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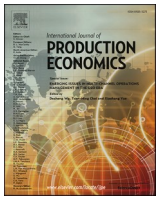



Beyond substitution: How virtual representations stabilize operational paradoxes in new product development

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ABSTRACT

Virtualization technologies—digital twins and virtual prototyping—are widely promoted as efficiency levers in new product development, yet we know little about how increasingly central virtual representations reorganize prototyping work over time and how ensuing contradictions become workable. We address this gap through a longitudinal case study of ALPHA, a luxury fashion engineering firm, tracing its virtualization trajectory (2015–2024) via 53 interviews plus archival and internal documents. Virtualization did not converge toward full digital substitution. As virtual representations became coordination hubs, three interdependent tensions persisted: optimization versus physicality, digital expertise versus craft knowledge, and collaboration intensification versus digital dependence. We theorize these as stable and habitable operational paradoxes—contradictory yet mutually enabling demands embedded in everyday prototyping work—stabilized through socio-technical configuration rather than cyclical reframing. We identify three stabilization mechanisms: interdependent representational architectures coupling physical prototypes with 2D/3D artefacts; epistemic authority that governs the enactment of digital competences while preserving craft-based evaluative closure; and partitioned discretion that combines traceability-critical digital workflows with bounded flexibility near material validation. We translate these insights into a diagnose–design–govern roadmap for building hybrid prototyping systems that accelerate iteration without displacing embodied expertise or inducing disabling rigidity.

1. Introduction

Virtualization technologies (VTs)—most notably digital twins (DTs) and virtual prototyping (VP)—are becoming integral to new product development (NPD) as firms seek to accelerate iteration, reduce material waste, and coordinate product decisions across design–engineering–production interfaces (Krems et al., 2017; Fixson, 2021). DTs are commonly defined as digital representations of physical products or processes that integrate data flows for monitoring, prediction, and optimization (Vickers, 2016; Ivanov, 2023), whereas VP refers to the use of digital models and simulations to evaluate design alternatives and performance characteristics before committing to physical artefacts (Stelzer, 2009; Gausemeier et al., 2005). For operations and production research, DT/VP diffusion is typically associated with gains in efficiency, transparency, and responsiveness in product development and manufacturing systems (Baptista et al., 2020; Vial, 2021). Yet, as virtual representations shift from supporting tools to coordination hubs that structure task sequencing and cross-functional alignment, they also reorganize work content, expertise dependencies, and decision authority within NPD (Fixson, 2021; Leonardi, 2011).

Despite the rapid diffusion of DT/VP, extant research still provides a partial account of how virtualization reorganizes prototyping work in practice and with what organizational consequences. While dominant accounts emphasize expected performance improvements and integration trajectories, a growing stream documents unintended outcomes such as altered interaction patterns, procedural dependencies, and frictions in cross-functional coordination (Leonardi, 2011; Lanzolla et al., 2021; Orlikowski, 2007). These issues become particularly consequential in design-intensive and craft-based settings, where product excellence depends on embodied evaluation, tacit judgment, and material specificity that resist full codification in digital artefacts (Lindkvist, 2005; Särmäkari, 2023; Kabalska, 2023). Moreover, studies of tensions in digitalization often remain cross-sectional or treat contradictions as temporary implementation obstacles, offering limited insight into how tensions persist, co-evolve, and become stabilized as virtualization becomes institutionalized (Melville, 2019; Moschko et al.,

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2023). We therefore need a process-oriented explanation of how increasingly central virtual representations generate enduring and interdependent tensions at the interface between digital coordination and material validation—and how organizations make such tensions operationally workable rather than attempting to eliminate them (e Cunha, 2023; Schad et al., 2016; Lewis, 2011).

To address this puzzle, we conducted a longitudinal case study of ALPHA, an Italian luxury fashion engineering firm operating at the intersection of artisanal craftsmanship and advanced manufacturing. Luxury fashion prototyping constitutes a theoretically generative extreme case: it is highly time-pressured, reputationally sensitive, and materially constrained, making it well-suited to observing how virtualization interacts with embodied expertise and craft-based evaluation (Särmäkari, 2023; Kabalska, 2023). We traced ALPHA's virtualization trajectory from 2015 to 2024 through 53 semi-structured interviews collected across three waves (2019–2024), complemented by internal documentation and archival sources spanning the entire decade. Following an abductive research logic, we iteratively connected empirical observations with sensitizing concepts from socio-technical systems, digital transformation, and organizational tensions research to theorize how contradictions emerged, evolved, and stabilized as virtualization became embedded in prototyping work (Dubois and Gadde, 2014; Pettigrew, 1990; Yin, 2011).

Our findings show that virtualization did not converge toward full digital substitution. As virtual representations became central coordination devices, ALPHA experienced three persistent, interdependent tensions: optimization versus physicality, digital expertise versus craft knowledge, and collaboration intensification versus digital dependence. First, digital representations accelerated early convergence and reduced the number of physical iterations, yet physical prototypes became more—not less—consequential as the locus of final material validation and decision closure. Second, as digital artefacts gained representational authority, specialized digital competences became increasingly valuable, but evaluative control over fit, feel, and constructability remained anchored in craft-based regimes of judgment—creating ongoing interdependence between digital modelling and embodied expertise. Third, digitally interconnected workflows intensified collaboration through traceability and shared visibility, while simultaneously raising the cost of deviation and relocating discretion to bounded downstream zones close to material realization. Across the decade, these tensions reinforced one another: upstream acceleration amplified downstream material anchoring; representational centrality reshaped authority and sequencing; and traceability requirements transformed improvisation from a routine feature of craft work into an explicitly governed exception.

This study makes two interrelated contributions. First, to digital transformation and operations research in NPD, we reframe virtualization as a representation-centered form of organizing, shifting attention from technological fidelity or integration ideals to the socio-technical conditions under which DT/VP improve performance without eroding material validation and adaptive capacity (Fixson, 2021; Vial, 2021; Leonardi, 2011). Second, to organizational tension and paradox research, we specify how virtualization generates stable and habitable operational paradoxes: contradictory yet mutually enabling demands embedded in everyday prototyping work that are rendered workable through socio-technical configuration rather than primarily through cyclical reframing or oscillation (Schad et al., 2016; Lewis, 2011; Farjoun, 2010). We identify three stabilization mechanisms—interdependent representational architectures, epistemic authority governing the enactment of digital competences, and partitioned discretion across stages and artefacts—that sharpen the paper's novelty beyond generic efficiency–flexibility or capability–rigidity framings (Atuahene-Gima, 2005; Leonard-Barton, 1992). Finally, we translate these insights into a transferable managerial roadmap—diagnose, design, govern—to guide leaders in configuring hybrid prototyping systems, preserving differentiated yet interdependent expertise, and balancing traceability with bounded discretion in craft-based digitalization efforts.

2. Theoretical background

2.1. Virtualization technologies in new product development

Virtualization technologies (VTs)—most notably digital twins (DTs) and virtual prototyping (VP)—have become increasingly central to contemporary new product development (NPD). By enabling simulation, visualization, and iterative testing prior to physical realization, VTs are expected to reduce development time, cost, and material waste while improving coordination across design and production interfaces (Krems et al., 2017; Fixson, 2021). DTs are typically defined as digital representations of physical products or processes that integrate data flows to support monitoring, prediction, and optimization (Vickers, 2016; Ucbasaran, 2024). VP, more specifically, denotes the use of digital models and simulations to evaluate design alternatives and performance characteristics before committing to physical artefacts (Stelzer, 2009; Gausemeier et al., 2005).

Across sectors such as automotive, aerospace, and advanced manufacturing, virtualization has been associated with accelerated development cycles, enhanced cross-functional collaboration, and tighter coupling between design intent and downstream production constraints (Baptista et al., 2020; Bailey et al., 2012). In operations and supply-chain research, DTs in particular are often discussed as enablers of integration, traceability, and system-level optimization (Cheng, 2020; Ivanov, 2023). At the same time, the term “digital twin” is used with varying precision in empirical domains, sometimes conflating real-time data-integrated twins with more general 3D representations or digital mock-ups used for visualization and iteration (Kuzmichev, 2018). This definitional breadth matters because the organizational implications of DT/VP depend not only on representational fidelity but also on how representations are embedded in workflows, decision routines, and interdependent artefact infrastructures (Fixson, 2021). In fashion and apparel, recent work highlights the potential of DT/3D tools to improve production-line balancing, enable virtual fitting, and reduce physical sampling (Kabalska, 2023; Alam et al., 2023), often in connection with broader visions of human-centric digitalization and Industry 5.0 (Donmezer et al., 2023). Yet, even where simulation accuracy improves, material properties and sensory evaluation remain difficult to fully capture, particularly in craft-intensive contexts where quality depends on fit, drape, and tactile coherence (Särmäkari, 2023; Zhao, 2018). As a result, virtualization tends to reorganize prototyping rather than simply dematerialize it.

