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XXXVIII ciclo
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Beyond the Code: Bridging the Human and Organizational Skill Gap in Digital Twin Implementation

Anno Accademico 2024-2025

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Keywords: *Digital Twin, Socio-Technical Systems, Innovation Ecosystems, Digital Competencies, Human-Centricity, Organizational Adaptation*

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To my grandparents, my silent guidance

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Introduction and overview of the study

In this introductory, I delineate the research problem, outlining the specific objectives and research question (RQ) that guide this dissertation. The aim is to provide a comprehensive overview of the entire study, offering a detailed description of the institutional background, the identification of theoretical gaps, and the strategic positioning of this thesis within the broader context of the National Research Centre for High Performance Computing, Big Data, and Quantum Computing (ICSC). Finally, I outline the structure of the dissertation to reinforce the logic and purpose behind the empirical investigation.

1. Research problem and Institutional context

We live in an era characterized by unprecedented data production and technological convergence, where the ability to extract value from information is becoming the primary driver of socio-economic development. In this scenario, High Performance Computing (HPC), Big Data analytics, and Artificial Intelligence (AI) are not merely technical tools but strategic assets essential for addressing complex societal challenges and fostering sustainable growth. Recognizing this imperative, the National Recovery and Resilience Plan (PNRR) has funded the establishment of the ICSC National Research Centre, a strategic initiative organized on a Hub-and-Spoke model. While the Hub coordinates governance, the 11 Spokes are dedicated to specific thematic areas of national interest. Specifically, this doctoral thesis is positioned within the framework of Spoke 9: "Digital Society & Smart Cities". The mission of Spoke 9 is to overcome the "complexity wall" that characterizes modern digital societies - intricate systems where social, organizational, and technological layers interact dynamically. To navigate this complexity, the Spoke adopts the Digital Twin (DT) paradigm as a foundational methodology (Grieves, 2014; Tao et al., 2019). The goal is to create faithful digital representations of social and organizational structures to replicate behaviors, predict future evolutions, and support experimentation. Within this broad mandate, my research specifically addresses the domain of "Socio-Economic Analysis", focusing on models for human behavior, learning, and adaptation. However, a critical discrepancy emerges. While the infrastructure (Spoke 0) and the computational models (Modelling & Computing lines) are advancing rapidly towards exascale capabilities, the human and organizational readiness to leverage these technologies lags behind. The transition to a "Digital Society" requires not only powerful algorithms but also a workforce capable of interacting with them. Current literature and industrial reports indicate that the deployment of Digital Twins is often stalled not by technical feasibility, but by a severe skill gap and cultural resistance (Li et al., 2025; Signorini & Pomè, 2025). The research problem driving this thesis is therefore rooted in the observation that the "Digital Twin" is mature as a technology but immature as an organizational practice. There is a lack of understanding of how human behaviors, skills, and organizational contexts must evolve to keep pace with the hyper-accelerated digital infrastructure promoted by the ICSC.

2. Research objectives and research question

The overall research objective of this thesis is to explore the human and organizational dimension of the Digital Twin implementation. In this framework, a conceptual distinction is maintained between ‘adoption’, referring to the strategic decision to embrace the technology and ‘implementation’, the operational process of integrating it into organizational routines. Both are treated not as isolated events, but as part of a single continuous cycle of organizational transformation. Consistent with the mandate of Spoke 9 to analyze "human behavior, learning, and adaptation," this study aims to map the competencies required to manage Digital Twins effectively and to understand how these competencies are influenced by different ecosystemic contexts. This knowledge is crucial to ensure that the massive investments in HPC infrastructure (Spoke 0) translate into tangible value for society and industries, avoiding the risk of technological underutilization due to a lack of human capital. The overarching research aim is explored and resolved through a specific Research Question (RQ), which emerged from the gap analysis in the literature (Chapter 2) and guides the empirical investigation (Chapter 3). The underlying research hypothesis is that competencies are not universal; rather, their definition is strictly dependent on the maturity of the innovation ecosystem (Bell et al., 2019; Yin, 2018). To investigate this continuous cycle of change and its impact on human capital, the study addresses the following Research Question:

RQ: *How does the organizational and ecosystemic context influence the definition, development, and management of the competencies necessary for the strategic implementation of the Digital Twin?*

To answer this question, the study adopts a multi-methodological approach, combining a Systematic Literature Review (SLR) with a qualitative critical case study of a global leader in the field (IBM), comparing the visionary approach of Silicon Valley with the application challenges in the European context.

3. Positioning of the thesis

The main goal of this thesis is to understand a) what specific skills are required to govern the Digital Twin and b) how the cultural context shapes these requirements. The thesis is strategically situated at the intersection of *Management Science*, *Organization Studies*, and *Information Systems*. It does not focus on the computational architecture of the Digital Twin (which is the domain of the "Computing" research line of Spoke 9) but rather explores its managerial and organizational implications (aligned with the "Socio-Economic Analysis" domain). I consider competence not just as technical proficiency, but as a multidimensional construct encompassing cognitive sense-making, cross-functional collaboration, and strategic vision. Empirically, this thesis contributes to the goals of the ICSC National Centre by providing a framework for "human adaptation" to high-performance technologies. Indeed, one of the objectives of the Centre is to "transfer skills and enable researchers and industries to make the best use of resources." This dissertation directly supports this mission by identifying exactly which skills need to be transferred. The positioning is further strengthened by a period of research abroad in Lausanne (Switzerland). This experience provided a privileged international vantage point to analyze advanced innovation ecosystems, which was then complemented by direct interaction with key thought leaders from Silicon Valley (USA), facilitating a comparative analysis between different cultural mindsets.

4. Structure of the thesis

This dissertation is organized into four main chapters, designed to guide the reader from the theoretical foundations to the empirical findings. (Figure 1).

Chapter 1. ***Introduction:*** Delineates the theoretical framework of Digital Transformation, framing it not merely as the adoption of new technical tools, but as a pervasive strategic change process. It introduces the research problem, the institutional context of the ICSC National Centre, the objectives, and the research questions. By exploring the socio-economic implications of Digital Twin technology, it sets the stage for the specific investigation into human capital and organizational readiness.

Chapter 2. ***Systematic Literature Review (SLR):*** Provides a systematic analysis of the state-of-the-art literature. Through a PRISMA compliant Systematic Literature Review (SLR) based on Web of Science and Scopus data, it maps the current academic understanding of the skills required for Digital Twins, identifying the "Context Gap" that justifies the subsequent empirical work.

Chapter 3 - ***Empirical Analysis:*** Illustrates the qualitative investigation conducted through a Critical Case Study of IBM. Adopting a data triangulation approach (Elite Interview and Documentary Analysis), this chapter explores how the strategic vision of the Digital Twin (matured in Silicon Valley) translates into specific competence requirements and how these interact with different cultural mindsets.

