that's not quite the case – many times what needs to be designed is impossible to do in 2D, and impossible without a set of parameterisations we couldn't achieve with CAD.

I'd say it was when we started working with metal structures (a relatively recent development) that we really began working with BIM in a more methodical and evolved way. We had done some things in BIM, three years ago or so, but very much in an embryonic way. I'd say for the past year, year and a half, we've been working almost 100% with BIM tools.

DS: Interesting. The work I know best from you is prefabrication, but with concrete.

SG: And that's what we've actually built so far. That is, what we've done with metal structure are projects and some factory prototypes – we don't yet have anything built. (Ok, ok.) I believe that maybe by the end of the first quarter of 2025 we'll have something built with a metal structure. Until now, it hasn't happened.

DS – Q1.2: What were the main motivations for adopting these technologies? Was it a response to digital evolution, or were there other reasons?

SG: Well, I'd say that the kind of work we do already pushed us toward this type of methodology, right? In fact, it becomes more practical and feasible to work this way. That said, even if we worked with more conventional or traditional solutions, sooner or later we would've made this transition – almost for procedural reasons. I think it's also related to the scale of the office's projects. Maybe two years ago, we started having slightly larger projects; we began taking on projects larger than what we were used to until then. And this sometimes happens somewhat exponentially, right? Just to throw in some numbers: until two years ago, our largest project was 1,500 square metres (I'm talking only about built areas, not outdoor spaces). And right now, we have ongoing projects of 9,000, 6,000, 6,500 m², so… it's almost...

DS: So, the scale has escalated considerably.

SG: Almost quadrupled, right? The built area. But that has to do with several factors – not just the evolution of the office, but also the type of project and client. We're now working quite a bit with public entities (municipal councils and the like), and that naturally...

DS: ...brings a different scale.

SG: A larger scale, right? When you go from private to public, that usually comes with more square metres attached.

DS: And different budgets.

SG: And different budgets too, of course. But this also led us to think about optimising the office's production process – that is, the office's own production process – to systematize certain operations. I'm talking about very basic things here, like drawing vertical sections, facades, profiles… which used to take a long time and are now immediate, once the building is fully drawn and "locked in."

DS – Q1.3: Can you describe a project where the adoption of digital technology was crucial to its success?

SG: Yes. I might even suggest sharing my screen to show you – would that be useful?

DS: Yes, absolutely.

SG: Right, this building we're designing for Oeiras Municipality (48 public houses project in modules) – actually, this is one of two buildings (a project that includes two identical buildings). Essentially, what we did was create two reinforced concrete structural cores, right? With staircases and elevator shafts. And everything you see in blue are prefabricated volumetric modules, made of metal structure, that are, let's say, "clipped" onto the concrete structure. The design of these modules ends up being very detailed, especially because they come from the factory with interior and exterior cladding, which requires us to do work on the flashing (the joints) to prevent water from entering the joints between modules, for example. That's only possible through the 3D model. Well… the module – the way it arrives – is what's shown here in this central module. This is the cut module; essentially, we stacked several modules and then inserted a bar through them that prestresses the entire structure, compressing the modules vertically and ensuring stability, right? Ok. The flashing issues I mentioned – preventing water infiltration in the horizontal joints – are represented and detailed here. Vertical joints are no longer a problem because it's clad with fibre cement slats; so, the vertical slats (the two side ones, this one and this one) aren't installed, so that when we join two modules, we can waterproof the vertical joint and then install these two slats. But all the other elements are already in place, so if the horizontal joint isn't properly detailed, it becomes a problem.

DS: Exactly.

GS: What we did to solve this problem was: on each floor we have a profile running around the entire building. This level of detail and coordination between structure, cladding, and flashing wouldn't be possible without working in 3D.

GS: In this drawing, we incorporated a 3D model from the structural project, right?

DS – Q1.4: Was there any model or example (national or international) that inspired your transition to using digital tools?

SG: Look, obviously the period I spent at ELEMENTAL isn't something I forget, right? And I learned a lot there – although I don't think there's a direct transposition between what I did in Chile and what

we're doing here. As far as I remember, while I was there, I never worked with "heavy" prefabrication, right? Which is what I have to do now in Portugal. There might be some guiding principles shared by both practices – like pragmatism, or this idea of simplifying construction processes – but I'd say that even if the goal is similar on both sides, the way to get there is quite different. Honestly, more than being inspired by or researching other offices and seeing what they're doing in the area of prefabrication, our research has been much more direct – we've been working directly with industry on this topic. Because, I mean, out of curiosity, it might be interesting to know what's happening in Germany with high-tech systems, but from a practical standpoint it's not that relevant if those systems can't be translated into the Portuguese context. Investigating prefabrication using a certain material that isn't used here in Portugal isn't very useful. So, I'd say our main source of information has always been the industry – and we've worked very closely with the plasterboard prefabrication industry, and more recently with metal prefabrication. We're also starting to develop a project with timber frame and CLT structures. Obviously, we continue to study this from within the discipline of architecture. In fact, we recently organised an exhibition called The Readings of Sight, and with that exhibition we brought together 25 cases – 25 construction systems that we consider paradigmatic in the historical evolution of prefabrication. Essentially, that exhibition served to create a sort of portfolio of solutions, originating from different materials, geographic regions, and contexts, allowing us a bird's-eye view of the state of the art in prefabrication through the lens of architecture. But I emphasize that, from a practical point of view, our main source of information...

DS: …is directly with the industry. And that's great – that you've been able to build that relationship. I didn't know you had done that exhibition, may I ask where it was shown?

SG: It started in 2018. Since then, it has been presented in several countries: it was shown at ESALA (Edinburgh School of Architecture and Landscape Architecture), in Germany for the Bauhaus centenary, in Boston (at the Boston Society of Architects), in Budapest, and more recently at Casa da Arquitectura in 2022.

DS: Ok, ok. I didn't know – it must have been super interesting, I had no idea you had done that exhibition.

SG: It's a virtual exhibition. All those 25 cases I mentioned are represented using the classic architectural exhibition trio (models, texts, and images), but instead of using panels or tables, everything is presented in a virtual environment. So, when you enter the exhibition, you use Rift goggles – virtual reality headsets – and navigate the exhibition virtually. Then there's a set of texts and images physically displayed in the exhibition space (written by external authors who worked with us on the exhibition). But essentially, the core of the exhibition is virtual – if you visit the Casa da Arquitectura website, they have the full summary of the exhibition, and you can see images there.

DS – Q1.5: What were the main perceived benefits that motivated the adoption of digital tools?

SG: Above all, it became more practical and feasible to work this way. BIM allowed us to optimise processes, gain speed in producing sections, facades, and details, and better coordinate complex prefabricated elements. As our projects grew in scale, these tools became essential to manage complexity and improve overall efficiency.

PART II: BARRIERS AND CHALLENGES

DS – Q2.1: What were the main barriers you faced in implementing digital fabrication technologies?

SG: Well, I'd say the main difficulties fall into three areas: costs, project timelines, and our partners (people who work with us outside the office). Costs – because, as you know, using BIM software (we use Revit, for example) tends to be more expensive than CAD software. So, once you want to migrate your entire office to that kind of software, suddenly it's a major investment, not something that happens overnight. Second aspect – deadlines. This is very much linked to a common (unfortunately) practice in Portugal, which is the idea that you can complete a 5,000-square-metre building design in three or four months. I mean, not just the execution project – but a preliminary study, licensing project, and execution project, all in four months. That leaves about a month, or a month and a week, for each phase… And in fact, BIM lets you speed things up if you at least get some time at the start; it lets you model the whole building, incorporate all the necessary information, and from there most of the work is done. Any section you want to create, any corner you want to study – it's there, it's easy. But for that, you need a few months to model everything. It's not just about having more people – that doesn't necessarily make the model go faster. Having five or six people working on the same building doesn't mean it will be modelled faster. Timeline issues are problematic. It's important that clients understand that sometimes just one or two extra months would be enough to result in a far higher-quality product – not just in architectural or functional terms, but mechanically speaking, where everything fits together, joints are thought through, the window aligns perfectly with the wall (not forward or backward), HVAC ducts run through the right places… Having all this clearly defined and modelled in advance is a huge step forward in producing a good final object. The third aspect: partnerships. Many engineers we work with still don't work in BIM – some do (especially in structural engineering, it's getting easier to find people), but in other specialties, not so much. So often we have trouble completing fully BIM-modelled projects, because they're made up of BIM architectural models (and maybe some services), but everything else is in CAD – with the old excuse of: "they're just 5 cm pipes, or 2 cm ducts, why model them in 3D?"… That's it. We're making that effort – and it's not just an internal effort, it's also about convincing our collaborators to migrate too. It's about showing them that this is a good strategy for everyone.

DS: Yeah… just an aside: in my previous office, we worked exclusively in BIM, and the HVAC engineer refused to work in BIM – he had this aversion like: "Why should I bother? You've got AutoCAD, do whatever you want…". And sometimes – depending on the project's size – we ourselves had to model all the HVAC ducts to figure out how things could work… just to get a grasp of it.

SG: We sometimes do that too, meaning we model the systems they send us.

DS – Q2.2: Are there any local policies or regulations that facilitated or hindered the adoption of digital fabrication in your practice?

SG: In general, policies and regulations in Portugal make everything harder – not just digital tools. The legislation is completely Kafkaesque. Well, sometimes it's absurd – in some parts of the law, we have the strictest conditions in Europe – for example, in terms of fire safety. It's fire safety legislation that, beyond being open to many interpretations (which also happens with architecture – though that's more understandable due to subjectivity), is extremely tight – tighter than in other European countries, when it comes to escape routes, etc. So, I'd say legislation and regulation are not promoters of this type of tool. On the contrary, they often act as deterrents. We have to worry about so many things that don't actually matter (but that are central from a regulatory perspective), that we often neglect the technical side of projects just to meet regulatory demands. And when that happens, something that could be much easier, more automatic, more straightforward – like developing our projects further using BIM tools – ends up not happening, because we don't have the time (or incentive) to invest in it.

DS – Q2.3: How has client perception influenced or affected the implementation of digital tools in your practice?

SG: Look, I think this kind of thing is like dealing with clients in general – obviously we can't generalize, but we need to clearly distinguish between what is a genuine request from a client and what's just a decorative part of the conversation. It has that merit, right? A person comes in and complains about all their ailments. Maybe you realise, ok: you're here lamenting about a knee problem – that's real. But suddenly there's also a headache (which you know is nothing) and a bruise on the arm (which you know will be gone in 15 days and doesn't matter). Because what really matters is the knee. This happens a lot with us: suddenly BIM is a concern (just like sustainability is a concern, just like design is also a concern, as a differentiator), but ultimately, what actually matters to them is time and cost. In the end, those two factors outweigh everything else. So, if you put several factors on the scale, they always choose either time or cost – not the others. In other words: of course, it would make total sense to fully implement BIM – but for that, we'd need an extra 3 months; and time weighs more. Of course, it would make sense to use a passive ventilation system – but that would require some

windows that would cost €50,000 more; and then budget weighs more than sustainability. I'd say BIM sits in the same place as sustainability: in theory, it's very important in the initial intention.