A socio-technical lens helps explain why. Rather than operating as purely technical tools, VTs function as socio-technical systems that reshape artefacts and representations while simultaneously reconfiguring expertise, authority, and coordination (Fixson, 2021; Leonardi, 2011; Orlikowski, 2007). As digital modelling, remote interaction, and traceability infrastructures become embedded in NPD, they alter the material and cognitive infrastructures through which products are conceived, tested, and validated, making virtualization a fertile context for persistent organizational tensions.

2.2. Persistent tensions in the integration of virtualization technologies

Prior research suggests that VT integration in NPD generates contradictory yet interdependent demands. While digital representations enhance speed, precision, and traceability, they rarely eliminate the need for physical validation, embodied expertise, and situated judgment (Kabalska, 2023; Piccinini et al., 2015). In design-intensive and craft-based settings, material testing and sensory coherence remain central to product excellence, limiting the feasibility of full substitution narratives (Särmäkari, 2023; Atkinson, 2017). Accordingly, virtualization is better understood as a reconfiguration of prototyping work in

which the relationship between virtual and physical representations must be continuously organized.

These dynamics resonate with paradox theory, which conceptualizes tensions as "contradictory yet interrelated elements that exist simultaneously and persist over time" (Schad et al., 2016; Lewis, 2011). In digital transformation contexts, scholars have documented how technological integration can intensify—rather than resolve—tensions related to control versus flexibility, standardization versus creativity, and capability development versus organizational rigidity (Moschko et al., 2023; Atuahene-Gima, 2005; Leonard-Barton, 1992). At the same time, much of this literature is cross-sectional or remains at the level of abstract dualities, providing limited insight into how tensions become operationally consequential in day-to-day prototyping and how organizations sustain workability over time (Melville, 2019). Building on this foundation, we focus on three interrelated tensions that are theoretically grounded in prior work but insufficiently understood in longitudinal, craft-based settings shaped by increasingly central virtual representations.

First, the pursuit of optimization through digital simulation can conflict with the persistence of physicality in product evaluation. Although virtual models can accelerate early convergence and resource efficiency, they cannot fully reproduce material properties, embodied interaction, or aesthetic judgment, especially where legitimacy and quality depend on sensory validation (Särmäkari, 2023; Piccinini et al., 2015). This generates a tension between digital optimization and physical validation that is not reducible to a temporary accuracy gap, because physical artefacts often remain the locus of final decision closure even as digital coordination expands.

Second, virtualization redistributes expertise and authority. The introduction of modelling software and data-centric workflows increases reliance on digital specialists while potentially marginalizing traditional artisans and established evaluative regimes, thereby reshaping professional identities and coordination across knowledge domains (Leonard-Barton, 1992; Xiao, 2006; Mazmanian et al., 2013). In fashion-related prototyping work, studies increasingly show that digital outcomes depend on tacit garment knowledge and ongoing translation between computational representation and embodied craft judgment (Zhao, 2018; Pesce et al., 2025). This creates a tension between expanding digital competences and the persistence of craft-based epistemic authority in defining what counts as a valid prototype.

Third, virtualization intensifies collaboration through shared digital environments and traceability, yet it can also increase procedural convergence and interdependence. Standardized digital workflows enhance visibility and accountability but may constrain local discretion and improvisation that remain necessary close to material realization (Leonardi, 2011; Pinsonneault, 2011; Röglinger, 2018). As representations become tightly coupled across stages, small changes can trigger cascading updates across linked files and roles, raising the cost of deviation and altering when and where flexibility is legitimate. This produces a tension between collaboration intensification and procedural rigidity that is structurally embedded in digitally interconnected work.

While scholarship acknowledges these contradictions, two gaps remain salient for VT-enabled prototyping. First, we know relatively little about how such tensions co-evolve over extended periods of digital transformation, particularly as virtual representations shift from peripheral tools to coordination infrastructures that govern sequencing, accountability, and decision rights (Melville, 2019; Andriopoulos et al., 2018). Second, the interplay between advanced virtualization tools and institutionalized craftsmanship remains underexplored: research often emphasizes technological affordances and performance promises, but less frequently examines how organizations govern the coexistence of algorithmic precision and embodied judgment as a durable feature of prototyping work (Kabalska, 2023; Donmezer et al., 2023). To address this puzzle, this study adopts a longitudinal, process-oriented perspective. By tracing a decade of virtualization within a luxury fashion engineering firm, we examine how optimization, expertise redistribution, and digitally mediated collaboration become intertwined and generate persistent, interdependent tensions—and how organizations sustain workability as these tensions persist rather than disappear.

3. Methodology

3.1. Research design and approach

This study adopts a longitudinal, single-case design to examine how VTs reorganize prototyping work in NPD and how the resulting operational tensions persist and become workable over time. A case-study approach is appropriate when the phenomenon of interest is deeply embedded in organizational context and unfolds through evolving interdependencies among technologies, roles, and work practices (Yin, 2011). The longitudinal design enables process-sensitive theorizing by tracing how virtualization shifted from discrete technological initiatives to an institutionalized infrastructure shaping coordination and decision closure (Pettigrew, 1990).

Our inquiry followed an abductive research logic (Dubois and Gadde, 2014). Rather than treating theory as either a prior template imposed on data or an outcome derived from purely inductive coding, we iteratively connected empirical observations with sensitizing concepts from socio-technical and digital transformation research and from work on organizational tensions (Dubois and Gadde, 2014). This approach was particularly suitable for our research question because it allowed us to preserve openness to empirical surprises—such as the reinforcement of physical validation alongside increased virtualization—while progressively sharpening conceptual categories and mechanism-based explanations.

The empirical window spans 2015–2024 and captures three analytically distinct phases in ALPHA's trajectory: early exploration of VP logics (2015–2018), scaling and integration of digital infrastructures across prototyping and production interfaces (2019–2021), and hybrid stabilization of workflows and decision rights (2022–2024). This temporal bracketing supported a reconstruction of how tensions co-evolved and how socio-technical arrangements gradually stabilized, rather than assuming that contradictions would dissipate as tools matured.

3.2. Research setting

The study was conducted in luxury fashion engineering, a theoretically generative setting for examining virtualization because it combines strong time-to-market pressures with stringent material and sensory constraints (Gong, 2014). Unlike industries where simulation-based validation has long been institutionalized (Shakantu, 2016), fashion prototyping remains difficult to fully dematerialize because quality depends on fabric behavior, fit, drape, and tactile coherence (Goldstein et al., 2009; Magnenat-Thalmann, 2007), dimensions that remain only partially representable in digital artefacts. This makes luxury prototyping an "extreme" context for observing how increasingly central virtual representations interact with embodied evaluation and craft-based authority.

ALPHA, an Italian B2B fashion engineering firm, was selected as a revelatory case (Yin, 2011) because it occupies a distinctive position at the intersection of craftsmanship and industrial precision. Founded in 2000, ALPHA provides garment engineering, prototyping, and production services for major luxury brands and has historically differentiated itself through tight feedback loops between design intent, pattern-making, and production feasibility. Since 2015, the firm has pursued a sustained virtualization trajectory, investing in 2D/3D CAD, VP, and production-linked automation (e.g., automated cutting). This extended and deliberate transformation made it possible to observe how virtual representations progressively moved from supportive tools to coordination infrastructures, thereby reshaping expertise dependencies, decision authority, and the sequencing of prototyping work.

3.3. Data collection

Data were collected through a longitudinal, multi-source strategy to ensure triangulation and enhance interpretive robustness (Yin, 2011). The core dataset consists of 53 semi-structured interviews conducted between 2019 and 2024, complemented by internal documentation and external archival materials covering the full 2015–2024 period. Interviews captured both retrospective accounts of early adoption and contemporaneous reflections on later stages of scaling and stabilization.