Chapter 4 - ***Discussion and Conclusions:*** Discusses the main findings, integrating theoretical insights with empirical evidence. It outlines the theoretical, managerial, and ethical implications, highlighting the need for a human-centric approach to technology (Liu et al., 2022; Signorini & Pomè, 2025). Finally, it acknowledges the limitations of the study and proposes a future research agenda aligned with the long-term goals of the Digital Society & Smart Cities Spoke.

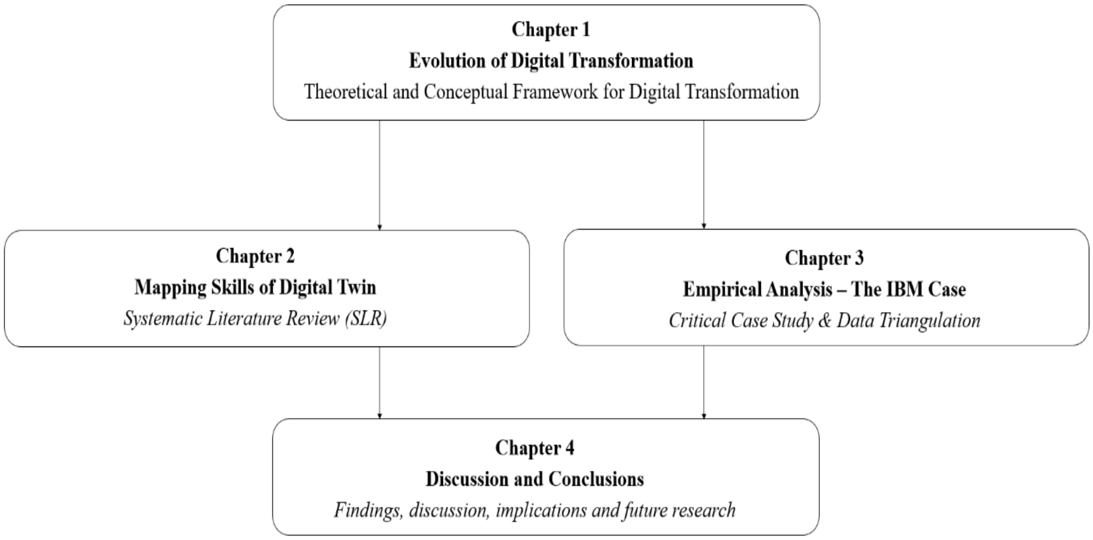

Fig.1: Structure of the thesis. Source: Author’s elaboration

Chapter 1. Theoretical and Conceptual Framework for Digital Transformation

Preface

Digital Transformation (DT) constitutes the most significant evolutionary and revolutionary phenomenon of the contemporary era, representing not a mere technical adoption but a pervasive strategic change process that integrates advanced digital technologies into all aspects of business, government, and society (Hanelt et al., 2021; Haug et al., 2024; Nadkarni & Prügl, 2021). Over the past decade, the concept of DT has gained unprecedented prominence as organizations attempt to navigate turbulent environments and radically innovate their business models to create new forms of value (Nadkarni & Prügl, 2021; Verhoef et al., 2021). However, a significant discrepancy persists between academic conceptualizations and practical understanding; while business decision-makers often label various technology initiatives as "digital transformation" based on the mere occurrence of popular buzzwords, high-caliber academic literature posits that true transformation requires a fundamental reinvention of organizational identity and value propositions (Riedl et al., 2024; Wessel et al., 2021). To provide conceptual clarity, it is necessary to rigorously distinguish digitization, the encoding of analog information into digital formats and digitalization, the use of IT to optimize existing business processes, from true digital transformation, which implies a holistic, company-wide change leading to the emergence of a new organizational identity (Verhoef et al., 2021; Wessel et al., 2021).

The objective of this chapter is to establish a robust theoretical and conceptual foundation for understanding the scope of DT through a multi-layered analysis that connects macro-level digital ecosystems, meso-level organizational structures and culture, and micro-level individual behaviors and perceptions (Plekhanov et al., 2023). This interpretative approach explains how the convergence of enabling technologies, such as Artificial Intelligence (AI), the Internet of Things (IoT), and High-Performance Computing (HPC), does not operate in a vacuum but serves as a critical accelerator for innovation cycles and organizational agility (Almeida & Okon, 2025; Hu et al., 2021). The treatment concludes by introducing the Digital Twin paradigm as the advanced synthesis of this technological convergence, providing a dynamic virtual replica of physical systems and a conceptual bridge toward the systematic literature review that follows (Hu et al., 2021; Tao et al., 2019).

1.1 Evolution and Definitions of Digital Transformation

The conceptual trajectory of Digital Transformation (DT) reflects a profound transition from simplistic technological adoption to an encompassing strategic metamorphosis that reshapes the organization at macro, meso, and micro levels (Hanelt et al., 2021; Plekhanov et al., 2023; Riedl et al., 2024). While the term has become ubiquitous in both managerial practice and academic discourse, its meaning has shifted from a focus on IT implementation toward a more holistic appreciation of organizational reinvention (Mergel et al., 2019; Nadkarni & Prügl, 2021). To achieve conceptual rigor, it is essential to distinguish between the incremental phases of digitization, defined as the technical conversion of analog information into digital formats and digitalization, which involves the use of IT to optimize or alter existing business processes, from the radical paradigm of true digital transformation (Verhoef et al., 2021; Wessel et al., 2021). At the meso-level, digital transformation is interpreted as the most pervasive phase of change, characterized by a company-wide evolution that leads to the development of entirely new business models and the emergence of a new organizational identity (Vial, 2021; Wessel et al., 2021). Unlike previous waves of IT-enabled organizational transformation (ITOT) that merely supported an existing identity, DT leverages digital technologies to fundamentally (re)define an organization’s value proposition and its very raison d’être (Wessel et al., 2021).

The macro-level evolution of DT is driven by the maturing of a technological constellation including Artificial Intelligence (AI), the Internet of Things (IoT), and High-Performance Computing (HPC), which have collectively reached a state of "digital ecodynamics" (Almeida & Okon, 2025; Hanelt et al., 2021). These technologies differ from traditional enterprise systems due to their generative, malleable, and combinatorial properties, which allow them to transcend firm boundaries and catalyze shifts in entire industry structures and digital business ecosystems (Hanelt et al., 2021). Consequently, digital transformation is seen not as a static achievement with a defined end-state, but as a continuous journey or a "constant unfreezing" of the organization, punctuated by episodic technological bursts that require firms to co-evolve with their turbulent environments (Hanelt et al., 2021; Mergel et al., 2019). This interpretative perspective explains why DT is often described as disruptive: it necessitates a strategic shift from linear value chains toward distributed value networks where value is co-created with users and ecosystem partners (Hanelt et al., 2021; Nadkarni & Prügl, 2021).