DS – Q2.4: Was there ever a case where technological or financial barriers prevented the implementation of digital tools in a project?

SG: Yes, yes, of course. Financial – and not only financial – it's also about deadlines…

PART III: EVOLUTION AND CURRENT IMPLEMENTATION

DS – Q3.1: Do you identify any historical milestone that you consider pivotal in the evolution of digital fabrication in architecture?

SG: Look, I can't pinpoint a specific moment, but that doesn't mean it doesn't exist – I'm just not a scholar in this field. I know there are some texts by Antoine Picon on the subject, and I think certainly – with Picon – you'll be able to find the best answer to that question.

DS: No, I meant more from your own experience and perspective – whether you could say: "well, in our practice, from this moment on we noticed…" – something along those lines.

SG: In our practice, it's more or less clear. As I mentioned earlier: about two years ago, due to reasons I already explained – not only the increasing focus on prefabrication, but also the growing scale of projects – we started using these methods. So, for process optimisation, it made total sense to shift to this type of method.

DS – Q3.2: How is digital fabrication currently used in your practice?

SG: At the moment, we're working almost 100% in a BIM environment. The integration of digital models is essential, especially for coordinating specialties and developing prefabricated elements with a high level of detail. We've been using these tools particularly in projects involving volumetric metal modules and are also starting to explore timber frame and CLT structures.

DS – Q3.3: What are the main lessons learned that you could share with other offices considering exploring digital fabrication?

SG: Look, I believe so – and the reverse as well. I have a confession to make: I don't know how to make a wall in Revit. So yes, our office works in BIM, but something I've noticed – like when I have lunch with Pedro (who's the person in our office most involved with BIM) or with someone else in the know – is that sometimes the conversation goes into areas I no longer understand. But I see there's a lot of exchange of information about how things are done. Being a relatively recent way of working,

and I'd say even in AutoCAD there are still many procedures that people do differently. I often hear things like: "I organise by blocks," "I use groups," "I organise by layers," "I organise by materials," "I organise by line weights," etc. And I've noticed that in Revit this happens too – there are still very different ways of working. In CAD, a kind of consensus has begun to form about methodologies (even though differences remain), but there's a cloud of agreement about how to work in CAD. I don't think that exists yet in Revit – there's still a lot of improvisation. In fact, those working daily with Revit constantly exchange information: how do you do this, how do you organise families, how do you manage data, etc. I also know some people are now selling that service – a kind of BIM integration for offices. They spend two or three weeks setting up a working methodology for everyone to follow. So, I imagine those people have been more systematically involved, maybe even through Autodesk training, I don't know. We've never done that – we haven't hired that kind of service; so far, we haven't felt the need, but I can't say we never will.

DS – Q3.4: What have been the key technological developments that facilitated the use of digital fabrication in your practice?

SG: The main shift was our move to BIM, especially Revit. It allowed us to systematize operations and model in 3D with the detail needed for prefabrication. More recently, we're looking into tools that integrate with Revit for parameterisation and generative studies—Finch is one of them.

DS – Q3.5: How has the integration of digital tools affected collaboration within the office and with other stakeholders?

SG: Look, I think it has made collaboration more agile and faster. Because… let's look at very specific cases: before, if we wanted to understand how a particular detail in a project was working – here in the office we always have a coordinator for every two or three projects – if we wanted to understand how a certain solution was being developed, we'd go talk to the coordinator. And if we were lucky, there would be a construction section of that area already drawn; if not, we'd sketch it next to it – sort of a real-time, improvised construction detail drawn by hand. That doesn't happen anymore. Now, we can immediately understand how that detail works using an automatic section, an automatic plan – or, on the contrary, sometimes it's that same automatic section that shows us it's actually not resolved, that it doesn't work. So, I'd say this has really sped up our internal communication within the office (between us and even with the engineers), because we can resolve coordination questions much more quickly.

PART IV: FUTURE

DS – Q4.1: How do you see the future of digital fabrication in architecture?

SG: Look, above all, as an inevitability. I recently read a report – The Next Normal in Construction – which, by the way, is produced not by architects but by engineers and people more connected to project management (rather than architectural documentation). I can send it to you, if you want.

DS: Oh, thank you, I'd love that!

SG: And one of the aspects constantly mentioned in that report is the optimisation that tools (BIM) can bring. This often translates into more efficient construction methods, with less waste and less dependence on human resources – which today are scarce. One way to reduce the growing labour shortage in the construction sector (at least in the Western world) is by optimising production processes and adopting new construction methodologies that reduce dependence on manual labour. In essence, the report says these new digital tools are a very important step toward construction automation and optimisation. Above all, their use is inevitable.

DS – Q4.2: What are your expectations or plans for expanding the use of digital tools in your office?

SG: Right now, we're trying to "let the dust settle" with Revit. I know there's a very clear goal among my colleagues – which I obviously support – to move toward other tools that allow us to improve the whole parameterisation component of projects. There's a tool by Autodesk (I can't recall the name) that works integrated with Revit and lets you, basically, do those studies of building placement, housing distribution, quick solar orientation tests, shading studies, and even energy efficiency related to each orientation. And now it's possible to do that relatively quickly using these parameterisation tools and artificial intelligence. I'd say that's the next step. Well, one tool that comes to mind is Finch. Finch is one of them, but there are many more. Our next step will be this: entering the generative design field.

DS – Q4.3: How do you think your approach to digital fabrication compares with that of other offices?

SG: Honestly, I think it depends more on the scale of the office than the country. In Portugal, there are offices that already work in very advanced ways. From what I know, we're aligned with practices that are adopting BIM seriously, though we still see many offices—even large ones—working in CAD.

DS – Q4.4: How would you compare the adoption of digital fabrication in architecture in Portugal with other countries?

SG: Well, I don't have extensive knowledge – I can only speak from what I know from some colleagues. I've heard of various situations: colleagues still working in offices (even fairly large ones) using CAD. I have a friend working in Switzerland, for example, in a 300-person office, where not a single sheet of paper is printed – everything is drawn in BIM. He works side by side with a draftsman,

and he says he barely draws anything: he works well, but when he has to do something, what takes him a day, the draftsman does in half an hour. These are offices with much more optimised processes. So, I'd say it's not… it's not so much about comparing Portugal to abroad – it's always more of a comparison…

DS: …perhaps of office scale…

SG: Exactly! That's what I was going to say – because in Portugal, as far as I know, there are some offices that already have these systems very well established and highly developed.

DS – Q4.5: What emerging trends in digital fabrication do you find promising or interesting for architectural practice?

SG: What seems most promising to us now is the integration of parameterisation and artificial intelligence with BIM. Tools that allow quick studies of building layout, solar orientation, shading, and energy efficiency—like Finch—point toward a more generative approach to design, which we see as our next step.

DS – Q4.6: What kind of support or resources do you believe could accelerate the adoption of digital fabrication in architecture?

SG: The most obvious answer would be obligation, but I don't think that's the best way to do things – especially since a forced implementation isn't necessarily a good implementation. But I know that in some European countries this is already the case. In London, for instance, to get a building permit you must submit a BIM file. And that would be one way (though, again, not the one I like best). I think, first of all, I don't know if this integration has to happen across all offices – because the smaller ones, dealing with renovations (where solutions are often decided case-by-case and sometimes on site), forcing those offices to adopt this kind of system might not be very productive. Regarding the others – those working on larger-scale buildings and who actually feel the need (because I know we all feel the need: we've all lost many hours making a section that could've been done in 30 seconds; we've all lost hours doing quantity take-offs that could've been automated from a metadata-rich file where all elements are already specified in the model) – so I'd say that in those offices, what's needed to take the leap is creating conditions. These conditions relate to what I mentioned earlier: financial breathing room to…

DS: …to be able to make that investment.

SG: …along with better project timelines and, again, a network of partners – especially engineers – who begin to function not as constraints, but also as BIM users ("consumers"). That could help drive the implementation – because once we start receiving Revit (or IFC) files from those partners, naturally we'll want to evolve and meet that level as well.

ANNEX I – INTERVIEW TRANSCRIPT

TEKSTUDIO

TEKSTUDIO Architects, founded in 2011 by Bruna Serralheiro, is based in Lisbon, Portugal. We strive to develop exciting and sustainable design solutions that exceed client expectations. Our philosophy embraces architecture as a form of human expression and a vehicle for addressing human needs through technology. We focus on innovation in architecture, urbanism, landscape, interior, and graphic design, emphasizing human and sustainable impacts. Each project involves tailored strategies combining technique, art, and client desires. Collaborating with specialists across disciplines, we ensure a comprehensive design approach, from detailed objects to urban design, prioritizing collaboration and client satisfaction.

Interview conducted at the office on 10/05/2024.

PART I: INTRODUCTION AND MOTIVATION

Daniela Silva (DS) - Q1.1: When and why did your office start incorporating digital tools into architectural practice? What was the initial catalyst?

Joana Pimenta (JP): In our case, we started using digital design tools right from the beginning, mainly BIM. Bruna (the founder of the office) opened the office in 2012/2013, and she was already using BIM in university. So, from the outset, we chose that method - it was a natural choice due to her background. Of course, today's Archicad is very different (and much more advanced) compared to ten years ago, but we've always worked in 3D. The initial catalyst was indeed our educational background: we started with BIM because we were already familiar with it.

DS – Q1.2: What were the main motivations for adopting these technologies? Was it a response to digital evolution, or were there other reasons?

JP: It was essentially tied to our education and work efficiency. We're part of a generation that began using these digital tools at university, so it was a logical step to continue. Designing in 2D nowadays makes no sense - it would be a step backward. Regardless of what other teams we collaborate with use, we maintain our workflow in Archicad because we believe it's more efficient. We're aware of digital evolution and look at other offices to identify more effective methods, but our main motivation was internal: to take advantage of a more integrated and productive process.

DS – Q1.3: Can you describe a project where the adoption of digital technology was crucial to its success?

JP: To be honest, almost all our projects depend on these tools - we can't even imagine working otherwise. From interior design and furniture pieces to subdivision plans and larger projects, we always model everything in Archicad/BIM. So, there isn't one specific project we can highlight; they all benefit. For instance, we can develop and present solutions with a speed and quality that would be impossible using traditional methods within the same timeframe. BIM has been crucial in all projects to achieve the quality and speed we aim for.

DS – Q1.4: Was there any model or example (national or international) that inspired your transition to using digital tools?

JP: I wouldn't say there was a specific office that served as a model for us to adopt digital tools - it was more an organic result of our education. Bruna might have a personal reference, but as far as I know, we weren't directly inspired by any reference office, national or international, to make the transition. For better or worse, we're part of a generation that started using these tools at university. Of course, we're always observing what other offices are doing, trying to see if there are more efficient approaches, but our main "inspiration" has been continuous learning and the support we receive from the software provider itself.

DS – Q1.5: What were the main perceived benefits that motivated the adoption of digital tools?

JP: The benefits are many. Especially during the preliminary study phase, working in BIM is fantastic - it allows us to study and adjust the project much faster because we see everything in 3D. Basically, by drawing a simplified plan, we can already visualize in 3D what we're proposing and place it in context, which greatly speeds up the initial creative process. Later, in the final phase, it's also advantageous. On the one hand, we can prepare renderings and 3D images to show clients, which is essential because not all clients can read 2D drawings; these images help explain and sell the project. On the other hand, the BIM model helps extract quantities and material lists for execution - it's much easier than doing it all manually.