Interviews were organized in three waves aligned with key phases of ALPHA's transformation. The first wave (2019–2020) focused on the early transition from manual and 2D workflows toward 3D modelling and VP experiments. The second wave (2021–2022) captured acceleration and intensified remote coordination during the COVID-19 period, when virtualization became critical for maintaining prototyping continuity. The third wave (2023–2024) examined the consolidation of hybrid arrangements and the organizational consequences of increased representational coupling and traceability. Informants were selected to reflect multiple functions and hierarchical levels involved in prototyping work and its digital infrastructure, including the CEO/founders, senior pattern makers, CAD/3D specialists, project managers, IT managers, and process specialists from acquired subsidiaries. Interviews lasted approximately 60–90 min, were recorded and transcribed verbatim, and produced a corpus exceeding one hundred pages of single-spaced text. To preserve temporal and role transparency, quotations reported in the Findings are labeled by role and interview year (e.g., *"Pattern Maker, 2021"*).

To extend historical coverage and mitigate reliance on retrospective recall, we triangulated interview evidence with internal documents (e.g., annual reports, audits, process documentation, software-related materials) and external sources (e.g., CEO speeches, press releases, and trade-press articles). These materials supported event verification, provided time-stamped anchors for key adoption milestones, and offered an additional perspective on how ALPHA articulated the rationale and expected performance implications of virtualization. Table 1 summarizes the main data sources and their analytic role.

3.4. Data analysis

Data analysis proceeded abductively through iterative cycles that linked empirical evidence to emerging conceptual categories and to prior theory (Dubois and Gadde, 2014; Gioia et al., 2013). The analysis unfolded in three interrelated steps.

First, we constructed a longitudinal case narrative by organizing interviews and documents chronologically and identifying key milestones in ALPHA's virtualization trajectory (e.g., introduction of 3D CAD, production-linked automation, and the pandemic-related shift toward remote validation). This process enabled a temporally grounded reconstruction of how virtual representations became increasingly central in coordination and how tensions emerged, intensified, and interacted across phases.

Second, we conducted a systematic analysis of interview transcripts and documents, following the principles of open and axial coding (Strauss, 2014). We began with open coding to capture informants' language and situated concerns (e.g., limits of virtual accuracy; reliance on physical fitting; emerging dependencies across 2D/3D artefacts; shifts in who can credibly "close" a decision). We then moved to axial coding to relate first-order categories to second-order themes consistent with our theoretical sensitization, particularly around representational centrality, authority, and discretion. This process yielded the three aggregate tensions that structure the Findings: optimization versus physicality, digital expertise versus craft knowledge, and collaboration intensification versus digital dependence. Coding and theme refinement proceeded through repeated iterations among the authors; divergent interpretations were discussed until alignment was reached. Table 2 presents the resulting data structure linking first-order categories, second-order themes, and aggregate dimensions.

Third, we theorized the process mechanisms that render these tensions operationally workable over time. We examined how specific socio-technical arrangements reconfigured (i) the architecture of representations across artefacts, (ii) epistemic authority over evaluative closure, and (iii) the partitioning of discretion and traceability across stages. These analyses produced the stabilization mechanisms developed in the Discussion and provided the basis for linking micro-level prototyping practices to a broader, representation-centered view of organizing. Throughout analysis, we maintained analytic memos to document interpretive decisions and theoretical refinements, and we conducted member-checking conversations with selected informants to validate factual accuracy and improve the credibility of our interpretations.

Table 1
Data table.

Data source	Type of data	Use in the analysis
Semi-structured interviews (2019–2024)	−16 interviews with the CEO and founders −15 interviews with pattern makers −9 interviews with CAD designers −7 interviews with IT and project managers −6 interviews with founders and process specialists from acquired companies	Used to track the adoption of technologies, assess implementation strategies, and understand their impact on stakeholders.
Secondary sources (2015–2024)	- Annual reports and company audits - Technical documents on software operations and digital design processes	Used for event tracking and to corroborate interview data with additional internal documentation.
Industry press (2015–2024)	−6 public speeches −13 press releases	Used to analyze industry-wide impacts, contextualize ALPHA's digital transformation, triangulate findings and validate interpretations.

4. Findings

ALPHA's virtualization trajectory from 2015 to 2024 reveals three persistent and interdependent tensions shaping prototyping work in NPD: (1) optimization versus physicality, (2) digital expertise versus craft knowledge, and (3) collaboration intensification versus digital dependence. These tensions did not emerge as isolated implementation "issues" to be solved and left behind. Instead, as virtual representations became increasingly central to coordination across design–engineering–production interfaces, the tensions intensified, co-evolved, and progressively stabilized into workable arrangements. We first examine each tension and then show how their interplay structured the decade-long evolution of ALPHA's prototyping system.

ALPHA operates as an engineering partner within luxury fashion supply chains, where prototyping is both time-pressured and materially constrained. The firm historically differentiated itself by bridging design intent and production feasibility through iterative craft-based work and fast responsiveness. As luxury brands accelerated product cycles and increasingly relied on digital tools to sustain speed and sustainability goals, ALPHA faced mounting pressure to modernize prototyping and strengthen coordination with clients. What began as incremental digitization expanded into a broader reconfiguration of representations, skills, and workflows (2D/3D CAD, VP, production-linked automation). Over time, this shift reshaped work content, authority, and discretion—creating enduring tensions at the interface between digital representations and material validation.

Table 2
Data structure.

Exemplary quotes	First-order concepts	Second-order themes	Aggregate dimension
[A1] «Using 3D printing on digitally printed fabrics brings savings of up to 30%, this leads to numerous advantages: greater penetration rate on that customer making them save money, greater sustainability which is increasingly important » CEO, 2019	Cost and waste reduction	**Upstream digital acceleration and resource efficiency**	**Optimization versus physicality**
[A2] «With 3D CAD […] we managed to save 40% of material from cutting the designed garments[…]» CEO, 2024			
[A3] «The custom process that previously included manual cutting has been completely digitized. Now, the model is digitized using a digitizer and inserted into a database. Subsequently, the various sizes are developed and the arrangements of the pieces to be cut are managed, which are then sent to automatic cutting. This step completely replaced the previous manual operations » Company Founder, 2019	End-to-end digitization and automation		
[A4] « The main reasons why we use digital modelling are 3: the first is that during the pandemic it was used to send the models around, the second is for us to see if what we have done reflects what we imagined, therefore to have an idea, thirdly it is used to ensure that what you are creating in 3D can cut down on time in moments of workload […] it was something that there was no technical time to cut and sew the garments » Project Manager, 2023	Lead time compression		
[A5] «Shipping time only, we make the prototype. So, the times are roughly halved because you can do an urgent physical prototype in 4 days, a super urgent one in 2. With a digital twin prototype, it takes 4 h. Imagine that the times between sewing and CAD development are more or less the same, but all the logistics to send the finished garment to the customer, all these parts » CEO, 2024			
[A6] «We had so little time because the client had to present to the creative director, it was one thing that there was no technical time to cut and sew the garments and so we did the entire presentation of this part of the collection virtually » CEO, 2022	Virtual sampling as workload buffer		
[A7] «You can see it in real time, and it costs zero, without the need to create a multitude of physical prototypes that will be discarded » CEO, 2023			
[A8] «Digitization allows us to incorporate more projects into a 'digital library'. This makes us flexible because it allows us to reuse items from old or vintage collections without having to start from scratch » Pattern Maker, 2023	Reuse through digital archives		
[B1] «We rely on digital after Covid when the physicality of the object is disintermediated, until that moment there was only one customer who had followed us, which was Burberry, because they told us that style wants to touch the garment » CEO, 2024	Irreplaceability of tactile validation	**Downstream material anchoring and representational limits**	
[B2] «To date, the steps for the actual use of 3D by the customer to technically see the model are slow, sometimes they ask us, or rather more than sometimes, they ask us but maybe they ask you for 6 prototypes that really have a very vague idea and they say oh well maybe make me the 3D so I can see a preview of it but they want to see it » Project Manager, 2023	Limits of virtual fidelity		
[B3] «The complexity is given by the fact that it is difficult to imagine on a monitor something that will actually be a physical garment» 3D Modeler, 2023			
[B4] «And then it's a physical thing, so they really have a way of interpreting things » Pattern Maker, 2023			
[B5] «Let's say if our client wants to prototype in a certain way, they can start seeing the prototype on the digital twin, but they still need the physical prototype » Project Manager, 2024	Physical prototype as decision closure		
[B6] «After that, they can make the physical sheet, but maybe instead of making two they make just one. Even after the drape, they will certainly make the physical prototype, because the physicality of the material is important» 3D Modeler, 2024			
[C1] «In CAD work, the use of tricks and shortcuts allows for significantly higher execution speed than traditional methods. With the same resources, efficiency can be up to five times greater » Company Founder, 2019	Execution speed via CAD	**Emergence of digital specialization and tool-based execution**	**Digital expertise versus craft knowledge**
[C2] «To learn CAD, they took courses. The most difficult transition was the transition from manual work to CAD. At the beginning, the productivity of the CAD pattern maker was lower, but then it improved. Today, they work mostly 95% with CAD (2D). The remaining 5% includes plotting and checking the model » Company Founder, 2020	Learning curve and digital upskilling		
[C3] «Also pay attention to the proportions because the 1:1 scale is one thing, a size on the screen you also have to acquire a perspective of the dimensions and detail in that precise dimension does not come immediately it comes with years of experience » Pattern Maker, 2022			
[C4] «We started with Cloe with a girl then we hired people and we started to insert 3D in the phase immediately after modelling » Company Founder, 2022			