At the micro-level, the process of defining DT reveals a significant discrepancy between academic rigor and practical perception. A survey of business decision-makers indicates that practitioners often label digitalization projects as "digital transformation" based on the mere occurrence of technological buzzwords rather than the actual magnitude of organizational change or innovation performance (Riedl et al., 2024).

The term digital transformation has become ubiquitous in both scholarly discourse and managerial practice, yet its definition has not always been consistent. In its early usage, digital transformation was often associated simply with the adoption of digital technology in an organization. Over time, however, researchers have come to distinguish digital transformation from related concepts such as digitization and digitalization. Digitization refers to the conversion of analog information into digital form (for example, scanning paper documents into electronic files). Digitalization, on the other hand, denotes the use of digital technologies to enhance or streamline existing processes – for instance, implementing IT systems to automate workflows or improve communication. Digital transformation, in contrast, goes beyond mere process improvement or IT enablement; it implies a holistic and fundamental change to how an organization operates, delivers value, and even defines its business model (Mergel et al., 2019). In other words, digital transformation encompasses not only the deployment of cutting-edge technologies but also the reshaping of products, services, organizational structures, and cultural norms on an enterprise-wide scale (Mergel et al., 2019; Riedl et al., 2024).

Scholars note that digital transformation is evolutionary in nature, building on decades of technological innovation and organizational change research, yet also revolutionary in its scope and impact. Early waves of IT-driven change, such as the advent of personal computing in the 1980s or the rise of the internet in the 1990s, laid the groundwork for today's transformations but did not necessarily entail the deep organizational reinvention characteristic of current digital transformation efforts. It is only in the past decade that we observe an accelerated convergence of multiple technologies – from cloud computing to data analytics and artificial intelligence – reaching a level of maturity that enables transformation at scale. As a result, academic discussions around what exactly constitutes digital transformation have intensified. A recent survey of business decision-makers highlighted that there is still ambiguity: practitioners often label various technology initiatives as "digital transformation" based on buzzwords rather than on the magnitude of change achieved (Riedl et al., 2024). This finding underscores a gap between academic conceptualizations of DT and its understanding in practice. High-caliber academic literature generally posits that true digital transformation involves a significant degree of organizational change and innovation, not just the introduction of new IT tools (Riedl et al., 2024). Yet, many practitioners tend to use the term broadly, sometimes applying it to any novel digital project even if it does not fundamentally alter structures or strategy.

Given this inconsistency, numerous scholars have proposed definitions to pin down the essence of digital transformation. While phrasing varies, most academic definitions converge on several key themes. First, digital transformation is described as a process or journey – a sequence of evolutionary steps by which an entity (a firm, public organization, or even society at large) leverages digital technologies to achieve significant improvements or innovations in its operations and value proposition (Hanelt et al., 2021). Second, it is generally emphasized that these changes are strategic and holistic in nature. Rather than isolated technology upgrades, DT involves integrating technology into every facet of the organization, often accompanied by changes in organizational structure, culture, and human capabilities (Mergel et al., 2019). Third, digital transformation is linked with the notion of value creation – it enables new forms of value for customers, stakeholders, or society, whether through enhanced efficiency, new products and services, or improved decision-making driven by data (Romero, 2025; Malik et al., 2025). Finally, scholars distinguish digital transformation from prior IT-enabled change by the pace and scope of change: DT tends to be faster and more all-encompassing, frequently described as disruptive in that it can upend traditional business models and competitive dynamics.

It is worth noting that the academic discourse on digital transformation spans multiple disciplines – from information systems and management to public administration and economics. As a result, perspectives can differ on what aspects are emphasized. For example, in the public sector, digital transformation might be defined with a focus on improving service delivery, transparency, and citizen engagement through digital means (Mergel et al., 2019). In the private sector, definitions often highlight market competitiveness, customer experience, and innovation of revenue models (Nadkarni & Prügl, 2021). Despite these variances, a unifying understanding is emerging that digital transformation is not primarily about technology per se but about leveraging technology as a catalyst for deep organizational and strategic change. As one set of authors succinctly put it, digital transformation can be seen as a holistic process to radically change an entity's products, services, and internal culture through the use of digital technologies (Mergel et al., 2019). This holistic nature is what differentiates true transformation from simpler digital modernization efforts.

Recent literature reviews have documented the surge in research on digital transformation and the diverse angles from which it has been studied. For instance, Hanelt et al. (2021) conducted a systematic review of digital transformation literature and found that researchers have examined the phenomenon at multiple levels (individual, organizational, industry) and through various theoretical lenses (e.g., dynamic capabilities, sociotechnical change, innovation management). The proliferation of studies, while enriching the field, also contributes to a profusion of definitions and conceptual frameworks. It should be noted that the generic use of the term "digital transformation" as a catch-all term for many digital-related changes risks obscuring theoretical clarity. In response, efforts are being made to refine the conceptual boundaries of DT. For example, Wessel et al. (2021) argue that clarifying what is not digital transformation (i.e., distinguishing it from routine IT upgrades or smaller-scale digitalization initiatives) is just as important as explaining what it is. Such scholarship stresses that digital transformation typically entails a transformative vision, endorsed by top management, to reinvent the business in light of digital possibilities – something far more profound than adopting a single new software tool.

In summary, the evolution of digital transformation as a concept reflects a journey from technology-driven jargon to a more nuanced appreciation of organizational change and innovation. The ambiguity in early usage is gradually giving way to a consensus that DT denotes a strategy-driven, systemic shift enabled by digital technologies (Riedl et al., 2024). Still, challenges remain in practice: organizations sometimes struggle to translate this concept into action, and the term continues to be used in heterogeneous ways. The next sections of this chapter will build on this definitional foundation by exploring the technological forces that make digital transformation possible and subsequently, the implications of transformation for organizations and the broader socio-economic context.

1.2 Enabling Technologies of Digital Transformation

Digital transformation is underpinned by a constellation of powerful enabling technologies that have matured in recent years. These technologies provide the tools and infrastructure that allow organizations to radically redesign processes and create new value propositions. Among the most critical enablers frequently cited in literature are Artificial Intelligence (AI), the Internet of Things (IoT), Machine Learning (ML), High-Performance Computing (HPC), and Big Data Analytics. Each of these plays a distinct role in driving digital transformation, yet they are highly interrelated, often converging in practice to produce transformative outcomes. Below, we outline each of these key technologies and their relevance to digital transformation.