The digital tool offers significant advantages, especially at the beginning (concept study) and the end (client visualisation and technical documentation). Of course, there's always a lot of work and study in between, but even then, BIM organises the information better. Overall, we see gains in practically every stage of the project.

PART II: BARRIERS AND CHALLENGES

DS – Q2.1: What were the main barriers you faced in implementing digital fabrication technologies?

JP: One of the biggest barriers was the learning curve and the mindset shift regarding the design process. Designing in BIM requires entering much more information from the start compared to drawing in 2D. For example, when I draw a simple line in Archicad, I'm actually creating a wall—I have to define its thickness, height, materials, elevation, etc. There's a whole set of parameters to define from the beginning for the model to "work" properly. For those used to just drawing lines, this can be overwhelming at first. It requires patience and method: just like hand-drawing or building a physical model, modelling in BIM forces you to think calmly and plan - otherwise, the model becomes chaotic. Many interns arrive thinking they've mastered the software (because they used it at university), but then they realise that the level of demand in an office is different - it takes experience to know what information is essential in the first iteration and what can be added later without having to redo the work. That initial adaptation is a challenge.

Another important barrier was the necessary technical resources. BIM software keeps doing more, but that means we need increasingly powerful (and expensive) machines to keep up. The software licenses themselves also represent a significant investment for a small office. For example, maintaining multiple Archicad licenses updated annually is costly. We felt that burden - we had to invest in better hardware and additional licenses/programs (like rendering plug-ins). So, the financial and technical issues (proper computers, etc.) were/are a barrier: implementing these technologies requires capital and constant equipment updates.

DS – Q2.2: Are there any local policies or regulations that facilitated or hindered the adoption of digital fabrication in your practice?

JP: So far, public policies have had a mixed and somewhat unclear impact. There's talk that in Portugal it might soon become mandatory to submit projects in BIM format (especially for public works), but honestly, I'm not sure how that will be implemented. If it happens, I imagine smaller offices will struggle because, again, this involves investment and time they might not have - it's easy to legislate, but adapting can be complicated and expensive. Anyway, I believe it won't be a huge problem for our generation of architects. Many older professionals have already adapted somewhat (we, for example, collaborate with senior engineers who started their careers drawing in 2D AutoCAD and now can work comfortably receiving our PDFs or even simple models). And those who don't adapt are probably nearing retirement and might not even face that obligation. So, from a generational perspective, I don't see a big shock.

What truly complicates things right now is the lack of standardisation in bureaucratic processes. Each municipality has its own requirements and digital platforms - some already accept digital projects, others ask for everything on paper, and others have a strange mix of formats.

DS: Yes, for example, at the office where I'm working now, sometimes I submit DWF to municipalities, other times they ask for PDFs.

JP: We encounter this daily and lose a lot of time converting and adjusting drawings to fit each platform. Archicad, in our case, doesn't even generate certain formats directly (for example, DWF doesn't export all layouts properly when using a Mac - we have to use a PC or external software to compile the files). We've found ways to get around those technical limitations - we even use free software to merge files when needed, as the municipalities suggest. But thinking about the future: how will the municipalities afford computers capable of reading heavy BIM models?

DS: Right, I ask myself the same. The machines and the staff who know how to use the models.

JP: Yes! And hiring trained staff to analyse 3D projects? That's a big question mark.

DS – Q2.3: How has client perception influenced or affected the implementation of digital tools in your practice?

JP: In general, clients love the fact that we work with 3D models and realistic images - they react very positively and find everything very "modern" and clear. However, that positive perception is accompanied by some misconceptions about the process. Many clients think that because it's digital, "it's just a click" and the project is done or changed instantly. They have a slightly false sense of timing: they think everything is super quick in BIM, when that's not really the case. For example, we can't show a typical client a digital model without details (like a white mass without windows), because they see it as unfinished or incomprehensible - they end up comparing it to a hyper-realistic render. So, to prepare a BIM model that's presentable to a layperson, we have to spend time adding details, materials, glass, etc., even in the early phases… work that often isn't necessary for execution or the municipality (which needs precise 2D drawings). There are things we model just to make it "look nice" for the client that later hinder or have to be adjusted so the 2D drawings come out well—and vice versa. So, that duality is a challenge. And the biggest issue is time: the client requests change after change thinking everything is simple digitally, but each change takes work and isn't instant. What they see as an advantage (visualizing everything in 3D) can lead to unrealistic expectations about timelines. In addition, we're starting to receive requests from more informed clients who want to take advantage of BIM in other ways - for example, to quantify costs and materials. In other words, they don't just want to see pretty 3D; they also want us to provide measurements and quantity take-offs extracted from the BIM model. In theory, that's great and the programs do that, but in practice, it requires much more effort on our part. First, to have reliable automatic quantities, we need to model everything in maximum detail (each wall, layer, component) - and that takes a lot of time. Second, not all team members have the specific know-how of a BIM Manager; in small offices, we'd probably need to train or hire someone for that task. I'll give an example: at the end of 2023, we had our first client request

a detailed budget with BIM-based quantities. We evaluated the possibility and ended up explaining to the client that to do it properly, we would need to spend many extra hours modelling and coordinating (far beyond the usual scope) and probably involve an external consultant for the specialties. In the end, the client gave up on that demand - they weren't willing to pay the fee increase that would entail. So far, clients really enjoy what the digital tool offers in terms of visualisation, but when they realise the costs of going deeper (like using BIM for real-time budgeting), they usually back out. I'd say client influence has led us to invest a lot in 3D images and renders (because it helps communication), but it also forces us to manage expectations - explaining that computer speed doesn't mean the real work is less complex.

DS – Q2.4: Was there ever a case where technological or financial barriers prevented the implementation of digital tools in a project?

JP: The case I just mentioned is a good example: at a certain point, we considered implementing a fully detailed BIM model in a project (to deliver automatic quantity take-offs to the client), but we hit a time/budget barrier. Technically it was possible - we always have software support, and any questions are resolved in minutes - but it required a level of detail and working hours that simply weren't accounted for in the project fee. Basically, the tool allows it, but it wasn't viable within the financial constraints.

In our day-to-day work, we constantly make this kind of decision: assessing how far it's worth taking digital tools in each project. For example, some construction elements are very complex, and instead of modelling them in 3D (which would take a lot of time and processing), we choose to draw them in 2D detail. We still work in BIM generally, but we have no problem switching to traditional methods for specific details if it's more efficient. It's not exactly a "technological failure," it's a conscious choice based on limited time. Ultimately, the biggest limitation we feel is time (which is related to the available budget). We can do practically everything digitally, but we can't do everything at once or without limits - so we set priorities. We model what saves time later or what we consider essential, and we simplify the rest. In short, we've never failed to implement a digital tool due to technical incapability (we always find a way), but we've opted not to implement certain advanced uses because they weren't cost-effective in a given project. It's our decision, adjusting the degree of technology adoption to the reality of each project.

PART III: EVOLUTION AND CURRENT IMPLEMENTATION

DS – Q3.1: Do you identify any historical milestone that you consider pivotal in the evolution of digital fabrication in architecture?

JP: I don't identify a single historical milestone as a turning point, mainly because in our case, the adoption of digital tools happened naturally from the very beginning of our practice. Perhaps the development of modelling and real-time rendering software - like Enscape, for instance - was a key moment, as it made the process more agile, accessible, and integrated into our daily workflow. But rather than a specific event, I'd say it's been a continuous evolution, closely tied to our education and curiosity to explore new tools.

DS – Q3.2: How is digital fabrication currently used in your practice?

JP: Currently, we use digital tools - especially BIM - at practically every stage of our work in the office. The entire project is developed in Archicad (BIM), from the first sketch to the final execution documents. For example, we start modelling in 3D right away: when we draft the preliminary plan, those walls already exist in the model with thickness, height, materials, etc. - and from there we can extract sections, elevations, and 3D views automatically. We don't follow that approach (still seen in some places) of drawing everything in 2D AutoCAD and only then "cleaning it up" in 3D; here we draw directly in 3D/BIM, even for simple things. We think drawing separately in 2D would be duplicated work and a waste of time. Up to a reasonable detail scale (I'd say 1:100, 1:50), we're always working in the 3D model and generating drawings from it. Only in very complex situations do we add something in 2D on top - for example, if a construction detail is too specific and hard to model, we do that part in 2D. But that's the minority of cases. In other words, we use BIM to the fullest: plans, sections, elevations - all come from the digital model, ensuring coherence and fast updates (you change the model, and all drawings update).

DS: So, in your case, from the study phase to execution, your base is ARCHICAD, right? Even for renders, etc.?

JP: Yes, and from it, if we need 3D images, we follow two paths depending on the case. For many projects, we can render directly here in the office using a real-time rendering plugin (Enscape) applied to our BIM model - that gives us quite good image quality quickly, and we can adjust and test internally. For projects that require a higher level of realism (e.g., sales images, marketing for developments), we collaborate with external rendering companies. In those cases, we provide them with the 3D model of the project (either in ArchiCAD's native format or exported in IFC), and they enrich it and generate the final images. Some rendering teams even take our model and refine it; others prefer to use it only as a reference and rebuild everything in their own software - it varies. Either way, even in those external collaborations, the starting point is always our digital modelling. So, digital fabrication - understood as BIM modelling and its derivatives - is fully integrated into our daily workflow, from concept to project communication.

DS – Q3.3: What are the main lessons learned that you could share with other offices considering exploring digital fabrication?

JP: An important lesson we learned is the need to balance the level of detail with efficiency. When working in BIM - especially at the start - the tendency is to model everything down to the tiniest detail, because the tool allows it. But you need discernment: not every minute detail must be in the model at every project stage. It's the same old issue from hand-drawing days: what detail belongs at which drawing scale? We've learned to calibrate effort according to the phase. Sometimes modelling a complex 3D detail consumes a lot of time without much practical benefit - so it may be better to represent that detail in 2D and move on. Conversely, there's information worth inserting early (even if it's work) because it saves time later - e.g., defining correct wall materials and thicknesses from the start helps extract schedules and quantities downstream. It's a constant balance between detail and productivity.

A concrete example: Archicad automatically generates a door-and-window schedule, but for a time that feature had customisation limits. We used to draw certain window details manually - everything looked lovely in sections and elevations, but then we had to count doors and windows "by hand." Today we prefer ArchiCAD's automatic schedule to get quantities and sizes immediately (and we want cost control as early as possible). The trade-off is giving up some decorative detail in those automated drawings, because the software may not represent it exactly as we'd like graphically. We sacrificed a bit of drawn detail to gain speed and quantitative information - more precise budgets, earlier. Managing the detail level - doing what's necessary for project goals, no more, no less - is one of the biggest lessons.

Another lesson involves choosing complementary visualisation tools. There's always temptation to chase the most advanced renderer with ultra-realistic images - but those "top" solutions can mean heavy workflows, long exports, cutting-edge hardware, etc. For us, Enscape gives a great compromise: fast, integrated in Archicad, good enough image quality for most clients.