(*continued on next page*)

Table 2 (*continued*)

Exemplary quotes	First-order concepts	Second-order themes	Aggregate dimension
[C5] «We have created a 3D team in the company of young guys, some come from IEED, so they have a minimum of skills, others don't, their aim is to focus on 3D not on the model » IT Director, 2022			
[D1] «The difference between CAD and manual is that since you cannot work all day, on paper you have more of a "trace" of where you arrived, simply where you left the pencil. On a CAD piece you have to go and get it and understand where you got to » Company Founder, 2022	Cognitive reorientation to digital artefacts	**Craft authority, embodied judgment, and skill preservation**	
[D2] «Let's start from the assumption that there are pattern makers who have never worked on paper and therefore probably put a paper pattern in front of them and don't know how to modify it » Company Founder, 2023			
[D3] «I only have the basics of modelling to understand what is asked of me, but I am not able to make models» 3D Modeler, 2023	Training bottlenecks and craft scarcity		
[D4] «Previously, learning the trade required long physical training courses. Today, schools that teach are rare, but they prepare directly for entry into the working field. Companies now recruit from regional vocational schools and train in-house. For example, the Zerboni Institute, with a section dedicated to CAD modelling, asked if they could train one of their pattern makers to teach. Only 2 out of 10 people were affected, while the other 8 were not. In the Turin area they are unique, apart from a few companies. The shortage of craftsmen is so critical that there is a real "auction" to acquire resources in the sector » Company Founder, 2020			
[D5] «Usually those who belong to our category (old school) of pattern makers have always been a little reluctant to too much technology applied to this type of profession because it is a way of being, of working, the eye that sees the detail » Company Founder, 2019	Cultural resistance and identity anchoring		
[D6] «I think that in the end, if we oriented ourselves completely towards digital, we would lose a little … we would flatten out … Personally, even though I often ride a bicycle, I understand that the more you use it, the more you learn. If you use it less, you risk losing skills » Company Founder, 2023			
[D7] «If the company you work for makes normal products or in any case makes classic products, they don't need (the integration of 3D prototyping) » IT Director, 2022			
[E1] «The introduction of the digital twin facilitates collaboration with the customer. The customer no longer waits for the report of a physical prototype, but provides real-time feedback based on the digital twin » Project Manager, 2023	Real-time client feedback and remote approvals	**Digital mediated co-creation and real-time visibility**	**Collaboration intensification versus digital dependence**
[E2] «If the customer is happy with the volume of the garment, if they want to shorten or lengthen a sleeve, with 3D they can do it without needing an immediate physical prototype» 3D Modeler, 2023			
[E3] «If there is something that doesn't work, you can use the digital twin to prove that it doesn't work. Or, for placement, you can offer the customer different options and show them in 3D» 3D Modeler, 2024			
[E4] «For the ability to work collaboratively, 3D has a medium-high impact because it is one more tool, they have to explain how they want the result to be. Having a tool with such great ability to show you details is very useful» 3D Modeler, 2024			
[E5] «To introduce the 3D prototype phase which gives him the possibility of not spending in quotes to make a physical prototype, of having an immediate yield, therefore much faster than creating a 3D physical prototype» 3D Modeler, 2023	Remote 3D prototyping enables shared visibility		
[E6] «You take the 2D to Cloè, I do the 3D and send it to the customer. The customer makes the changes on the virtual garment, and I bring it back. They often anticipate errors before prototyping. Travel less physically, less transportation costs and greater sustainability » CEO, 2022			
[E7] «There was a gigantic expansion in terms of 3D so many customers obviously came to request it because they had no other way of seeing the prototypes » CEO, 2022			
[F1] «Because then there are many things (digital projects in 3D) that perhaps are done more for communication for ourselves, to communicate the fact that we innovate that we try, etc. but then we know very well that they are perhaps not things that we could actually sell for real » IT Director, 2023	Increased coordination load	**Traceability-driven coupling and constrained discretion**	
[F2] «Today the pattern maker has multiple levels, he talks to the designer, he talks to the PD, he talks to the design […] So the idea is that this wireless telephone game has become much longer » Company Founder, 2022			
[F3] «The traditional method (physical fitting) is the most reliable, because they have been working like this for years and therefore trust this method » Project Manager, 2023	Misinterpretation in remote exchange and rework		
[F4] «The digital twin facilitates collaboration with the customer, but it is a 'possible' representation of reality […] in the end, before sending a garment into production, the customer is interested in the physical prototype » CEO, 2023			

(*continued on next page*)

Table 2 (*continued*)

Exemplary quotes	First-order concepts	Second-order themes	Aggregate dimension
[F5] «Sometimes something is interpreted in a different way compared to how it was intended by the style (due to long-distance contacts) and therefore you come across more than one prototype, therefore having to redo the same prototype several times and perhaps receiving some feedback a little less positive, not due to the fault of one party or the other, but precisely because clearly not having a direct exchange is more complex » Project Manager, 2019	Task interdependencies and cascading updates		
[F6] «Pattern makers develop the product in 2D, then pass the models to the 3D office which creates the digital twin and sends it to the customer. If the customer requires simple changes, these can be done directly in 3D, while for complex changes we return to 2D. Interdependencies increase, everyone must know how to do a bit of everything, time is compressed, but instead of working in parallel on different products, we work in series on the same product » Pattern Maker, 2023			

4.1. Balancing process optimization and physicality

ALPHA's turn to virtualization was initially motivated by the need to reduce lead times, material waste, and iteration costs. Prior to advanced digitalization, prototyping relied on manual routines: pattern makers drafted patterns by hand (Fig. 1), produced samples, and refined fit and construction through repeated physical iterations. This mode ensured high-quality control but was slow and resource-intensive, particularly for complex garments requiring multiple rounds of sampling and adjustment.

ALPHA's earlier adoption of 2D CAD—used to digitize pattern-making and accelerate modifications—provided the infrastructural baseline for later virtualization. A senior pattern maker summarized the efficiency gains enabled by automated grading tools: *"Before, resizing a garment across sizes meant adjusting each pattern by hand. Now, with PGS, we do it in minutes instead of hours." (Pattern Maker, 2016)*. These changes improved speed and interoperability with downstream processes, but physical prototypes remained the authoritative basis for validation and approval.

A qualitative shift occurred with the introduction of 3D CAD and VP around 2015 (Fig. 2). Virtual representations enabled earlier visualization and faster alignment among internal roles and clients, elevating digital artefacts from technical aids to coordination devices. This increased the pace of iteration upstream and reduced the need for multiple physical samples, but it did not remove the need for material evaluation. Instead, it reconfigured when and how physicality mattered.