1.2.1 Artificial Intelligence (AI)

AI encompasses a broad range of computing techniques that enable machines to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and language translation. In the context of digital transformation, AI is a game-changer that can automate complex decision processes and enable data-driven insights at scale. For example, AI algorithms can optimize supply chains in real time, personalize customer interactions through recommendation systems, and even identify patterns in data that humans would miss. The infusion of AI into organizational processes allows for unprecedented levels of efficiency and innovation – from intelligent chatbots providing customer service, to AI-driven analytics that guide strategic decisions. A key aspect of AI's transformative power lies in its ability to learn and improve over time (especially via machine learning, discussed below), which means organizations can continually refine operations and offerings. By leveraging AI, companies can not only streamline existing operations but also create new capabilities and business models (for instance, offering predictive maintenance services enabled by AI predictions). In short, AI acts as a catalyst for transformation by augmenting or substituting human intelligence in various functions, thus significantly boosting an organization's agility and innovative capacity. As digital transformation accelerates, human–AI collaboration is also emerging as an important theme – rather than replacing humans, successful transformation often involves using AI to complement human skills.

1.2.2 Internet of Things (IoT)

The Internet of Things refers to the network of physical objects ("things") embedded with sensors, software, and connectivity, allowing them to collect and exchange data over the Internet. IoT essentially bridges the physical and digital realms by turning everyday objects and industrial equipment into data-generating smart devices. In a digitally transforming organization, IoT devices can provide real-time data streams about operations, environments, and product usage. For example, IoT sensors in a factory can monitor machine performance and trigger maintenance before a breakdown occurs, or smart products can communicate usage patterns back to the manufacturer to inform product development.

The data harvested through IoT is a vital resource for transformation: it enables companies to gain granular visibility into processes and customer experiences that was previously impossible. This, in turn, supports data-driven decision-making and new services. Entire industries have been reshaped by IoT – for instance, smart manufacturing (Industry 4.0) leverages IoT for interconnected production systems, and smart cities deploy IoT to manage infrastructure and services in real time. The transformative impact of IoT comes from its ability to enable continuous monitoring, automation, and optimization across a distributed network of assets. When combined with AI and analytics, IoT data can lead to predictive insights and autonomous decision loops (such as self-regulating systems in energy or logistics). In summary, IoT is a foundational technology of digital transformation that extends digital intelligence into the physical world, creating cyber-physical systems that drive efficiency and innovation.

1.2.3 Machine Learning (ML)

Machine Learning is a subset of AI that focuses on algorithms and statistical models enabling systems to learn from data and improve their performance without being explicitly programmed. Given its emphasis on learning from examples, ML is particularly powerful for identifying complex patterns, correlations, or anomalies in large datasets. In the era of big data, ML has become indispensable for making sense of the vast volumes of information that organizations collect. Within digital transformation initiatives, ML techniques (such as neural networks, decision trees, and clustering algorithms) are used for tasks ranging from customer segmentation and demand forecasting to image recognition and natural language processing. One hallmark of machine learning in transformation is predictive analytics – organizations can forecast trends or user behaviors and proactively adapt strategies accordingly. For instance, retailers employ ML to predict inventory needs and personalize marketing, while healthcare providers use ML on patient data to predict health risks and improve diagnostics. By enabling data-driven predictions and automated decisions, ML accelerates the shift from reactive to proactive operations in organizations. It also underpins advanced AI applications like autonomous vehicles or intelligent virtual assistants. It should be noted that machine learning often works in tandem with big data and HPC: large datasets ("big data") provide the fuel for learning, and high-performance computing provides the processing power to train complex ML models quickly. In sum, ML contributes to digital transformation by empowering computers to adapt and optimize processes on the fly, thus enhancing innovation and responsiveness in a way that static software or human analysis alone could not achieve.

1.2.4 High-Performance Computing (HPC)

High-Performance Computing refers to the practice of aggregating computing power in a way that delivers far higher performance than one could get out of a typical desktop computer or server. HPC often involves the use of supercomputers or distributed computing clusters to process massive amounts of data or perform complex simulations at very high speeds. In the context of digital transformation, HPC is an essential enabler behind the scenes: it makes it feasible to tackle computationally intensive tasks that drive innovation. For example, training a deep learning AI model on millions of data points, running elaborate simulations of market scenarios or engineering designs, or analyzing big data in real time all require substantial computing horsepower. HPC provides the infrastructure that allows AI, ML, and big data analytics to reach their full potential in transforming an organization. Sectors like finance, pharmaceuticals, and aerospace rely on HPC to perform advanced analytics and modeling that lead to breakthrough products and solutions (such as drug discovery or aerodynamic optimizations), illustrating how HPC-fueled computations can translate into competitive advantage. Moreover, as digital twins (discussed later in this chapter) become more prevalent, HPC will be pivotal in running the complex physics-based simulations that digital twins entail. In a broader sense, HPC accelerates the *innovation cycle*: analyses that once took days or weeks can be completed in hours or minutes, allowing decision-makers to iterate faster and explore more alternatives. By enabling organizations to process and analyze data at unprecedented scale and speed, HPC pushes the boundaries of what transformations are technically achievable.

1.2.5 Big Data Analytics

The term *Big Data* refers to extremely large and complex datasets – so vast that traditional data processing software is inadequate to handle them. Big data is often characterized by the "4 Vs": Volume (sheer amount of data), Variety (different forms of data, from text to images to sensor readings), Velocity (the speed at which data is generated and must be processed), and Veracity (the uncertainty or quality of the data). The rise of big data is both a driver and a byproduct of digital transformation: as organizations digitize more activities, they generate more data, and in turn the availability of data allows for new insights and services. Big Data Analytics refers to the methods and tools used to analyze these massive datasets to uncover hidden patterns, correlations, and insights. In digital transformation initiatives, big data analytics is the linchpin of *evidence-based decision making*. It empowers organizations to move from decisions based on intuition or limited information to decisions grounded in comprehensive, real-time data analysis. For example, analyzing large datasets on customer behavior can reveal micro-segments and personalization opportunities; mining operational data can pinpoint inefficiencies in a complex global supply chain; and aggregating data from connected devices can enable predictive maintenance across an entire fleet of machines. Techniques such as distributed computing (e.g., Hadoop, Spark), data mining, and visualization tools are employed to make sense of big data. The insights derived can lead directly to new business strategies or optimizations that were previously unattainable. Furthermore, big data analytics often works hand-in-hand with the other technologies mentioned: AI and ML are used to analyze big data; IoT is a significant source of big data; and HPC provides the computational muscle to perform analytics. In essence, big data analytics provides the intelligence in digital transformation – converting raw data into actionable knowledge and competitive advantage.

It is important to recognize that these enabling technologies are interconnected and mutually reinforcing. In practice, transformative digital solutions typically combine several of these building blocks. For instance, an advanced smart factory might use IoT sensors to collect operational data, transmit it via cloud networks to a big data platform, where machine learning algorithms analyze it in real-time (leveraging HPC for processing power), and then use AI-driven robotic systems to adjust processes on the fly. Similarly, a digital transformation in customer experience might integrate big data from social media (captured and processed at high velocity), apply AI/ML to glean sentiment and preferences, and deliver personalized services through IoT-connected devices or applications. The synergy of AI, IoT, ML, HPC, and big data creates a technology ecosystem that propels organizations toward new frontiers of performance and innovation. As these technologies continue to mature, their cost barriers decrease and accessibility improves (e.g., via cloud computing services), thus accelerating the pace at which even traditional industries can embark on digital transformation.