DS – Q3.4: What have been the key technological developments that facilitated the use of digital fabrication in your practice?

JP: The biggest evolution we noticed - the one that eased our work most - was in 3D visualisation and rendering. Recently, there's been an enormous leap. At university we modelled in Archicad, but to get a decent render we had to export to Cinema 4D or 3ds Max, assign materials, lights… and wait hours! We'd let the computer render overnight - and even then the result often needed Photoshop touch-ups. Today it's totally different: with real-time engines like Enscape we press a button and, within seconds,

get a nearly photoreal image, navigable in 3D. Visualisation quality has skyrocketed while the process became quicker and less hardware-demanding.

DS – Q3.5: How has the integration of digital tools affected collaboration within the office and with other stakeholders?

JP: Inside the office, BIM changed teamwork - for the better, in my opinion. We use Archicad in teamwork mode (several architects working at once on the same shared model), so everyone must align on methodology. This has led us, for instance, to prefer hiring collaborators who already know Archicad/BIM. We're a small team and can't spend extensive time training someone from scratch while deadlines loom. In our hiring process, knowing Archicad carries weight. Communication-wise, BIM helps: we all look at the same model, clear doubts there, spot 3D issues… a shared understanding of the project that the tools facilitate. Still, the condition is everyone mastering the basics - when that happens, internal collaboration flows.

Outside the office (engineers, clients, builders, etc.), it's different because not everyone adopts the same tools. Most specialty engineers still work in 2D. We send them DWG or PDF; they return structure, water, electrical designs also in 2D, and we manually integrate/coordinate. Truly digital/BIM collaboration with others is rare. When it happens, it's usually with structural engineers using Revit - we exchange via IFC files. Even then, it's basic: IFC just to view and spot clashes, not dynamic model integration. Many engineers actually say, "Just send PDF, it's fine." So external collaboration is still largely traditional.

PART IV: FUTURE

DS – Q4.1: How do you see the future of digital fabrication in architecture?

JP: I see architectural practice becoming increasingly digital, no doubt - but with challenges. There's a clear trend toward universal BIM: soon, especially for public tenders, an integrated digital project will likely be mandatory. In Portugal they've discussed this for some time. Submitting a simplified digital model to municipalities wouldn't be a problem - we already produce 3D models. If the goal is more ambitious - controlling budgets and construction phases through BIM in real-time - there are serious implications, mainly fees and work organisation. Delivering a fully detailed BIM model demands many more hours - someone has to pay. Current Portuguese fees don't cover that level of detail (often barely covering basics). So, if authorities truly want exhaustive BIM models, fees must rise and the profession be valued economically; otherwise, no one can comply.

Technologically, tools will keep evolving and getting more powerful and accessible. Hopefully bureaucracy evolves too - ideally you'd submit a BIM model to a municipality and get a faster, more

transparent licensing process. But institutions must modernize as well; it's not enough for offices to adopt tech.

DS – Q4.2: What are your expectations or plans for expanding the use of digital tools in your office?
JP: We like to test new technologies but filter what makes sense for our scale. For instance, we bought a 3D printer around 2020 to make models and small prototypes. Unfortunately, it arrived defective, never worked properly, and we returned it - so for now that's on hold. We may revisit 3D printing later, but it's not an immediate priority. Software-wise, we constantly update. The office is called TekStudio because Bruna loves tech and follows the "latest fashion" in architecture. For rendering: we once used Twinmotion (one of the first to integrate easily with Archicad for interactive 3D). Later we discovered Enscape - faster and better quality within Archicad - so we switched. Tomorrow, if something better fits us, we'll switch again.

DS – Q4.3: How do you think your approach to digital fabrication compares with that of other offices?
JP: Among similar-size colleagues I see two main groups: those who adopted BIM early (some still in university) and those who stayed with 2D longer and only recently started changing.
Bruna Serralheiro (BS): I used Vectorworks; we were a minority - because it was cheap and the student version.
Undoubtedly, those who started Archicad/BIM earlier ended up a step ahead. We decided from the start to invest seriously: we buy all our software licenses (nothing pirated) and keep them updated annually. That alone differentiates us - many small offices, due to costs, run outdated software or unofficial versions. We chose to be fully legal and professional, despite the expense (each Archicad license costs several thousand euros plus yearly maintenance). We think it pays off: we get tech support and training and stay on the software's cutting edge. We all work in a single BIM model per project via teamwork - enabling efficient internal collaboration but requiring everything properly licensed.

From experience, many architects who tried both BIM programs end up preferring Archicad, reinforcing our choice. I know colleagues who started in Revit and migrated to Archicad; conversely, architects leaving Archicad for Revit - I hardly know any cases. That says something about ArchiCAD's usability for architecture, at least in our European context.
Another point: we don't let technology dictate everything - we invest in BIM, use BIM, but aren't slaves to it. Whenever the software seems limiting, we contact specialists, find workarounds - so the project comes out as intended. Many offices with superficial BIM use get stuck by tool constraints and simplify projects to fit; we avoid that.

We balance digital and traditional perhaps better than some competitors. We're BIM fans - we even promote it on our website - but we know its limits. We still value hand sketching, physical models, off-screen creativity. And crucially, we stop modelling when further detail isn't paid for. Some colleagues get so excited that they over-detail models, and financially it doesn't pay off. We use BIM for efficiency and quality, then stop when it's wasteful. In Portugal especially, the market doesn't pay infinite modelling hours, so we're pragmatic. That places us in a balanced position: neither technologically behind nor BIM fundamentalists at any cost - getting the best of both worlds.

DS – Q4.4: How would you compare the adoption of digital fabrication in architecture in Portugal with other countries?

BS: Adoption varies greatly by country, but I can share impressions. Some Central/Northern European countries were a bit ahead of Portugal in integrating BIM into education and practice. I recall a German colleague on Erasmus c. 2006: she and almost her whole class already used Archicad/BIM for university projects. I was impressed - while in Portugal most of us clung to 2D AutoCAD and timid 3D steps, she presented fully modelled projects and even had mandatory construction-site internships. That showed me that abroad (at least in some places) digital tools arrived earlier and with more weight.

Yet Portugal isn't irretrievably behind. In recent years - especially with younger generations - we've been catching up. Today many work in Revit or Archicad here. There's also regional software dominance: Archicad, being European, long had traction in Hungary (its origin), Germany, etc., whereas in the U.S. Revit became standard. American project scales - and the fact that large multidisciplinary teams collaborate - made Revit the "common language" there. Europe had more diversity, and many renowned offices adopted later. For instance, David Chipperfield's office adopted BIM only a few years ago and picked Archicad. Even internationally, not everyone advanced simultaneously - it's not linear "they're all advanced abroad and we're behind." It depends.

In multinational collaborations, Revit tends to be the common platform, probably due to Autodesk's global presence. Domestically, each uses what they like. In Portugal, most large 100+-person offices working abroad invested in Revit, to speak the same language as international engineering. Many medium- and small-size offices here choose Archicad - cost-benefit and user-friendliness. So: Portugal wasn't a pioneer, but is now aligning with global trends. Germany or the U.S. may have diffused practices earlier and at larger scale, but the gap is closing, and with possible government BIM mandates we'll converge further.

DS – Q4.5: What emerging trends in digital fabrication do you find promising or interesting for architectural practice?

BS: Two big technological trends fascinate me (and seem inevitable): Virtual/Augmented Reality and Artificial Intelligence.

In Virtual Reality (VR) we see more tools - VR headsets, immersive apps - letting clients "enter" the project before it's built. That's here to stay. Going forward, virtual space experience may become as important as physical models once were. I think we're heading toward inhabiting the virtual to some degree. Today we live glued to virtual realities without noticing—Instagram, for example, where people "live" a filtered, perfect version of life. In architecture, I wouldn't be surprised if soon clients want to decorate and customize their houses virtually and be satisfied regardless of real space. It may sound strange, but tech makes creating virtual environments easy enough that the tangible might become secondary for many. So, VR/AR - from headsets to on-site 3D projections - is very promising. We've shown projects with VR goggles; the client grasps the space immediately. I believe that immersion will only grow.

Artificial Intelligence (AI) is the other major revolution. Generative AI tools such as ChatGPT and others are advancing at frightening speed. Architects must pay attention because AI may automate many tasks we do manually. Experimental software already exists where you input site parameters (area, regulations, permitted floors, etc.) and it auto-generates a building volume within the rules—something that used to take days of regulation study and testing. It's not perfect yet, but it shows where we're headed. If we aren't careful, in a few years the basic preliminary study might be done by a computer in seconds, leaving our work for premium or artistic projects. AI will surely accelerate processes: facade options, layout optimisation, code compliance checks… freeing us to think about ideas. The danger is if AI also does ideas better than we do - then we're in trouble. So, I insist: the only way to remain relevant is to be distinctive, creative, human. Architecture might become a luxury, an author service, if common parts are automated. It's a bit scary but also challenging. I see it like Kodak: we can't hide technology in a drawer - we must reinvent ourselves and use it to our advantage. Evolution is inevitable; best to be at the forefront using VR, AI, advanced digital fabrication (like 3D-printed buildings), rather than being run over by them.

DS – Q4.6: What kind of support or resources do you believe could accelerate the adoption of digital fabrication in architecture?

BS: From our perspective, the biggest boost would be financial support and recognition of the investment's value. Subsidies or grants for software and digital equipment purchases would help tremendously - especially small offices that often want to adopt these tools but are stopped by upfront costs. If there were a government program - vouchers for digital transformation of architecture offices, interest-free or even non-repayable - I believe adoption would skyrocket. During the pandemic, for instance, our specific sector received zero help. We went through that difficult period without layoffs,

holding projects that paused, and had no support - zero. That showed us that unfortunately the architect profession lacks institutional backing. So, any resource lightening the financial burden of tech investment would be welcome.

Beyond direct financial aid, another crucial resource would be changing mindsets and rules around hiring architectural services - valuing the architect's work itself. Today, the average Portuguese client can't pay fees that allow the architect to work calmly and in detail, let alone incorporate costly new tech. Construction and housing prices are so high (due to thermal, acoustic, and structural demands - good for quality, but expensive) that the first place people cut is the project fee. We feel it: they ask for increasingly complete projects (now even total BIM coordination) but fees don't reflect the extra responsibility and work. If there were a fairer fee table or greater awareness from clients and authorities that "BIM doesn't do itself; it takes hours and expertise," adoption would speed up because offices could devote time to fully implementing digital tools without going broke.

A concrete example tied to policy: municipalities may soon demand BIM projects. Fine - we can deliver a BIM model. But to produce that complete model the architect will spend far more hours than producing a handful of mandatory 2D drawings. If we keep being paid the same (or poorly), the math doesn't work - nobody will adopt tech just to lose money. For BIM/digitalisation adoption to be fast and effective, it must come with updated service models and fees. Right now, for each permitting process, we almost pay to work - bureaucratic demands and back-and-forth with municipalities (often hours fixing silly platform or format issues) are unpaid hours. Any architect will tell you: licensing projects in Portugal rarely turn a profit; they're a loss leader to "keep" the client and hope to balance later phases. That's harsh reality. If you add "make a fancy BIM model for the municipality" without paying more, many offices will fake it or do the bare minimum.