The deepening of digitalization in 2019—particularly automated cutting linked to digitized patterns—tightened the coupling between representations and production. As the company founder explained: *"The custom process that previously included manual cutting has been completely automated. Now, the model is digitized using a digitizer and inserted into a database. Subsequently, the various sizes are developed and the arrangements of the pieces to be cut are managed, which are then sent to automatic cutting. This step completely replaced the previous manual operations." (Company Founder, 2019)*. At this stage, optimization increasingly depended on representational interoperability: 3D visualization

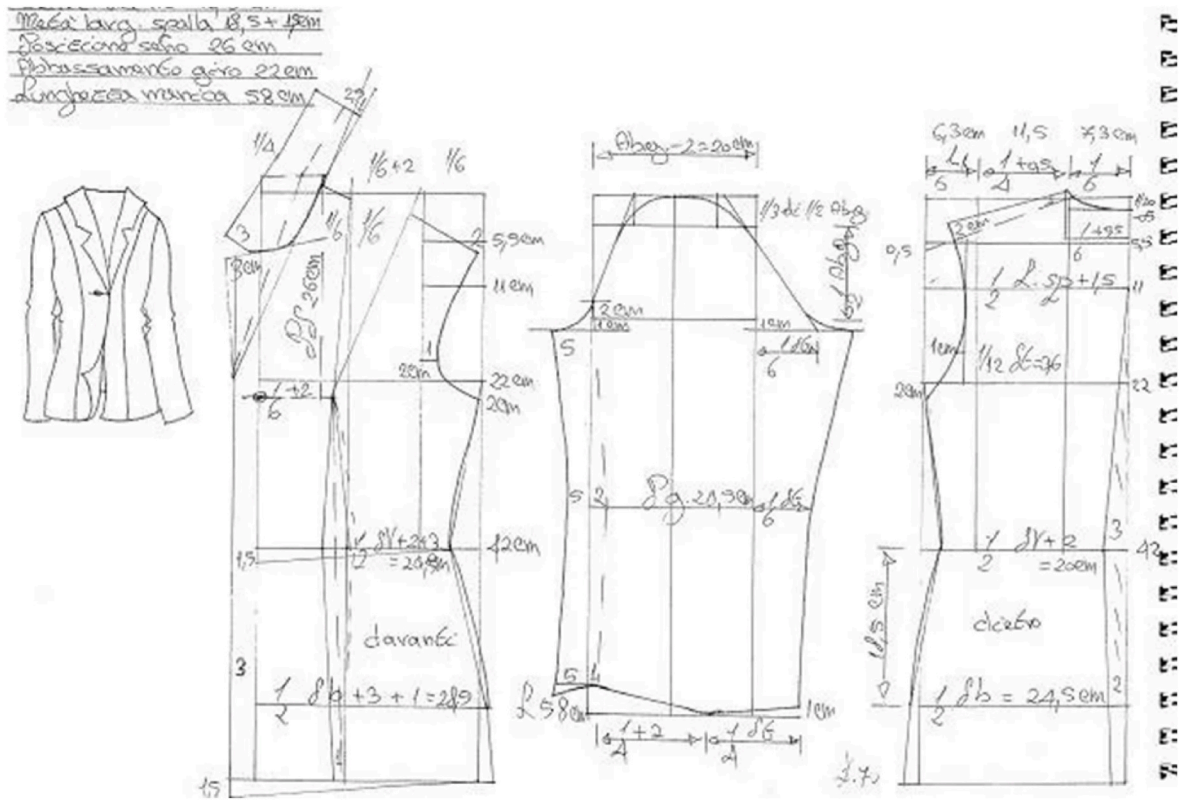

Fig. 1. Manual paper pattern of the product.

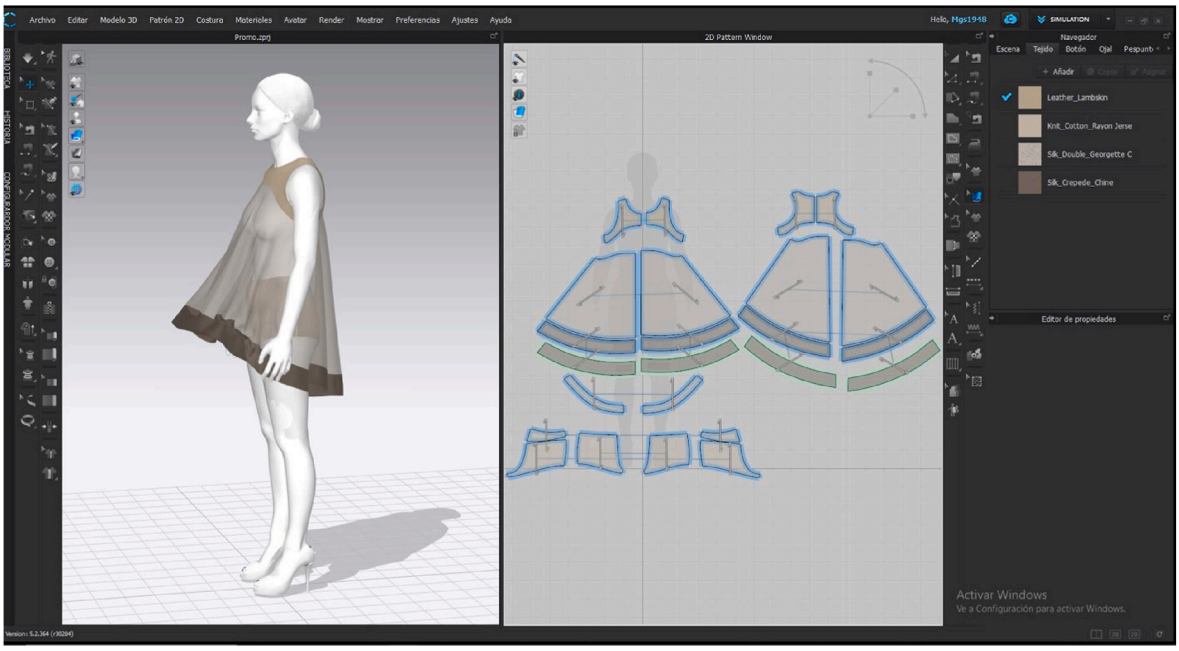

Fig. 2. – Virtual representation of the product, in 3D and 2D.

accelerated early convergence, while 2D formats remained critical for production translation.

The COVID-19 period (2020–2021) pushed virtualization further by constraining physical meetings and fittings. A project manager recalled: *"During the pandemic we used digital modelling to send models around, to check if what we did reflected what the customer imagined, and to reduce time in workload peaks." (Project Manager, 2023)*. Yet the limits of virtual representations became salient precisely as they were used more intensively. Material properties—weight, drape, tactile sensation—remained difficult to reproduce. A product manager captured the resulting asymmetry: *"3D simulations help us cut down on prototypes, but luxury brands won't approve a collection without touching the fabric. Digital tools get us 90% there, but the last step still needs to be physical." (Product Manager, 2022)*.

By 2024, ALPHA had institutionalized a layered prototyping system: virtual prototypes were used upstream to compress exploratory cycles and align interpretations early, while the physical prototype became the high-stakes locus of final material validation and decision closure. As a project manager noted, *"Clients can start seeing the prototype on the digital twin, but they still need the physical prototype." (Project Manager, 2024)*. Importantly, optimization did not converge toward a single representation. Instead, it stabilized through a multi-format representational sequence in which 3D supports early convergence and communication, while 2D and physical artefacts remain indispensable for production translation and material anchoring. The tension between optimization and physicality thus persisted as an operational condition of the prototyping system rather than a temporary technological limitation.

4.2. Increasing digital expertise versus craft knowledge

As ALPHA's prototyping system became more representationally dense, the composition and organization of expertise changed. Traditional pattern makers—historically the custodians of product feasibility and quality—faced increasing exposure to digital artefacts that shaped early-stage decisions. An experienced pattern maker described the cognitive shift required: *"For decades, I worked with my hands feeling the fabric, adjusting proportions instinctively. Learning CAD was like starting over. It's precise, but it lacks the intuitive adjustments we used to make manually." (Pattern Maker, 2019)*. Early efforts emphasized training and internal upskilling, but the organization progressively recognized that advanced 3D modelling could not simply be "absorbed" into existing craft roles without creating friction in evaluation, timing, and authority.

Between 2021 and 2022, ALPHA moved toward a dual-talent strategy, introducing specialized 3D roles rather than forcing full role conversion. As the IT director explained: *"We have created a 3D unit in the company of young guys; some come from design institute, so they have a minimum of skills, others don't. Their aim is to focus on 3D, not on the traditional model." (IT Director, 2022)*. This step improved modelling capacity and upstream responsiveness, but it also created a structural interdependence: digital specialists could generate increasingly realistic virtual representations, yet they lacked deep knowledge of fabric behavior, assembly constraints, and the situated heuristics that support feasibility judgments. Conversely, senior pattern makers retained embodied expertise but were less fluent in the tools and logics shaping upstream representational work.

This shift also affected authority and sequencing. As discussions and client interactions increasingly hinged on 3D outputs, influence tended to accrue to those who could intervene early on digital representations, while craft-based judgment risked being deferred to downstream stages. Pattern makers were often engaged once key parameters had already been stabilized digitally (e.g., lengths, placements, volumes), increasing the cost of late revisions and amplifying the need for translation mechanisms between domains.