In summary, the enabling technologies of digital transformation provide the capabilities to digitize processes, analyze and learn from data, automate complex tasks, and connect myriad components of operations in intelligent ways. They serve as the engine powering the transformation journey. However, technology alone does not guarantee successful transformation. Equally important are the organizational and human factors that determine how effectively these tools are deployed. Therefore, in the next section, we shift focus to the organizational and socio-economic implications of digital transformation – essentially, how these technologies intersect with people, structures, and society, and what changes and challenges arise as a result.

1.3 Organizational and Socio-Economic Implications of Digital Transformation

Implementing digital transformation is not merely a technical endeavor; it fundamentally impacts organizations' structures, cultures, and external environments. As companies integrate AI, IoT, big data, and other digital tools into their core strategies, they encounter profound organizational changes and a ripple of effects that extend into the socio-economic sphere. In this section, we analyze the implications of digital transformation on organizations internally, as well as the broader socio-economic implications at industry and societal levels.

1.3.1 Implications for Organizations - Strategic and Structural Changes

Digital transformation drives organizations to revisit their strategy and business models. Traditional strategies focused on incremental improvement are often supplanted by visions of disruptive innovation and new value creation through digital platforms, ecosystems, or services. For example, manufacturers are moving from pure product sales to digital service models (such as offering IoT-enabled preventive maintenance as a service), requiring shifts in strategy and revenue models. Malik et al. (2025) highlight that embracing digital transformation often goes hand-in-hand with business model innovation, as firms discover new ways to deliver value by leveraging digital capabilities. This strategic pivot frequently necessitates structural changes within the organization: silos are broken down in favor of more integrated, agile structures; new units or teams may be established to spearhead digital initiatives (such as a dedicated digital innovation hub); and roles/responsibilities are redefined. A notable development in many companies has been the creation of leadership roles like the Chief Digital Officer (CDO), signifying a structural commitment to driving the transformation from the top. These structural changes aim to enhance an organization's ability to respond quickly to technological opportunities and market changes, reflecting a shift towards more fluid and dynamic organizational designs.

Leadership and Culture: Perhaps the most critical factor in organizational transformation is the human element – leadership and organizational culture. Leadership plays a pivotal role in steering digital transformation. Effective digital transformation requires visionary leaders who not only understand the potential of new technologies but can also articulate a compelling transformation roadmap and motivate the organization to follow it. Research indicates that leaders must champion the change, allocate resources, and overcome inertia (Malik et al., 2025). This idea of digital leadership involves blending technological savvy with change management skills, ensuring that the workforce buys into the transformation vision. In parallel, the organizational culture must evolve to support transformation.

Digital transformation often flourishes in cultures that embrace innovation, experimentation, and continuous learning. Organizations may need to shift from rigid, risk-averse cultures to more agile and entrepreneurial cultures that tolerate failure as a learning process and encourage creative problem-solving. Mergel et al. (2019) note that true digital transformation "includes the whole organization," meaning cultural change is not peripheral but central – employees at all levels need to adopt a mindset receptive to new ways of working and collaborating (Mergel et al., 2019). Many companies undergoing DT engage in cultural change programs, such as training in digital mindsets, establishing innovation labs to exemplify new behaviors, or updating their core values to emphasize adaptability and customer-centricity. A change in culture is also needed to break down organizational silos; digital initiatives often require cross-functional collaboration (e.g., IT working closely with marketing, operations, etc.), which can be a departure from traditional compartmentalized working styles.

Workforce and Skills: The workforce implications of digital transformation are considerable. As routine tasks become automated by AI and processes are optimized through data, the nature of many jobs changes. Some roles are diminished or eliminated, while new roles emerge. This necessitates a strong focus on reskilling and upskilling employees. Organizations must invest in developing digital skills among their staff – from basic data literacy to advanced analytics and programming skills for those in technical roles. Moreover, so-called "soft" skills like adaptability, complex problem-solving, and the ability to work alongside intelligent machines are increasingly valued. Furthermore, find that providing ICT training and development opportunities to employees is positively correlated with a company's digital transformation success and performance outcomes. Involving employees in the transformation process, through participation and training, not only builds the necessary skills but also helps mitigate resistance to change. Indeed, employee resistance can be a significant barrier: introducing new technologies can lead to uncertainty, fear of job loss, or simply discomfort with new routines. Such resistance can manifest as low adoption of new systems, active pushback against process changes, or a decline in morale. Overcoming this requires transparent communication about the transformation's purpose, how it benefits both the organization and employees, and reassurance about support during the transition. It also involves demonstrating quick wins that can build employee confidence in the changes.

Change Management and Approaches: Given the complexities above, disciplined change management is essential. Organizations often adopt structured change management frameworks to guide their digital transformation journey, addressing people, process, and technology dimensions in tandem. An interesting discussion in the literature revolves around whether transformation should be driven in a top-down versus bottom-up manner. A top-down approach implies that top management defines the digital strategy and pushes it through the hierarchy, ensuring alignment and resource allocation from the top. In contrast, a bottom-up approach encourages innovation and initiative-taking at lower levels (such as empowering business units or grassroots teams to experiment with new digital solutions, which can then be scaled up if successful). Each approach has advantages: top-down can ensure coherent vision and eliminate fragmentation, while bottom-up can harness on-the-ground creativity and achieve greater buy-in from employees. Marienfeldt et al. (2025) explore this dynamic and suggest that many organizations find a hybrid approach optimal – leadership provides direction and an overarching framework, but also creates space for bottom-up innovation and feedback. This balance helps to avoid the pitfalls of exclusively top-driven programs (which might alienate employees or miss local insights) and purely bottom-driven efforts (which might lack strategic cohesion).

Furthermore, digital transformation often requires overcoming internal barriers such as legacy systems and processes. Established organizations may have significant technical debt – outdated IT systems or data silos – that hinder agility. Transforming such organizations might involve significant IT architecture overhauls (e.g., moving to cloud platforms, rebuilding data infrastructure) which can be resource-intensive and risky. There are also paradoxes and tensions that managers must navigate. For instance, Qin (2025) discusses the "digital transformation paradoxes" – organizations must continue to exploit their existing competencies and revenue streams (to stay afloat in the short term) while also exploring radically new digital innovations that could cannibalize or change those very revenue streams. Balancing the present and future is inherently challenging: invest too much in experimental digital projects and core operations might suffer; invest too little and the organization risks obsolescence. Such paradoxes require careful management – often involving phased strategies, pilot projects, and iterative scaling of what works.