Resources that would help include: funding for tech acquisition, accessible training (subsidized BIM courses), process standardisation (so each municipality doesn't invent a different format - standardisation alone would speed things up), and most of all, professional valorisation - understanding that if you want everything digital and perfect, it has a cost that must be covered. If these conditions align, I believe digital fabrication adoption in architecture would advance rapidly, because architects have plenty of willingness - what's often missing are the means.

ANNEX J – INTERNATIONAL OFFICES – EMPIRICAL VALIDATION

Source	Office Name	Size of Office		Digital Maturity (X-Axis)		Research Engagement Spectrum (Y-Axis)		webpage	Region/Country
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	3XN	150	Medium	4	Advanced use of BIM and digital tools	4	Research-Active, involved in sustainability research	https://3xn.com/	Denmark
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	AL_A	50	Medium	3	Moderate use of BIM	3	Research-Informed, exploring material innovation	https://www.ala.uk.com/	United Kingdom
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Aranda\Lasch	6	Small	4	Advanced, uses digital tools and fabrication	3	Research-Informed	https://arandalasch.com/	USA
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Archi-Union	60	Medium	5	Leading, integrates robotics and AI in design	5	Research-Led, innovative research in digital fabrication	https://www.archi-union.com/	China
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Architecture Workshop	10	Small	2	Basic use of digital tools	2	Research-Aware	https://www.architectureworkshop.co.nz/	New Zealand
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Arup	300	Large	5	Leading in digital engineering	5	Research-Led, global research initiatives	https://www.arup.com/	Global
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Asif Khan	40	Small	3	Intermediate use of digital tools	3	Research-Informed	https://www.asif-khan.com/	United Kingdom
Walliss, J., & Rahmann, H. (2016). Landscape Architecture and Digital Technologies: Re-conceptualising design and making (1st ed.). Routledge.	ASPECT Studios	76	Medium	3	Intermediate, uses BIM and visualisation tools	3	Research-Informed, sustainability-driven	https://www.aspect-studios.com/	Australia
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	BKK Architects	23	Small	3	Intermediate use of BIM	2	Research-Aware	https://b-k-k.com.au/	Australia
Staab, M. (2023). 3D printing and material extrusion in architecture. DOM Publishers.	BVN	400	Large	4	Advanced, uses parametric design tools	4	Research-Active	https://www.bvn.com.au/	Australia
Walliss, J., & Rahmann, H. (2016). Landscape Architecture and Digital Technologies: Re-conceptualising design and making (1st ed.). Routledge.	ecoLogicStudio	6	Small	5	Leading, integrates AI, bio-digital research	5	Research-Led, focus on ecological innovation	https://www.ecologicstudio.com/	United Kingdom
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	EMBT	27	Small	4	Advanced, uses digital tools and fabrication	4	Research-Active	https://www.mirallestagliabue.com/	Spain
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Facit Homes	13	Small	5	Leading, uses digital fabrication	4	Research-Active	https://www.facit-homes.com/	United Kingdom
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Foster + Partners	1 800	Large	5	Leading, pioneer in BIM and parametric tools	5	Research-Led, with in-house R&D	https://www.fosterandpartners.com/	United Kingdom
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Franken\Architekten	20	Small	3	Intermediate	3	Research-Informed	https://franken-group.com/	Germany
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	GAP Architects	50	Medium	2	Basic	3	Research-Informed	https://www.gap-the-mind.com/	Hong Kong
Walliss, J., & Rahmann, H. (2016). Landscape Architecture and Digital Technologies: Re-conceptualising design and making (1st ed.). Routledge.	Grant Associates	50	Medium	3	Intermediate use of digital tools	3	Research-Informed, sustainability-focused	https://grant-associates.uk.com/	United Kingdom
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Greg Lynn	4	Small	5	Leading, computational and robotics research	5	Research-Led	https://glform.com/	United States
Walliss, J., & Rahmann, H. (2016). Landscape Architecture and Digital Technologies: Re-conceptualising design and making (1st ed.). Routledge.	Gustafson Porter	21	Small	3	Intermediate	3	Research-Informed	https://www.gp-b.com/	United Kingdom

Staab, M. (2023). 3D printing and material extrusion in architecture. DOM Publishers.	Hannah Office	2	Small	5	Leading, computational and robotics research	5	Research-Led	https://www.hannah-office.org/	United States
Walliss, J., & Rahmann, H. (2016). Landscape Architecture and Digital Technologies: Re-conceptualising design and making (1st ed.). Routledge.	HASSELL	88	Medium	4	Advanced, uses BIM and computational design	4	Research-Active	https://www.hassellstudio.com/	Australia
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Hopkins Architects	140	Medium	4	Advanced	4	Research-Active	https://www.hopkins.co.uk/	United Kingdom
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	HYBRIDa	20	Small	5	Leading	5	Research-Led	https://www.hybridarch.net/	United States
Staab, M. (2023). 3D printing and material extrusion in architecture. DOM Publishers.	Joris Laarman Lab	6	Small	5	Leading, digital fabrication and robotics	4	Research-Active	https://www.jorislaarman.com/	Netherlands
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Kreysler & Associates	50	Medium	5	Leading, specializes in digital fabrication	3	Research-Informed	https://www.kreysler.com/	United States
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	KTA Architects	30	Small	3	Intermediate use of digital tools	2	Research-Aware	https://kerstinthompson.com/	United States
Walliss, J., & Rahmann, H. (2016). Landscape Architecture and Digital Technologies: Re-conceptualising design and making (1st ed.). Routledge.	LAAC	15	Small	3	Intermediate	5	Research-Led	http://www.laac.eu/	Austria
Walliss, J., & Rahmann, H. (2016). Landscape Architecture and Digital Technologies: Re-conceptualising design and making (1st ed.). Routledge.	LDA Design	245	Medium	4	Advanced, uses digital tools for large-scale projects	3	Research-Informed	https://www.lda-design.co.uk/	United Kingdom
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	MAD Architects	200	Medium	5	Leading, advanced in digital tools and fabrication	4	Research-Active	http://www.i-mad.com/	China
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Marble Fairbanks	10	Small	3	Intermediate	3	Research-Informed	https://www.marblefairbanks.com/	United States
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Marc Fornes & TheVeryMany	4	Small	5	Leading, computational design and fabrication	5	Research-Led	https://theverymany.com/	United States
Staab, M. (2023). 3D printing and material extrusion in architecture. DOM Publishers.	Mario Cucinella Architects (MCA)	111	Medium	4	Advanced	4	Research-Active, sustainability-focused	https://www.mcarchitects.it/	Italy
Staab, M. (2023). 3D printing and material extrusion in architecture. DOM Publishers.	Massimiliano Locatelli | Locateli Partners	70	Medium	3	Intermediate	3	Research-Informed	https://www.locatellipartners.com/	Italy
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	MOS Architects	5	Small	3	Intermediate	3	Research-Informed	https://www.mosarchitects.com.au/	USA
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Nex-	50	Medium	4	Advanced	4	Research-Active	https://www.nex-architecture.com/	United Kingdom
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	OCEAN Design Research Association	2	Small	5	Leading, focus on computational design	5	Research-Led	https://www.ocean-a-e.com/	International
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	ONL [Oosterhuis_Lénárd]	20	Small	5	Leading, integrates advanced computational methods	5	Research-Led	https://www.oosterhuis.nl/	Netherlands
Walliss, J., & Rahmann, H. (2016). Landscape Architecture and Digital Technologies: Re-conceptualising design and making (1st ed.). Routledge.	PARKKIM	7	Small	3	Intermediate	3	Research-Informed	http://parkkim.net/home/	South Korea
Walliss, J., & Rahmann, H. (2016). Landscape Architecture and Digital Technologies: Re-conceptualising design and making (1st ed.). Routledge.	PEG office of landscape + architecture	5	Small	3	Intermediate	5	Research-Led	https://peg-ola.com/	United States
Staab, M. (2023). 3D printing and material extrusion in architecture. DOM Publishers.	Pragma	9	Small	3	Intermediate	2	Research-Aware	https://pragma.ae/	Dubai
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	SHoP	108	Medium	4	Advanced	3	Research-Informed	https://www.shoparc.com/	United States

Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Snøhetta	351	Large	5	Leading	5	Research-Led	https://www.snohetta.com/	Norway
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Studio Gang	150	Medium	4	Advanced	4	Research-Active	https://studiogang.com/	USA
Staab, M. (2023). 3D printing and material extrusion in architecture. DOM Publishers.	Studio RAP	7	Small	5	Leading, focus on digital fabrication	5	Research-Led	https://studiorap.nl/	Netherlands
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Thomas Heatherwick	300	Large	4	Advanced	4	Research-Active	https://heatherwick.com/	United Kingdom
Burry, M. (2016). Prototyping for architects. Thames & Hudson.	Zaha Hadid Architects	400	Large	5	Leading, pioneers in computational design	5	Research-Led	https://www.zaha-hadid.com/	United Kingdom
Staab, M. (2023). 3D printing and material extrusion in architecture. DOM Publishers.	Zecc Architecten	21	Small	3	Intermediate	3	Research-Informed	https://www.zecc.nl/nl/	Netherlands
Interviews	Research Studio for Architectural Visualisation: 18—25	17	Small	4	Advanced	5	Research-Led	https://www.1825.pt/	Portugal
Interviews	atelier peninsular	7	Small	3	Intermediate	2	Research-Aware	https://atelierpeninsular.com/	Portugal
Interviews	CVDB Arquitectos	12	Small	3	Intermediate	3	Research-Informed	https://www.cvdbarquitectos.com/	Portugal
Interviews	fahr 021.3	4	Small	4	Advanced	4	Research-Active	https://www.fahr0213.com/	Portugal
Interviews	Konceptness	20	Small	3	Intermediate	2	Research-Aware	https://konceptness.pt/	Portugal
Interviews	Rebelo de Andrade	30	Small	4	Advanced	4	Research-Active	https://www.rebelodeandrade.com/	Portugal
Interviews	Saraiva + Associados	150	Medium	4	Advanced	4	Research-Active	https://www.saraivaeassociados.com/pt-pt/	Portugal
Interviews	Summary	10	Small	4	Advanced	5	Research-Led	https://summary.pt/	Portugal
Interviews	TEKSTUDIO	8	Small	3	Intermediate	2	Research-Aware	https://www.tekstudio.pt/	Portugal

ANNEX K – PORTUGUESE OFFICES - PROFILE SHEET

OFFICE PROFILE SHEET

This form aims to collect basic and contextual information about the office after the interview, enabling a better understanding of its profile and experience in the use of digital fabrication.