ALPHA responded by redesigning interaction conditions to reduce misalignment between virtual representations and embodied evaluation. A central intervention was the co-location of 3D specialists and senior pattern makers in a shared open space (Fig. 3), enabling frequent, informal exchanges and rapid correction of representational inaccuracies before they propagated. A senior pattern maker explained: *"The 3D team is excellent with digital tools, but they don't always understand how a fabric stretches or behaves. We have to guide them to ensure that virtual designs actually work in production." (Pattern Maker, 2023)*. Over time, such situated guidance allowed craft expertise to remain authoritative without requiring a return to craft monopolies over early-stage coordination.

By 2024, ALPHA had stabilized around a differentiated yet interdependent expertise configuration. Digital specialists concentrated on upstream visualization and virtual sampling; senior pattern makers

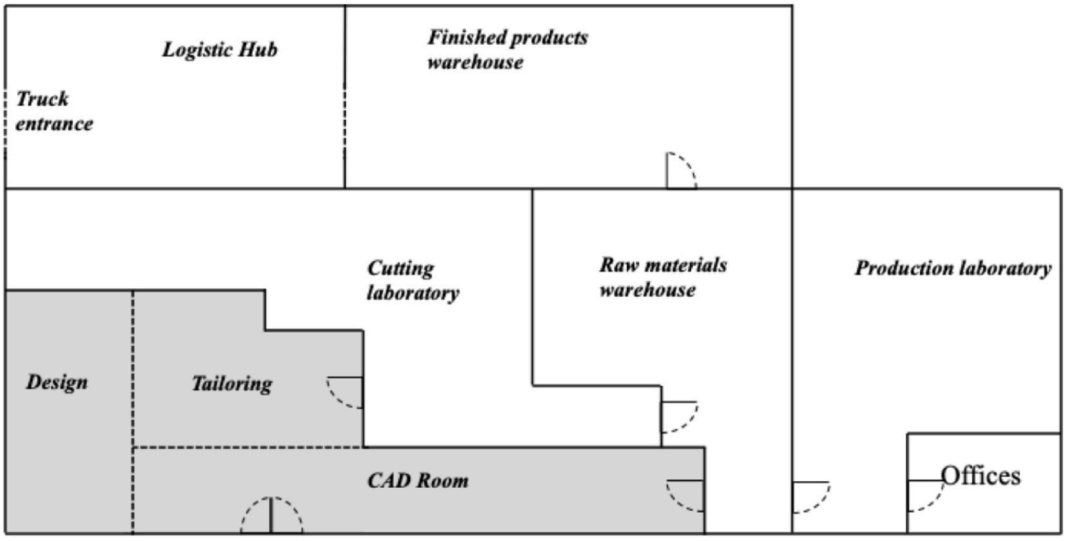

Fig. 3. ALPHA's workspace layout in 2023.

retained evaluative closure over fit, constructability, and production translation, including the critical return to 2D representations required for cutting and manufacturing interoperability. In this stabilized arrangement, the tension between digital expertise and craft knowledge did not disappear. Rather, it became manageable through structural interdependence and redesigned interaction conditions that preserved craft-based evaluation while leveraging digital capacity.

4.3. Collaboration intensification versus digital dependence

VP also transformed collaboration with clients and internal coordination. By enabling remote visualization and rapid feedback, 3D representations reduced delays associated with shipping samples and organizing physical fittings. The CEO emphasized the advantage: *"With digital twins, our clients don't need to wait for a prototype to arrive. They can evaluate, modify, and approve designs remotely." (CEO, 2023)*. This intensified collaboration, improved transparency, and compressed development cycles—especially when clients needed quick previews or alignment under tight deadlines (Fig. 4).

However, the same infrastructures that enabled real-time collaboration also introduced digital dependence and procedural convergence. Remote interactions reduced opportunities for tacit negotiation and embodied alignment typical of physical fittings. A project manager captured the interpretive risk of distance: *"Sometimes something is interpreted in a different way compared to how it was intended by the style […] not having a direct exchange is more complex." (Project Manager, 2019)*. As work became increasingly mediated by interconnected representations, coordination improved but also became more fragile: small changes required synchronization across linked files and formats, and deviations incurred higher costs due to traceability and interdependence.

The pandemic amplified this dynamic. As virtualization became a necessity rather than an option, demand expanded rapidly. The CEO recalled: *"There was a gigantic expansion in terms of 3D — so many customers obviously came to request it because they had no other way of seeing the prototypes." (CEO, 2022)*. Yet increased representational coupling constrained responsiveness when material contingencies emerged late. A production manager explained: *"Before, we could make quick, on-the-spot adjustments. Now, even a small change, like modifying a sleeve, needs to go through the digital system, updating all linked files before its implemented, so in some cases we leave a little 'freedom' to the designers." (Production Manager, 2024)*.

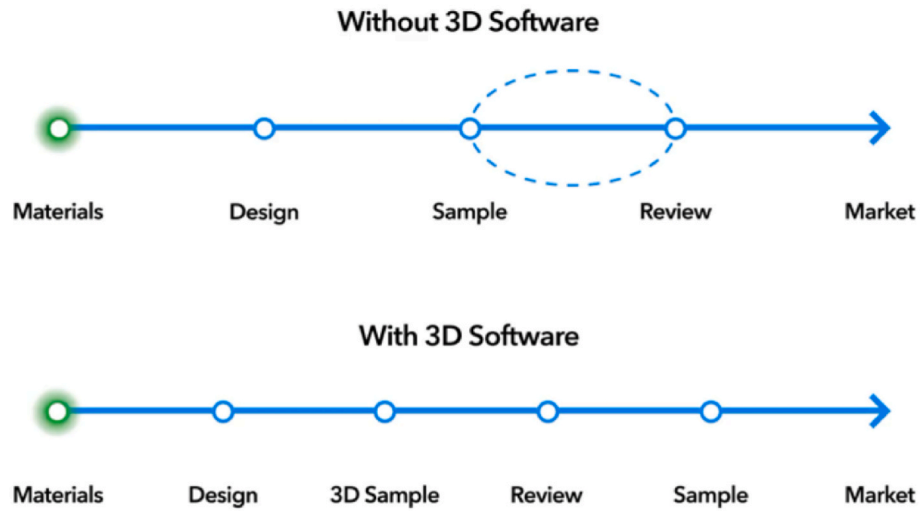

Fig. 4. – NPD phases before and after the adoption of 3D software; the dashed circle highlights a resource-intensive iterative cycle, reduced through digital prototyping.

By 2023–2024, ALPHA's workflows were more transparent and tightly coordinated, but also more dependent on representational integrity. A key shift concerned the organizational status of improvisation. Localized adjustments had always been part of craft-based prototyping; what changed was that improvisation became explicitly recognized as a deviation from digitally traceable workflows and therefore required justification and subsequent reconciliation. Importantly, discretion did not extend uniformly across the process. It was largely relocated downstream, closer to physical prototyping and material realization, where experienced actors could implement small localized corrections to address fit or fabric issues without immediately updating the full digital chain. These interventions were bounded in scope.

4.4. Dynamic interplay of tensions over time (2015 – 2024)

The three tensions co-evolved rather than unfolding independently. Early optimization efforts through 2D/3D modelling compressed upstream cycles and increased representational reliance, which in turn heightened the stakes of downstream physical validation. As 3D representations became central to coordination, demand for digital expertise expanded, intensifying interdependence between modelling capacity and craft-based evaluative closure. At the same time, digitally mediated collaboration increased transparency and speed, but also tightened coupling across stages—raising the cost of deviation and relocating discretion to bounded downstream zones where material contingencies could still be addressed without destabilizing representational chains.

A senior pattern maker described how this interplay shaped everyday coordination: *"Pattern makers develop the product in 2D, then pass the models to the 3D office which creates the digital twin and sends it to the customer. If the customer requires simple changes, these can be done directly in 3D, while for complex changes we return to 2D. Interdependencies increase—everyone must know how to do a bit of everything. Time is compressed, but instead of working in parallel we work in series on the same product." (Pattern Maker, 2023)*. Here, "simple" versus "complex" changes reflected not only production requirements but the representational implications of coordination: some revisions could be stabilized quickly through 3D visualization and shared interpretation, while others required return to 2D patterns to assess constructability and production translation.