The organizational implications can ultimately be measured in terms of performance and competitive position. Successful digital transformation can lead to dramatically improved operational efficiency, higher customer satisfaction, and new growth opportunities, thereby strengthening an organization's competitiveness. However, transformation is also fraught with risk – studies frequently cite that a large proportion of digital transformation initiatives fail to meet their objectives, often due to non-technical factors like lack of leadership, poor change management, or cultural misalignment. Therefore, organizations must approach digital transformation not just as a technology upgrade, but as a comprehensive organizational change program. This entails aligning strategy, cultivating supportive leadership and culture, investing in people, and maintaining flexibility to adjust course as learning occurs. Finally organizations that adopt innovative strategies to overcome barriers (such as clear communication, stakeholder engagement, and phased implementation) are more likely to succeed in their transformation efforts.

1.3.2 Broader Socio-Economic Implications

Beyond the confines of individual organizations, digital transformation is reshaping industries, economies, and society at large. Its impacts are evident in how industries are structured, how work is organized, and how value is created and distributed across the economy. Understanding these socio-economic implications is crucial, as it frames the context in which organizations operate and points to external factors that can influence the success of transformation initiatives.

Industry Disruption and Ecosystems: At an industry level, digital transformation tends to blur traditional boundaries and foster the rise of new digital ecosystems. Companies are no longer competing just as single entities but as part of broader platforms and networks. For example, the transformation of the transportation industry via digital platforms (rideshare apps, etc.) has brought in new players from outside the traditional auto sector, fundamentally altering competitive dynamics. Industries such as media, retail, and finance have been dramatically disrupted by digital-native entrants leveraging data and technology (think of the impact of streaming services on entertainment, e-commerce on retail, or fintech on banking). The emergence of platform-centric business models allows companies to scale rapidly and dominate markets by creating winner-takes-most scenarios. This raises important socio-economic questions about market concentration and competition policy. Policy-makers and regulators are increasingly grappling with how to ensure fair competition and consumer protection in a landscape where digital giants can leverage network effects to gain significant power.

Economic Growth and Productivity: On the positive side, digital transformation is often touted as a driver of economic growth and productivity improvements. The adoption of digital technologies has the potential to significantly increase productivity by automating routine tasks, optimizing resource use, and enabling innovation. Sectors that effectively integrate digital tools often see output gains and new value creation. At a macroeconomic level, investments in digital infrastructure and capabilities can contribute to GDP growth. Governments around the world acknowledge this potential and have launched digitalization initiatives and Industry 4.0 programs to boost competitiveness. For instance, the European Union and many national governments have agendas for digital transformation of SMEs (small and medium enterprises) to ensure that even smaller players can contribute to and benefit from a digital economy. Countries that rapidly embrace digital transformation across industries might achieve competitive advantages in the global market, as seen in the dominance of certain countries in the digital platform economy. However, these gains are not automatic or evenly distributed; they depend on factors like the education level of the workforce, the regulatory environment, and infrastructure quality.

Labor Market and Employment: One of the most debated socio-economic implications of digital transformation concerns the future of work. As advanced technologies – particularly AI and robotics – become capable of tasks once performed by humans, there is potential for significant job displacement in certain areas. Routine and repetitive jobs (whether cognitive or manual) are the most vulnerable to automation. This has raised concerns about technological unemployment and widening inequality if displaced workers cannot easily transition to new roles. On the other hand, digital transformation also creates new jobs and categories of work. There is growing demand for roles such as data scientists, AI specialists, cybersecurity experts, and digital product managers – positions that were rare or non-existent a couple of decades ago. Moreover, the efficiency gains from technology can lower costs, potentially leading to expansion and job creation in other areas (for instance, e-commerce has created vast logistics and delivery networks employing millions). The net impact of digital transformation on employment is complex: some studies predict more jobs will be transformed than lost outright, with many roles changing in their skill requirements rather than disappearing completely. What is clear is that skills mismatches are a critical challenge – the workforce needs to evolve in tandem with technological change. This underscores the importance of education and continuous learning at a societal level. Lifelong learning initiatives, vocational training in digital skills, and partnerships between industry and educational institutions become vital to ensure that workers have opportunities to reskill into

emerging roles. From a policy perspective, supporting workers through this transition (via training programs, social safety nets, etc.) is a key consideration to mitigate negative impacts.
Social Equity and the Digital Divide: Digital transformation has the potential to either bridge or widen social divides. Access to digital technologies and the internet has become a prerequisite for participating fully in the modern economy. There is a risk of a digital divide where individuals, communities, or even whole regions that lack access to technology or the skills to use it effectively get left behind. This divide can be urban versus rural, or along income and education lines, and can exacerbate existing inequalities. Socio-economic benefits of digital transformation – such as better services, new job opportunities, or remote work flexibility – might accrue primarily to those who are digitally equipped, while others might see few benefits or even be negatively affected (e.g., if their jobs are automated and they lack alternatives). Addressing this requires conscious effort: investments in digital infrastructure (like broadband access in underserved areas), inclusion programs to improve digital literacy among disadvantaged groups, and designing technologies that are accessible and affordable. There is also a cultural aspect – ensuring that digital services (like e-government portals or online banking) are user-friendly and available in multiple languages can influence how broadly the benefits are shared.

Public Sector and Service Delivery: On a societal level, digital transformation significantly affects how public services are delivered and how citizens interact with government and community services. The concept of digital government or e-government has gained momentum, where public administrations use digital tools to provide services more efficiently and transparently. As Mergel et al. (2019) indicate in the public sector context, citizen expectations have risen for real-time, high-quality digital services from government akin to those they experience from private-sector digital platforms. This pressure is driving transformations in areas such as healthcare (telemedicine, electronic health records), education (online learning platforms), and smart city initiatives (leveraging sensors and data to improve urban living, from traffic management to public safety). When successfully implemented, these transformations can enhance citizen satisfaction, increase transparency (e.g., open data initiatives that allow citizens insight into government operations), and improve outcomes (such as quicker response times for public services). However, they also require careful management of privacy, security, and ethics. The more data that is collected and algorithmically processed in societal functions, the more concerns arise around data privacy and the potential for misuse or bias. Ensuring robust cybersecurity and ethical guidelines for AI usage in sensitive areas (like criminal justice or social services) is a critical societal implication that accompanies the march of digital transformation.

Sustainable Development: An emerging discourse links digital transformation with sustainable development goals. On one side, digital technologies can be instrumental in addressing environmental and sustainability challenges. For example, smart grids and IoT-based energy management can significantly reduce resource consumption and support a transition to renewable energy, aligning with climate change mitigation efforts. Similarly, digital platforms can enable the sharing economy, which some argue makes more efficient use of resources (though the evidence on net environmental impact is mixed). On the other side, there are legitimate concerns: the technology sector's own carbon footprint (such as the energy usage of data centers and blockchain mining) is non-trivial, and e-waste from rapid device obsolescence is a growing environmental issue. There is a push for green IT and ensuring that digital transformation strategies incorporate sustainability as a core principle rather than an afterthought. In socio-economic terms, this means aligning economic incentives with sustainable practices, for instance by leveraging AI to optimize supply chains for lower emissions or using big data to track and improve environmental impact metrics.