1. General Information about the Office:

Office Name:	18-25 Research Studio for Architectural Visualisation
Location:	Lisbon
Number of Staff:	16/17
Year Founded:	2010
Website / Online Portfolio:	https://www.1825.pt/

2. Profile of the Interviewed Architect:

Full Name:	Luca Martinucci
Position in the Office:	Architect | Coordination and Project manager
Academic Background:	Facoltà di Architettura del Politecnico di Milano
Year of Graduation:	2005
Professional Experience (years of experience, other institutions/companies worked at):	19 Years (Patrícia Barbas and Diogo Lopes Architects – Lisbon, Collective Kaputt! - Lisbon, Catarina Ramos Pinto - Lisbon, Lorenaassis Arquitectos – Lisbon)
Areas of Expertise:	-
Contact (email, phone):	studio@1825.pt

3. Office Profile:

Areas of Expertise:	Visualisation	
Most Common Project Types	☒ Housing ☒ Urbanism ☒ Culture & Institutional ☒ Education ☒ Offices	☒ Rehabilitation ☒ Industrial ☒ Interior Design ☒ Furniture ☐ Healthcare

	☒ Parking ☒ Commercial/Retail ☒ Tourism	☒ Services ☒ Hospitality ☒ Equipment
Digital Tools Used	☒ Modelling & Design Software ☒ Digital Fabrication Software (CAM – Computer-Aided Manufacturing) ☒ Digital Fabrication Technologies	
Available Digital Fabrication Equipment	☒ 3D Printers (FDM – Fused Deposition Modelling; SLA – Stereolithography & DLP – Digital Light Processing; SLS – Selective Laser Sintering) ☐ CNC Routers (Computer Numerical Control) ☐ Laser Cutters ☒ 3D Scanning Systems ☐ Fabrication & Assembly Robots ☒ Auxiliary Equipment (hand tools) ☒ Drones	

4. Implementation of Digital Fabrication:

Year Digital Tools Were First Used:	2019
Key Project(s) Using Digital Fabrication:	-
Approximate Percentage of Projects Incorporating Digital Tools:	100%
Collaborations with Academic or Research Institutions (if applicable):	☒ Yes ☐ No

5. Development & Training:

Internal Training programmes (related to digital fabrication):	☒ Yes ☐ No

Partnerships with External Institutions for Training (if applicable):	☐ Yes ☒ No
Participation in Digital Fabrication Workshops/ Conferences:	☒ Yes ☐ No

OFFICE PROFILE SHEET

This form aims to collect basic and contextual information about the office after the interview, enabling a better understanding of its profile and experience in the use of digital fabrication.

1. General Information about the Office:

Office Name:	Atelier Peninsular
Location:	Lisbon
Number of Staff:	7
Year Founded:	2017
Website / Online Portfolio:	https://atelierpeninsular.com/

2. Profile of the Interviewed Architect:

Full Name:	Emanuel Diogo
Position in the Office:	Founding Director & Lead Architect
Academic Background:	Architecture (Autonomous University of Lisbon) + Economics (Alliance Manchester Business School)
Year of Graduation:	2014 / 2003
Professional Experience (years of experience, other institutions/companies worked at):	18 years (Chartier Dalix – Paris, Alison Brooks Architects Ltd – UK, Bruther Architects – Paris, STAR strategies + architecture – Netherlands, Global Landscape Architecture – Lisbon, Pedro Campos Costa – Lisbon, Santa Rita Arquitectos – Lisbon, Atelier dos remédios - Lisbon
Areas of Expertise:	-
Contact (email, phone):	info@atelierpeninsular.com

3. Office Profile:

Areas of Expertise:	-	
Most Common Project Types	☒ Housing ☐ Urbanism ☐ Culture & Institutional	☐ Rehabilitation ☐ Industrial ☐ Interior Design

	☐ Education ☐ Offices ☐ Parking ☐ Commercial/Retail ☐ Tourism	☐ Furniture ☐ Healthcare ☐ Services ☒ Hospitality ☐ Equipment ☒ Landscape
Digital Tools Used	☒ Modelling & Design Software ☐ Digital Fabrication Software (CAM – Computer-Aided Manufacturing) ☒ Digital Fabrication Technologies	
Available Digital Fabrication Equipment	☒ 3D Printers (FDM – Fused Deposition Modelling; SLA – Stereolithography & DLP – Digital Light Processing; SLS – Selective Laser Sintering) ☐ CNC Routers (Computer Numerical Control) ☐ Laser Cutters ☐ 3D Scanning Systems ☐ Fabrication & Assembly Robots ☒ Auxiliary Equipment (hand tools)	

4. Implementation of Digital Fabrication:

Year Digital Tools Were First Used:	2022 (Digital Fabrication)
Key Project(s) Using Digital Fabrication:	n.a.
Approximate Percentage of Projects Incorporating Digital Tools:	50%
Collaborations with Academic or Research Institutions (if applicable):	☐ Yes ☒ No

5. Development & Training:

Internal Training programmes (related to digital fabrication):	☒ Yes ☐ No

Partnerships with External Institutions for Training (if applicable):	☐ Yes ☒ No
Participation in Digital Fabrication Workshops/ Conferences:	☐ Yes ☒ No

OFFICE PROFILE SHEET

This form aims to collect basic and contextual information about the office after the interview, enabling a better understanding of its profile and experience in the use of digital fabrication.

1. General Information about the Office:

Office Name:	CVDB Arquitectos
Location:	Lisbon
Number of Staff:	12
Year Founded:	1999
Website / Online Portfolio:	https://www.cvdbarquitectos.com/

2. Profile of the Interviewed Architect:

Full Name:	Cristina Verissimo
Position in the Office:	co-founder
Academic Background:	Faculty of Architecture – University of Lisbon / Harvard
Year of Graduation:	2002
Professional Experience (years of experience, other institutions/companies worked at):	40 years (Profabril – Macau, Zaha Hadid Architects - London, Loures Municipality – Lisbon, Carrilho da Graça - Lisbon)
Areas of Expertise:	-
Contact (email, phone):	cvdb@cvdbarquitectos.com

3. Office Profile:

Areas of Expertise:	-	
Most Common Project Types	☒ Housing ☒ Urbanism ☒ Culture & Institutional ☒ Education ☒ Offices	☒ Rehabilitation ☐ Industrial ☒ Interior Design ☒ Furniture ☒ Healthcare

	☐ Parking ☒ Commercial/Retail ☒ Tourism	☒ Services ☐ Hospitality ☒ Equipment
Digital Tools Used	☒ Modelling & Design Software ☐ Digital Fabrication Software (CAM – Computer-Aided Manufacturing) ☐ Digital Fabrication Technologies	
Available Digital Fabrication Equipment	☐ 3D Printers (FDM – Fused Deposition Modelling; SLA – Stereolithography & DLP – Digital Light Processing; SLS – Selective Laser Sintering) ☐ CNC Routers (Computer Numerical Control) ☐ Laser Cutters ☐ 3D Scanning Systems ☐ Fabrication & Assembly Robots ☒ Auxiliary Equipment (hand tools)	

4. Implementation of Digital Fabrication:

Year Digital Tools Were First Used:	2022 (BIM)
Key Project(s) Using Digital Fabrication:	Supreme Court in Maputo, Mozambique
Approximate Percentage of Projects Incorporating Digital Tools:	30%
Collaborations with Academic or Research Institutions (if applicable):	☒ Yes ☐ No

5. Development & Training:

Internal Training programmes (related to digital fabrication):	☒ Yes ☐ No
Partnerships with External Institutions for Training (if applicable):	☐ Yes ☒ No

Participation in Digital Fabrication Workshops/ Conferences:	☐ Yes ☒ No

OFFICE PROFILE SHEET

This form aims to collect basic and contextual information about the office after the interview, enabling a better understanding of its profile and experience in the use of digital fabrication.

1. General Information about the Office:

Office Name:	FAHR 021.3
Location:	Porto
Number of Staff:	4
Year Founded:	2012
Website / Online Portfolio:	https://www.fahr0213.com/

2. Profile of the Interviewed Architect:

Full Name:	Hugo Reis
Position in the Office:	co-founder
Academic Background:	Porto School of Arts and Design
Year of Graduation:	2009
Professional Experience (years of experience, other institutions/companies worked at):	17 years (J. Mayer H. Architekten – Berlin, Arquitetos Anonimos – Porto)
Areas of Expertise:	-
Contact (email, phone):	info@fahr0213.com

3. Office Profile:

Areas of Expertise:	installations	
Most Common Project Types	☒ Housing ☐ Urbanism ☐ Culture & Institutional ☐ Education ☒ Offices	☒ Rehabilitation ☐ Industrial ☐ Interior Design ☒ Furniture ☐ Healthcare

	☐ Parking ☐ Commercial/Retail ☐ Tourism	☐ Services ☒ Hospitality ☐ Equipment
Digital Tools Used	☒ Modelling & Design Software ☒ Digital Fabrication Software (CAM – Computer-Aided Manufacturing) ☒ Digital Fabrication Technologies	
Available Digital Fabrication Equipment	☒ 3D Printers (FDM – Fused Deposition Modelling; SLA – Stereolithography & DLP – Digital Light Processing; SLS – Selective Laser Sintering) ☒ CNC Routers (Computer Numerical Control) ☒ Laser Cutters ☒ 3D Scanning Systems ☒ Fabrication & Assembly Robots ☒ Auxiliary Equipment (hand tools)	

4. Implementation of Digital Fabrication:

Year Digital Tools Were First Used:	2012
Key Project(s) Using Digital Fabrication:	Metamorfose
Approximate Percentage of Projects Incorporating Digital Tools:	100% (Digital Tools) 30% (Digital Fabrication)
Collaborations with Academic or Research Institutions (if applicable):	☒ Yes ☐ No

5. Development & Training:

Internal Training programmes (related to digital fabrication):	☒ Yes ☐ No
Partnerships with External Institutions for Training (if applicable):	☒ Yes ☐ No

Participation in Digital Fabrication Workshops/ Conferences:	☒ Yes ☐ No

OFFICE PROFILE SHEET

This form aims to collect basic and contextual information about the office after the interview, enabling a better understanding of its profile and experience in the use of digital fabrication.

1. General Information about the Office:

Office Name:	Konceptness
Location:	Lisbon / Porto
Number of Staff:	20
Year Founded:	2009
Website / Online Portfolio:	https://konceptness.pt/

2. Profile of the Interviewed Architect:

Full Name:	Susan Cabeceiras
Position in the Office:	Founder & Chair
Academic Background:	Lusíada University of Lisbon
Year of Graduation:	2003
Professional Experience (years of experience, other institutions/companies worked at):	21 years (business area, Municipality-Óbidos)
Areas of Expertise:	-
Contact (email, phone):	geral@konceptness.com

3. Office Profile:

Areas of Expertise:	Industrial / SCI / Project Management	
Most Common Project Types	☐ Housing ☐ Urbanism ☐ Culture & Institutional ☐ Education ☒ Offices	☐ Rehabilitation ☒ Industrial ☐ Interior Design ☐ Furniture ☒ Healthcare

	☐ Parking ☐ Commercial/Retail ☐ Tourism	☐ Services ☐ Hospitality ☐ Equipment
Digital Tools Used	☒ Modelling & Design Software ☐ Digital Fabrication Software (CAM – Computer-Aided Manufacturing) ☐ Digital Fabrication Technologies	
Available Digital Fabrication Equipment	☐ 3D Printers (FDM – Fused Deposition Modelling; SLA – Stereolithography & DLP – Digital Light Processing; SLS – Selective Laser Sintering) ☐ CNC Routers (Computer Numerical Control) ☐ Laser Cutters ☐ 3D Scanning Systems ☐ Fabrication & Assembly Robots ☐ Auxiliary Equipment (hand tools)	

4. Implementation of Digital Fabrication:

Year Digital Tools Were First Used:	2019
Key Project(s) Using Digital Fabrication:	-
Approximate Percentage of Projects Incorporating Digital Tools:	90%
Collaborations with Academic or Research Institutions (if applicable):	☒ Yes ☐ No

5. Development & Training:

Internal Training programmes (related to digital fabrication):	☒ Yes ☐ No
Partnerships with External Institutions for Training (if applicable):	☒ Yes ☐ No

Participation in Digital Fabrication Workshops/ Conferences:	☐ Yes ☒ No

OFFICE PROFILE SHEET

This form aims to collect basic and contextual information about the office after the interview, enabling a better understanding of its profile and experience in the use of digital fabrication.