Over the decade, ALPHA did not resolve any single tension. Instead, the organization stabilized a set of recurring arrangements: the continued use of physical prototypes for authoritative material closure; interaction conditions that preserved craft-based evaluation while enabling digital modelling to structure upstream work; and a workflow architecture that combined traceability with bounded downstream discretion. By 2024, virtualization neither supplanted craftsmanship nor eliminated improvisation; it reconfigured when, where, and by whom decisions could legitimately be closed. Digital innovation therefore unfolded not as linear substitution, but as the progressive stabilization of interdependent tensions within a representationally mediated prototyping system.

5. Discussion

This study examined how increasingly accurate virtual representations reorganize prototyping work in NPD. Rather than depicting digitalization as a linear substitution of physical artefacts, our findings show that when DT/VP representations become central coordination devices, they restructure how decisions are closed, how expertise is mobilized, and how discretion is authorized across stages. The key theoretical implication is that virtualization does not primarily "solve" prototyping problems through higher fidelity; instead, it intensifies persistent and interdependent operational tensions that organizations must render workable through socio-technical configuration. This stabilization-oriented account clarifies the novelty of our contribution and addresses concerns that the observed contradictions might resemble simple technological trade-offs rather than structurally embedded tensions.

5.1. Stable and habitable operational tensions

The three tensions identified—optimization versus physicality, digital expertise versus craft knowledge, and collaboration intensification versus digital dependence—capture how virtual representations reshape everyday work from early concept validation to final prototyping. At face value, the first tension may appear as a technological limitation: digital models accelerate iteration but cannot fully replicate embodied sensory evaluation. Our findings, however, indicate that the relationship between virtual and physical representations is not one of sequential substitution but of structural interdependence. As virtual representations become more accurate and consequential upstream, they do not make physical prototypes redundant; instead, they make physical validation more consequential downstream, as fewer—and more "final"-—iterations concentrate decision closure on a single material moment. Optimization and physicality thus become mutually enabling rather than mutually exclusive: virtual convergence raises the value of material confirmation, while such confirmation legitimizes virtual acceleration.

This logic matters for positioning. If these were merely trade-offs, organizations could resolve them through prioritization (e.g., "go more digital" or "stay more physical"). Instead, the tensions persist because both poles are simultaneously required within the same prototyping system: material evaluation remains the legitimacy basis for quality, while digital representations become the dominant medium for early coordination and compression of cycles. This pattern is consistent with paradox theory's definition of tensions as "contradictory yet interrelated elements that exist simultaneously and persist over time" (Schad et al., 2016; Lewis, 2011), but it also clarifies where persistence resides: in the workflow role of representations, not only in actors' interpretive frames.

Importantly, the tensions we observe do not primarily unfold as episodic contradictions resolved through cycles of reframing or oscillation. They do not resemble transient implementation frictions that disappear once users "learn the technology," nor do they follow the recurring separation–integration dynamics highlighted in paradox management work (Andriopoulos and Lewis, 2009; Jay, 2013). Instead, they become stabilized as durable and habitable operational paradoxes embedded in socio-technical arrangements. Organizational actors do not repeatedly reinterpret the tensions at a cognitive level; they repeatedly coordinate around them through representational architectures, authority regimes, and rules of discretion. This complements paradox research that has increasingly emphasized material and relational foundations (Schad et al., 2016; Putnam et al., 2016) but still tends to privilege dynamic equilibrium and cyclical navigation (Lewis, 2011). In line with Farjoun (2010) view that stability and change are mutually constitutive, we show how "stability" can be enacted through concrete, engineered configurations in digitally mediated prototyping work.

This framing also clarifies how our contribution differs from adjacent dualities. Unlike exploration–exploitation tensions, which typically concern resource allocation between competing strategic logics (Andriopoulos and Lewis, 2009), the tensions observed here operate within the same prototyping episode and are produced by representational coupling across stages. Virtual optimization and physical anchoring are not alternative orientations; they are jointly required to close a single product decision. Likewise, the digital expertise–craft knowledge tension is not reducible to a capability that gradually turns into rigidity (Atuahene-Gima, 2005; Leonard-Barton, 1992). The contradiction is not that "digital becomes too strong" but that digital infrastructures expand capacity through traceability and anticipatory coordination while simultaneously constraining discretion and reclassifying who can legitimately close decisions. By specifying these mechanisms, we move beyond generic efficiency–flexibility narratives and

show how virtualization produces operational paradoxes embedded in workflow architectures.

5.2. Socio-technical stabilization mechanisms

Our principal theoretical contribution is to explicate three socio-technical mechanisms through which digitalized prototyping becomes workable without eliminating underlying tensions.

Interdependent representational architectures. The optimization–physicality tension is stabilized through the deliberate maintenance of multiple representations—physical prototypes alongside 2D and 3D digital artefacts—configured as an operating architecture rather than as redundant alternatives. Rather than converging toward a single authoritative representation, artefacts mutually constrain and authorize one another: 3D supports early visualization and alignment, 2D enables production translation and interoperability, and the physical prototype anchors material legitimacy and closure. This differs from classic boundary object arguments, where artefacts facilitate translation across domains (Carlile, 2002). Here, representations become structurally coupled: no single artefact can close design decisions independently. While visual artefacts have been described as epistemic and boundary objects in design work (Whyte, 2009), our findings show that in virtualized prototyping they operate as a hierarchically interdependent system that organizes sequencing and closure. This challenges substitution narratives in the digital twin literature that depict DTs as comprehensive replicas spanning design, prototyping, and production (Alam et al., 2023; Donmezer et al., 2023). Even where DT-enabled integration improves coordination and optimization (Kabalska, 2023; Oruthotaarachchi, 2025), empirical usage often conflates "digital twin" with 3D mock-ups (Kuzmichev, 2018) and continues to require physical anchoring. Our contribution is to specify why: performance relies on interdependence, not representational dominance.

Epistemic authority and digital competences. The digital expertise–craft knowledge tension is stabilized not through role fusion or universal reskilling, but through the preservation of evaluative authority anchored in embodied craft regimes. Digital modelling supports anticipation, simulation, and upstream iteration; however, judgment over fit, material behavior, and constructability remains anchored in craft expertise. This resonates with evidence that digital fashion work depends on tacit garment knowledge and symbiotic collaboration between digital designers and patternmakers (Särmäkari, 2023; Zhao, 2018; Pesce et al., 2025), and that expanding digital skills may risk eroding embodied competencies (Atkinson, 2017). In sociomaterial terms, digital artefacts possess affordances that reshape coordination (Leonardi, 2011), yet their enactment remains constrained by regimes of evaluation embedded in professional authority. Stabilization therefore hinges less on artefact properties than on authority structures that define what counts as valid evidence and who can close decisions.

Partitioned discretion across stages and artefacts. The collaboration intensification–digital dependence tension is stabilized through a redistribution of legitimate discretion. Upstream digital representations are subjected to formal update procedures and traceability, enhancing organizational memory and coordination (Gal et al., 2008; Bechky, 2009). Downstream physical prototyping remains the primary locus of improvisation and situated problem solving, consistent with improvisation as competent adaptation to unfolding conditions (Weick, 1998). Digitalization thus does not eliminate improvisation; it relocates and contains it. Traceability—often celebrated in DT scholarship as an enabler of real-time integration and feedback loops (Alam et al., 2023)—simultaneously constrains speed and autonomy upstream, because representational coupling increases the cost of deviation. By partitioning discretion, organizations preserve responsiveness near material realization while preventing local adjustments from destabilizing tightly coupled digital systems. This mechanism is largely absent from paradox and digital coordination literatures, which typically treat flexibility as either reduced or restored through broad "ambidexterity" solutions rather than through explicit discretion boundaries.

5.3. Implications for digital transformation and operations research

Taken together, our findings suggest that effective virtualization in prototyping does not depend on eliminating tensions through increasingly accurate representations. It depends on configuring artefacts, roles, and workflows so that persistent operational tensions remain workable over time. This shifts attention from resolution-oriented expectations (e.g., "higher fidelity will replace physical prototypes") toward a stabilization-oriented perspective in which virtual representations reorganize authority, coordination channels, and legitimate zones of discretion.

For DT and operations research, this implies that integration and representational fidelity are insufficient descriptors of transformation. While DT narratives often emphasize vertical integration across design, prototyping, and production (Kabalska, 2023; Donmezer et al., 2023), our findings show that integration amplifies interdependence and intensifies the need for material anchoring. Performance gains derive not from full virtualization but from representational architectures that specify where speed is created, where legitimacy is anchored, and how translation is organized. Conceptually, DT/VP can be theorized not only as technical tools but as coordination devices that reshape sequencing, closure, and accountability in prototyping work.