In summary, the socio-economic landscape is being redefined by digital transformation. While it promises enhanced economic productivity, better services, and solutions to complex problems, it also poses challenges in terms of labor displacement, inequality, and ensuring that the benefits are widely shared. Societies must adapt by updating education systems, regulatory frameworks, and social contracts to fit a digitally transformed world. Businesses, for their part, do not operate in a vacuum – their transformation trajectories will be influenced by these external factors. An organization's success with digital transformation can depend on the maturity of its surrounding digital ecosystem, the regulatory environment (e.g., data protection laws), and the readiness of its customer base or supply chain to engage digitally. Crucially, these external factors vary significantly across different geographical and cultural contexts. The reception and speed of digital transformation are often contingent upon the specific “innovation ecosystem” in which a firm operates. For instance, highly dynamic environments like Silicon Valley tend to foster a risk-taking mindset and rapid adoption cycles, whereas more traditional or regulated European markets may exhibit different adoption patterns driven by institutional constraints and cultural aversion to uncertainty. This divergence suggests that the implementation of identical technologies, such as the Digital Twin, can yield vastly different organizational outcomes depending on the national and cultural backdrop. Therefore, savvy leaders track these broader implications as part of their strategic planning, engaging with policy-makers and community stakeholders to foster an environment that supports mutually beneficial digital advancement.

1.4 Introducing the Digital Twin: A Bridge to the Next Chapter

As digital transformation reaches maturity, it gives rise to advanced paradigms that epitomize the seamless integration of physical and digital realms, most notably the Digital Twin (DT). A Digital Twin is defined as a high-fidelity virtual representation equivalent to a physical product or system, characterized by a dynamic, real-time link that allows the virtual model to mirror the state and health of its physical counterpart throughout its entire lifecycle (Grieves, 2014; Hu et al., 2021). While the conceptual roots of the "twin" can be traced back to NASA’s Apollo program in the 1970s, modern DT technology has evolved into a sophisticated five-dimensional model, comprising the physical entity, the virtual model, enabling services, twin data, and the connection layer, that provides the dynamics for how complex systems operate and evolve (Hu et al., 2021; Tao et al., 2017). Unlike static digital models, the DT functions as a powerful decision-support tool, enabling a proactive approach to management through predictive maintenance, performance optimization, and virtual verification (Hu et al., 2021; Tao et al., 2019).

The emergence of the Digital Twin represents the quintessence of technological convergence, acting as an orchestration layer where the sensory capacity of the Internet of Things (IoT), the analytical power of Big Data, and the predictive intelligence of Artificial Intelligence (AI) intersect (Mergel et al., 2024; Tao et al., 2019). By leveraging High-Performance Computing (HPC) for intensive physics-based simulations, organizations can perform "what-if" analyses and scenario planning with unprecedented fidelity, thereby reducing the costs and risks associated with physical experimentation (Almeida & Okon, 2025; Hu et al., 2021). For example, in wind engineering, a DT can process real-time sensor data to simulate environmental impacts, allowing operators to implement adaptive control strategies before a failure occurs (Hu et al., 2021; Tao et al., 2018d). This transition from reactive to predictive paradigms fundamentally alters organizational roles, shifting product development toward a twin-driven logic where prototypes are predominantly tested in a virtual space (Hu et al., 2021; Tao et al., 2019).

Despite its transformative potential, the adoption of DT technology introduces a higher order of managerial and technical complexity. The primary challenges currently hindering its proliferation include the difficulty of achieving high-fidelity modeling that goes beyond simple geometric consistency to include behavioral and rule-based accuracy, as well as the need for robust environmental coupling to reflect real-world interactions (Hu et al., 2021). Furthermore, the implementation of such convergent paradigms necessitates the development of digital trust, as stakeholders must be confident in the integrity and security of the data flows that govern physical assets (Strazzullo, 2024). A significant dichotomy remains in the academic discourse: while engineering literature has consolidated the technical specifications of the Digital Twin, management research has yet to fully bridge the gap regarding how organizations navigate the cultural and structural barriers to its adoption (Hu et al., 2021; Tao et al., 2019).

The introduction of the Digital Twin concept serves as a critical bridge to the subsequent chapter of this work. Having established the broader theoretical framework of digital transformation, from its enabling technologies to its structural paradoxes, the DT provides a focused case of transformation in action. It embodies the deep integration of data and physical systems that defines the current technological era. The next chapter will proceed with a systematic literature review focused specifically on the Digital Twin, analyzing how scholars define the concept, identifying observed benefits and challenges, and pinpointing the research gaps that remain at the intersection of technical excellence and strategic implementation.

Chapter 2. Systematic Literature Review

2.1 Introduction

The Digital Twin (DT) is ontologically defined as a high-fidelity virtual replica of a physical system, maintained in constant synchronization via real-time data flows (Bělohlav et al., 2024; Zhang et al., 2022). While its conceptual roots are embedded in NASA's aerospace monitoring programs for spacecraft flight behavior simulation (Maculotti et al., 2025), the formal theoretical formalization of the paradigm is attributed to Michael Grieves in 2003 within the Product Lifecycle Management (PLM) framework (Grieves, 2014; Lossie et al., 2025; Speicher et al., 2025). Over the last decade, DT has emerged as a catalytic element of digital transformation, acting as a bidirectional bridge between physical and cyber spaces through the integration of the Internet of Things (IoT), advanced simulation, and Artificial Intelligence (AI) (García et al., 2022; Zhao & Zhu, 2024).

The adoption of DT technology must be situated within the broader evolution of industrial revolutions, marking a critical transition from the Industry 4.0 model, centered on automation and system autonomy, toward the Industry 5.0 paradigm, which emphasizes sustainability, resilience, and human-centricity (Liu et al., 2022; Signorini & Pomè, 2025). In this evolving landscape, the DT ceases to be a mere technical artifact and transforms into a complex organizational platform that enables advanced decision-making capabilities (Liu et al., 2022; Perno et al., 2025). The literature highlights that the architecture of a DT is not uniform but varies based on the level of data integration: the foundational classification distinguishes between the *digital model* (lacking automatic data exchange), the *digital shadow* (characterized by unidirectional flow from physical to virtual), and the *digital twin* proper, defined by automatic bidirectional synchronization (Ebiloma & Aigbavboa, 2025; Lossie et al., 2025). This structure has been further refined into five-dimensional models comprising physical entities, virtual models, services, digital twin data, and the connection layer (Signorini & Pomè, 2025; Tao et al., 2019).