1. General Information about the Office:

Office Name:	Rebelo de Andrade
Location:	Lisbon
Number of Staff:	30
Year Founded:	1989
Website / Online Portfolio:	https://www.rebelodeandrade.com

2. Profile of the Interviewed Architect:

Full Name:	Tiago Rebelo de Andrade
Position in the Office:	co-founder
Academic Background:	FAUP
Year of Graduation:	2010
Professional Experience (years of experience, other institutions/companies worked at):	19 years (Subvert – Lisbon, llaollao - Lisbon, Proun - London, Arquitraço – Lisbon)
Areas of Expertise:	-
Contact (email, phone):	info@rebelodeandrade.com

3. Office Profile:

Areas of Expertise:	Housing, Hospitality and Rehabilitation	
Most Common Project Types	☒ Housing ☐ Urbanism ☐ Culture & Institutional ☐ Education ☐ Offices	☒ Rehabilitation ☐ Industrial ☒ Interior Design ☒ Furniture ☐ Healthcare

	☐ Parking ☐ Commercial/Retail ☒ Tourism	☐ Services ☒ Hospitality ☒ Equipment
Digital Tools Used	☒ Modelling & Design Software ☒ Digital Fabrication Software (CAM – Computer-Aided Manufacturing) ☒ Digital Fabrication Technologies	
Available Digital Fabrication Equipment	☒ 3D Printers (FDM – Fused Deposition Modelling; SLA – Stereolithography & DLP – Digital Light Processing; SLS – Selective Laser Sintering) ☒ CNC Routers (Computer Numerical Control) ☒ Laser Cutters ☐ 3D Scanning Systems ☐ Fabrication & Assembly Robots ☒ Auxiliary Equipment (hand tools)	

4. Implementation of Digital Fabrication:

Year Digital Tools Were First Used:	1989
Key Project(s) Using Digital Fabrication:	n.a.
Approximate Percentage of Projects Incorporating Digital Tools:	100%
Collaborations with Academic or Research Institutions (if applicable):	☐ Yes ☒ No

5. Development & Training:

Internal Training programmes (related to digital fabrication):	☒ Yes ☐ No
Partnerships with External Institutions for Training (if applicable):	☒ Yes ☐ No

Participation in Digital Fabrication Workshops/ Conferences:	☐ Yes ☒ No

OFFICE PROFILE SHEET

This form aims to collect basic and contextual information about the office after the interview, enabling a better understanding of its profile and experience in the use of digital fabrication.

1. General Information about the Office:

Office Name:	Saraiva + Associados
Location:	Lisbon (Portugal / Algeria / Brazil / Colombia / Kazakhstan / Singapore / Switzerland / Vietnam / USA)
Number of Staff:	150
Year Founded:	1996
Website / Online Portfolio:	https://www.saraivaeassociados.com

2. Profile of the Interviewed Architect:

Full Name:	Luís Barros
Position in the Office:	Chief Operating Officer and Architect
Academic Background:	Faculty of Architecture – University of Lisbon
Year of Graduation:	1996
Professional Experience (years of experience, other institutions/companies worked at):	33 years (Ae-tec – Macau, CCR Carlos & Cristina Ramos – Lisbon, MA Silva Fernandes – Lisbon)
Areas of Expertise:	-
Contact (email, phone):	geral@msa.com.pt

3. Office Profile:

Areas of Expertise:	-	
Most Common Project Types	☒ Housing ☒ Urbanism ☒ Culture & Institutional ☒ Education	☒ Rehabilitation ☒ Industrial ☐ Interior Design ☒ Furniture

	☒ Offices ☒ Parking ☒ Commercial/Retail ☒ Tourism	☒ Healthcare ☒ Services ☒ Hospitality ☒ Equipment
Digital Tools Used	☒ Modelling & Design Software ☐ Digital Fabrication Software (CAM – Computer-Aided Manufacturing) ☒ Digital Fabrication Technologies	
Available Digital Fabrication Equipment	☒ 3D Printers (FDM – Fused Deposition Modelling; SLA – Stereolithography & DLP – Digital Light Processing; SLS – Selective Laser Sintering) ☒ CNC Routers (Computer Numerical Control) ☒ Laser Cutters ☐ 3D Scanning Systems ☐ Fabrication & Assembly Robots ☒ Auxiliary Equipment (hand tools)	

4. Implementation of Digital Fabrication:

Year Digital Tools Were First Used:	2016 (BIM)
Key Project(s) Using Digital Fabrication:	n.a.
Approximate Percentage of Projects Incorporating Digital Tools:	100% (Digital Tools) 80% (Digital Fabrication)
Collaborations with Academic or Research Institutions (if applicable):	☒ Yes ☐ No

5. Development & Training:

Internal Training programmes (related to digital fabrication):	☒ Yes ☐ No

Partnerships with External Institutions for Training (if applicable):	☒ Yes ☐ No
Participation in Digital Fabrication Workshops/ Conferences:	☒ Yes ☐ No

OFFICE PROFILE SHEET

This form aims to collect basic and contextual information about the office after the interview, enabling a better understanding of its profile and experience in the use of digital fabrication.

1. General Information about the Office:

Office Name:	Summary
Location:	Porto
Number of Staff:	10
Year Founded:	2015
Website / Online Portfolio:	https://summary.pt

2. Profile of the Interviewed Architect:

Full Name:	Samuel Gonçalves
Position in the Office:	Founder
Academic Background:	FAUP
Year of Graduation:	2012
Professional Experience (years of experience, other institutions/companies worked at):	1 year (ELEMENTAL - Chile)
Areas of Expertise:	-
Contact (email, phone):	info@summary.pt

3. Office Profile:

Areas of Expertise:	controlled costs	
Most Common Project Types	☒ Housing ☐ Urbanism ☐ Culture & Institutional ☐ Education ☒ Offices	☐ Rehabilitation ☐ Industrial ☐ Interior Design ☐ Furniture ☐ Healthcare

	☐ Parking ☒ Commercial/Retail ☐ Tourism	☒ Services ☐ Hospitality ☐ Equipment
Digital Tools Used	☒ Modelling & Design Software ☐ Digital Fabrication Software (CAM – Computer-Aided Manufacturing) ☐ Digital Fabrication Technologies	
Available Digital Fabrication Equipment	☐ 3D Printers (FDM – Fused Deposition Modelling; SLA – Stereolithography & DLP – Digital Light Processing; SLS – Selective Laser Sintering) ☐ CNC Routers (Computer Numerical Control) ☐ Laser Cutters ☐ 3D Scanning Systems ☐ Fabrication & Assembly Robots ☐ Auxiliary Equipment (hand tools)	

4. Implementation of Digital Fabrication:

Year Digital Tools Were First Used:	2022 (BIM)
Key Project(s) Using Digital Fabrication:	n.a.
Approximate Percentage of Projects Incorporating Digital Tools:	70%/80%
Collaborations with Academic or Research Institutions (if applicable):	☒ Yes ☐ No

5. Development & Training:

Internal Training programmes (related to digital fabrication):	☐ Yes ☒ No
Partnerships with External Institutions for Training (if applicable):	☒ Yes ☐ No

Participation in Digital Fabrication Workshops/ Conferences:	☐ Yes ☒ No

OFFICE PROFILE SHEET

This form aims to collect basic and contextual information about the office after the interview, enabling a better understanding of its profile and experience in the use of digital fabrication.

1. General Information about the Office:

Office Name:	TEKSTUDIO
Location:	Lisbon
Number of Staff:	8
Year Founded:	2011
Website / Online Portfolio:	https://www.tekstudio.pt

2. Profile of the Interviewed Architect:

Full Name:	Joana Pimenta
Position in the Office:	Office Coordination
Academic Background:	FAUP
Year of Graduation:	2009
Professional Experience (years of experience, other institutions/companies worked at):	6 years (Artotec Architectes Urbanistes Associés, MLRP, meier + associés architectes)
Areas of Expertise:	-
Contact (email, phone):	info@tekstudio.pt

3. Office Profile:

Areas of Expertise:	Architecture, Urbanism & Landscape, Interior Design, Real Estate & Investment Consulting	
Most Common Project Types	☒ Housing ☐ Urbanism ☐ Culture & Institutional ☐ Education ☒ Offices	☒ Rehabilitation ☐ Industrial ☒ Interior Design ☒ Furniture ☐ Healthcare

	☐ Parking ☒ Commercial/Retail ☒ Tourism	☐ Services ☐ Hospitality ☐ Equipment
Digital Tools Used	☒ Modelling & Design Software ☐ Digital Fabrication Software (CAM – Computer-Aided Manufacturing) ☐ Digital Fabrication Technologies	
Available Digital Fabrication Equipment	☐ 3D Printers (FDM – Fused Deposition Modelling; SLA – Stereolithography & DLP – Digital Light Processing; SLS – Selective Laser Sintering) ☐ CNC Routers (Computer Numerical Control) ☐ Laser Cutters ☐ 3D Scanning Systems ☐ Fabrication & Assembly Robots ☒ Auxiliary Equipment (hand tools)	

4. Implementation of Digital Fabrication:

Year Digital Tools Were First Used:	2011 (BIM)
Key Project(s) Using Digital Fabrication:	n.a.
Approximate Percentage of Projects Incorporating Digital Tools:	100%
Collaborations with Academic or Research Institutions (if applicable):	☐ Yes ☒ No

5. Development & Training:

Internal Training programmes (related to digital fabrication):	☐ Yes ☒ No
Partnerships with External Institutions for Training (if applicable):	☒ Yes ☐ No