For paradox theory, our contribution is to articulate a form of stabilized operational paradox embedded in representational infrastructures rather than primarily navigated through cognitive reframing or strategic oscillation. By specifying interdependent representational architectures, epistemic authority regimes, and partitioned discretion as stabilization mechanisms, we clarify how contradictions become habitable in materially intensive, design-driven contexts—without assuming that persistence requires ongoing cycles of sensemaking or alternating attention.

5.4. Managerial and practical implications

Our findings offer actionable guidance for managers leading digital transformation in design-intensive, craft-based industries where VP and DT technologies are introduced into entrenched development systems. Consistent with the stabilization perspective developed above, digitalization is not a linear migration from physical to virtual artefacts; it is a socio-technical reconfiguration that requires deliberate arrangements to stabilize persistent operational tensions. To enhance transferability, we propose a three-stage roadmap—diagnose, design, govern—that translates our insights into implementable guidance.

Diagnose representational architectures and authority regimes. Before scaling DT/VP, organizations should map (i) which artefacts are authoritative at each stage (physical, 2D, 3D, production-linked), (ii) how decisions propagate across representations, and (iii) where discretionary adjustments are routinely enacted. In design-intensive settings, decision closure is often embedded in embodied routines and tacit evaluative practices (Orlikowski, 2007; Lindkvist, 2005). Implementing digital infrastructures without making these regimes explicit risks misalignment between digital acceleration and material feasibility. Managers should also identify the authority regime—who legitimately decides "what counts" as evidence for fit, quality, and constructability (Leonard-Barton, 1992; Leonardi, 2015)—because digital adoption often shifts upstream influence without necessarily shifting downstream responsibility.

Design a multi-representational prototyping architecture. Effective transformation rarely follows convergence toward a single "authoritative" DT. Instead, it requires a multi-representational system in which digital and physical artefacts remain differentiated yet tightly coupled. Virtual simulations can accelerate iteration (Fixson, 2021; Kroh et al., 2018), but they do not fully reproduce sensory and embodied dimensions of material evaluation (Puerta, 2006; Bilalis, 2017). Managers

should therefore institutionalize hybrid prototyping policies and stage gates (Marion, 2012) that specify when virtual convergence is sufficient and when physical validation is mandatory. Crucially, design should also preserve differentiated expertise while enabling structured translation across domains. When evaluative frames diverge, reskilling alone is rarely enough (Edmondson et al., 2003; Buechley, 2013). Boundary-spanning interfaces—co-location, paired reviews, rotational assignments, and joint validation routines—help maintain specialization while enabling interdependence (Xiao, 2006; Carlile, 2004; Dieste et al., 2022).

Govern traceability and flexibility through partitioned discretion. Digital infrastructures increase visibility and accountability but can introduce rigidity (Leonardi, 2011; Röglinger, 2018). Effective governance requires defining where traceability is non-negotiable and where bounded improvisation is legitimate. Managers should identify traceability-critical zones (e.g., production-linked representations and compliance interfaces) and discretion zones near material realization where local judgment can correct contingencies without destabilizing the representational chain. Embedding structured overrides, reconciliation routines, and review checkpoints within digital workflows preserves responsiveness while sustaining coherence (Pinsonneault, 2011; Bechky, 2009). Partitioning discretion does not weaken digital discipline; it clarifies the conditions under which flexibility is authorized and prevents ad hoc deviations from propagating through tightly coupled systems.

Across the three stages, digital transformation is less a time-bounded implementation project than an ongoing governance capability. Leaders need an orientation that sustains both technological efficiency and human creativity (Schad et al., 2016; Lewis, 2011) and treats persistent tensions as inherent to virtualization rather than as failures to be eliminated (Putnam et al., 2016). Organizations that institutionalize multi-representational architectures, preserve differentiated yet interdependent expertise, and govern partitioned discretion are better positioned to sustain innovation under technological complexity. By shifting managerial attention from substitution to stabilization, firms can convert enduring tensions into sources of resilience, learning, and sustained differentiation.

6. Conclusion

This study examined how increasingly accurate virtual representations reorganize prototyping work in NPD. Drawing on a longitudinal case study of ALPHA—a luxury fashion engineering firm—we show that virtualization does not unfold as a linear substitution of physical artefacts. Instead, when DT/VP representations become central coordination devices, they intensify persistent and interdependent operational tensions that cannot be "solved" through higher fidelity or deeper integration. Over time, what changes is not the presence of contradiction, but the socio-technical arrangements through which it becomes operationally workable.

Empirically, we traced three tensions that co-evolved over a decade of virtualization: optimization versus physicality, digital expertise versus craft knowledge, and collaboration intensification versus digital dependence. These dynamics can be misread as temporary implementation frictions or straightforward tensions. Our evidence indicates the opposite. As virtual representations tend to gain epistemic authority upstream, physical validation becomes more consequential downstream because decision closure concentrates in fewer, higher-stakes material moments. As digital competences expand, their organizational influence remains bounded by craft-based evaluative regimes that define what counts as credible evidence for fit, quality, and constructability. And as digitally interconnected workflows increase transparency and traceability, they also raise the cost of deviation and relocate discretion toward bounded zones close to material realization. In short, virtualization produces not a transition from "craft to code," but a reconfiguration of when, where, and by whom prototyping decisions can legitimately be closed.

Theoretically, our contribution is to specify how these tensions persist as stable and habitable operational paradoxes—contradictory yet mutually enabling demands embedded in everyday prototyping work (Schad et al., 2016; Lewis, 2011). Whereas much paradox research emphasizes cycling, reframing, or dynamic equilibrium, our case highlights a pathway of stabilization through socio-technical configuration (Farjoun, 2010). Specifically, we identify three stabilization mechanisms that render digitalized prototyping workable without eliminating underlying tensions. First, organizations can build interdependent representational architectures in which physical prototypes, 2D formats, and 3D models mutually constrain and authorize one another rather than converging on a single "dominant" representation (Carlile, 2002; Whyte, 2009). Second, stabilization can rely on epistemic authority—anchoring evaluative closure in embodied craft regimes while allowing digital competences to structure upstream coordination (Leonardi, 2011). Third, organizations can achieve workable hybridity by partitioning discretion across stages and artefacts, combining traceability-critical infrastructures with bounded flexibility near material validation (Gal et al., 2008; Bechky, 2009). Together, these mechanisms extend digital transformation and DT research beyond substitution narratives by clarifying the organizational conditions under which integration yields performance improvements without inducing disabling rigidity (Kabalska, 2023; Alam et al., 2023).

For managers, the implication is that successful digital transformation in craft-based, design-intensive settings is an ongoing governance capability. Virtualization initiatives should begin by diagnosing representational architectures and authority regimes, proceed by designing a multi-representational prototyping system (rather than pushing for full digital substitution), and be sustained by governing explicit boundaries between traceability and discretion across stages. This roadmap translates the central insight of the study into practice: performance improvements depend on configuring artefacts, roles, and workflows so that tensions remain workable over time.

This study has limitations that invite future research. First, our findings derive from a single case in luxury fashion engineering—an extreme setting where sensory evaluation and embodied expertise are central to product legitimacy. Comparative research across industries with different materialities, modularity, and regulatory constraints (e.g., medical devices, automotive, aerospace) could test boundary conditions of the stabilization mechanisms identified here and assess whether alternative representational architectures and authority regimes prevail. Second, while our longitudinal design captures evolution over a decade, our evidence relies primarily on interviews and documentary sources. Future studies could complement this approach with ethnography or digital trace/process data to examine at higher temporal resolution how representational authority, discretion, and coordination are negotiated in day-to-day work. Third, as AI increasingly enters simulation, design decision support, and workflow automation, new questions emerge about how algorithmic optimization interacts with craft-based evaluative authority and how organizations maintain interpretability, accountability, and creativity as representational infrastructures become more autonomous.

Overall, this study reframes what it means to "go digital" in prototyping-intensive NPD. Digital transformation in such contexts is not best understood as a move toward full virtualization, but as the capability to stabilize enduring tensions at the interface of virtual representations and material practice. Organizations that learn to design and govern this interface can convert structural contradictions into sustained performance and resilient innovation.

CRediT authorship contribution statement

Danilo Pesce: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Gabriele Aimonino:** Writing –

review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paolo Neirotti:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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