Participation in Digital Fabrication Workshops/ Conferences:	☐ Yes ☒ No

ANNEX L – ENLARGED IMAGES

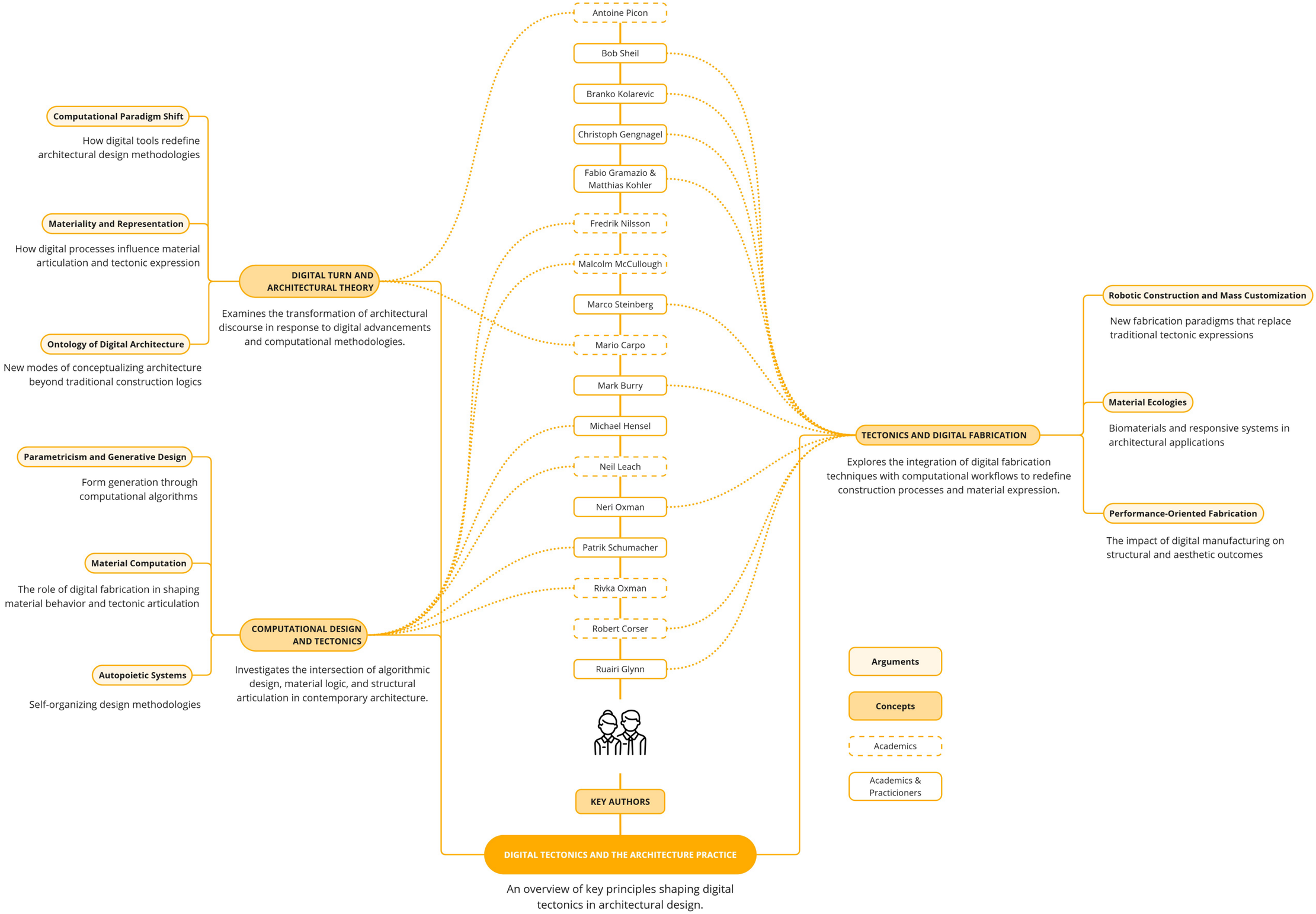


Figure L.1: Enlarged version of Figure 1.2: Mind Map on the Conceptual Landscape of Digital Tectonics in Architectural Theory and Practice.

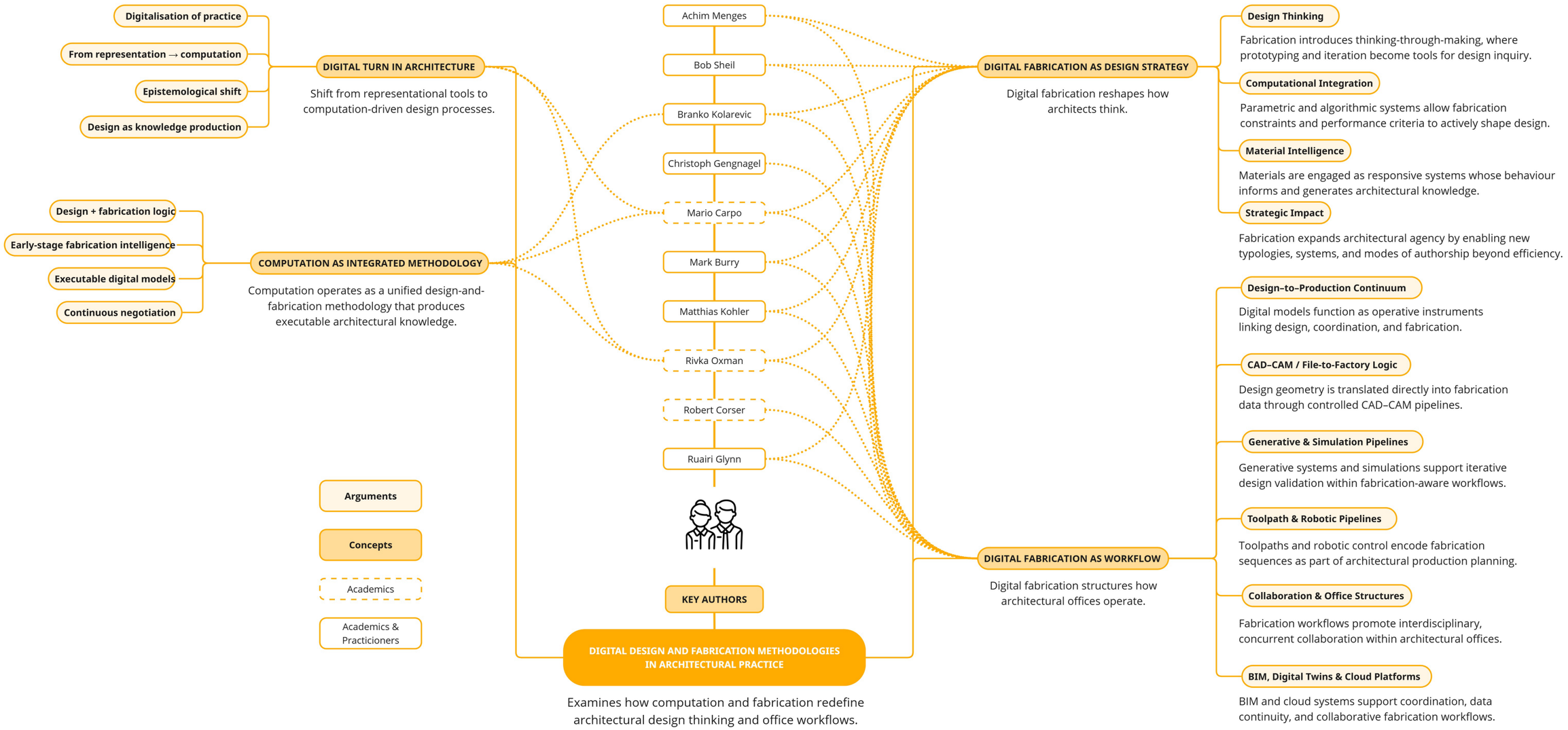


Figure L.2: Enlarged version of Figure 2.1: Mind Map on Digital Design and Fabrication Methodologies in Architectural Practice, outlining digital fabrication as both a design strategy and an operational workflow shaping contemporary architectural practice.

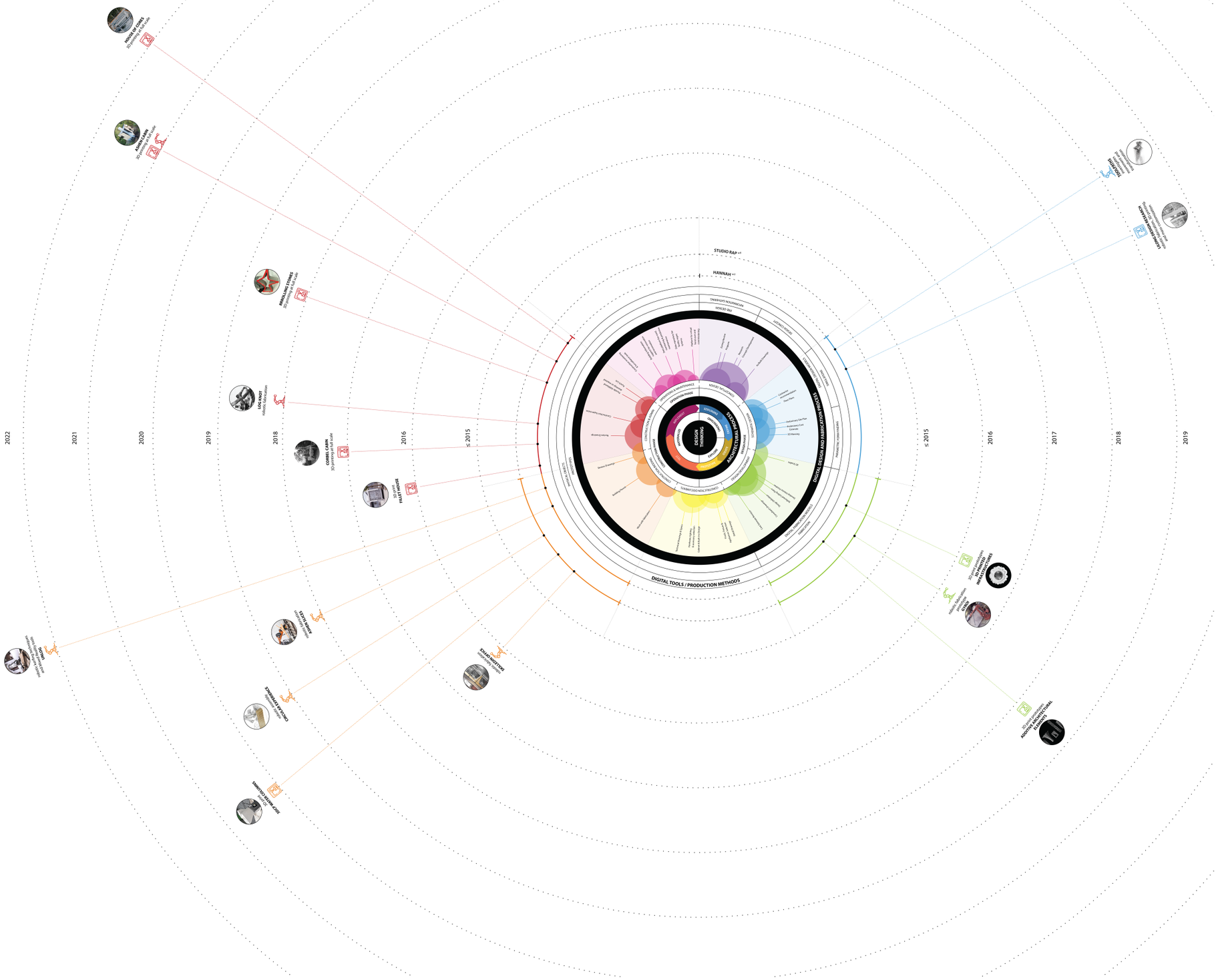


Figure L.3: Enlarged version of Figure 5.5: Process-based analysis of projects by HANNAH Office and Studio RAP.