From a managerial and organizational perspective, the implementation of DTs redefines decision-making processes by introducing the capacity to conduct hypothetical "what-if" simulations (Ebiloma & Aigbavboa, 2025; Li et al., 2025). This approach allows for the evaluation of decisions in protected virtual environments, mitigating risks and optimizing performance metrics before physical execution (Nielsen & Tambo, 2025; Signorini & Pomè, 2025). The ability of the DT to "close the loop" between decision and performance transforms massive streams of sensor data into systemic cognitive capabilities (Li et al., 2025). However, the increase in operational complexity resulting from mass customization and digital convergence has made human oversight more indispensable than ever (Li et al., 2025; Nielsen & Tambo, 2025). Recent literature emphasizes a critical tension: while system autonomy grows, the need for specialized human competencies to interpret and govern such systems becomes the primary bottleneck for large-scale adoption (Li et al., 2025; Signorini & Pomè, 2025).

Despite market forecasts indicating an unprecedented expansionary trajectory, a significant skills gap persists that hinders the effective integration of DT into organizational models (Speicher et al., 2025; Sridharan & Kumar, 2024). The success of the Digital Twin does not depend exclusively on the maturity of hardware and software infrastructures, but on the availability of human capital endowed with an interdisciplinary analytical mindset capable of integrating engineering, data science, and domain knowledge (Nithyanandam et al., 2022; Speicher et al., 2025). The scientific debate reveals a lack of standardized metrics and methodologies to assess which human capabilities are necessary to make Digital Twin solutions effective. Despite the practical and strategic relevance of this skills gap, the academic literature on the topic remains fragmented. While studies focusing on the technical and architectural aspects of Digital Twins abound (e.g., communication protocols, modeling algorithms, network latency), there is a lack of research that systematically addresses the managerial, cognitive and soft skills required to govern this complexity in the era of Industry 5.0. In other words, there is still no integrated framework capable of guiding organizations in identifying and developing the profiles needed to transform technological potential into strategic and sustainable value.

In light of this gap, this chapter aims to systematically analyze the state of the art of the scientific literature on competencies for Digital Twins. The objective of this Systematic Literature Review (SLR) is twofold: on the one hand, to map the competencies, understood as knowledge, skills, and experience, essential for the implementation and adoption of the technology; on the other hand, to propose a structured synthesis that supports workforce development by aligning academic and corporate training with contemporary industrial needs. The chapter is structured as follows: Section 2.2 describes the research methodology adopted, illustrating the study selection process according to the PRISMA protocol; Section 2.3 discusses the results through an in-depth thematic analysis, classifying the identified competencies into technical, cognitive, soft and managerial dimensions; finally, the conclusions highlight the implications for human capital development in twin-enabled organizations.

2.2 Research Methodology

This Systematic Literature Review (SLR) was conducted with the aim of identifying, mapping, and synthesizing the competencies required for the effective adoption of Digital Twins in modern organizations. Unlike a traditional narrative review, which may be subject to selection bias, the adopted methodology follows a structured, transparent, and replicable approach.

Specifically, the research protocol complies with the international PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which represent the reference standard for ensuring scientific rigor in the selection and analysis of bibliographic sources (Page et al., 2021). The research process was structured into four sequential phases: (1) definition of the research strategy and sources; (2) definition of inclusion and exclusion criteria; (3) study selection and screening; and (4) data extraction and synthesis.

2.2.1 Research Strategy and Database Selection

The choice of the bibliographic database represents a critical step in ensuring the quality of the review. For this study, the investigation was conducted exclusively using the Web of Science (WoS) Core Collection and Scopus databases. The decision to limit the search to WoS and Scopus was intentional and guided by quality rather than quantity criteria. Web of

Science is widely recognized in the academic domain for its rigorous indexing processes and for its coverage of high–impact-factor journals in the fields of Management, Industrial Engineering, and Social Sciences. Given the objective of the thesis to analyze high-level strategic competencies rather than niche technical implementations, WoS and Scopus ensure the retrieval of validated, high-quality scientific literature, reducing the “noise” of predatory or marginal publications that may affect more generalist databases.

2.2.2 Construction of the Search Query

The search string was constructed through an iterative process aimed at capturing the intersection between the technological domain (Digital Twin) and the human capital domain (competencies/HR).

The final query used was as follows ("Digital Twin" OR "Digital Twins") AND ("Competenc*" OR "Skill*" OR "Human resource" OR "Training" OR "Workforce").

The Boolean logic adopted responds to specific research objectives. The first block ("Digital Twin"..) defines the technological scope, including both singular and plural forms to maximize retrieval. The second block ("Competenc*", "Skill*", "Human resource"…) uses the AND operator to restrict results exclusively to studies addressing the human factor. The use of truncation with the asterisk (*) allows the inclusion of lexical variants such as competence, competencies, competency, skills and skilled.

Semantic exclusions were also applied. The term “Capabilities” was deliberately avoided, as preliminary testing of the query revealed that it generated a high number of false positives, primarily referring to software functional capabilities (e.g., computational capabilities) rather than human skills. Its exclusion significantly improved the precision of the results.

2.2.3 Inclusion and Exclusion Criteria (Eligibility Criteria)

To ensure the timeliness and relevance of the results with respect to the Industry 5.0 paradigm, rigorous filters were applied both during the automated search phase and the manual screening phase. Table 1 summarizes the adopted criteria.

Table 1: Inclusion and Exclusion Criteria. Source: Author's elaboration

Criterion	**Inclusion (Keep)**	**Exclusion (Drop)**	**Rationale**
Time Frame	2021 – 2026	Publications prior to 2021	The concept of "Human-Centric Digital Twin" has predominantly emerged in the post-pandemic period. Earlier studies tend to adopt a purely technocratic perspective.
Document Type	Articles (Journal), Early Access	Review, Conference Proceedings, Book Chapters, Editorials	Only primary peer-reviewed research was considered in order to ensure the highest level of data depth and originality, excluding secondary syntheses.
Language	English	Other languages	English is the lingua franca of technological and managerial research.

Criterion	Inclusion (Keep)	Exclusion (Drop)	Rationale
Subject Areas	Management, Business, Industrial Engineering, Education, Social Sciences, Applied Psychology	Medicine, Agriculture, Physics, Chemistry, Telecommunications, Civil Engineering	The objective is to isolate transversal and organizational competencies.
Content Focus	Skill gaps, training, organizational roles, human–machine interaction, managerial adoption	Pure algorithms, sensor validation, network architectures, mathematical models without HR implications	Purely technical articles do not address the research question concerning human competencies

2.2.4 Selection Process (PRISMA Flow)

The application of the research strategy followed a funnel-based selection process, detailed in the PRISMA flow diagram (Figure 2). The initial search conducted on Web of Science and Scopus, applying the defined query and automated temporal and categorical filters, returned a total of 149 records. The metadata of the 149 records (Title, Abstract, Keywords) were exported and subjected to an initial manual screening. During this phase, each article was assessed for thematic relevance. A total of 94 records were excluded: first, duplicates were removed; second, studies that, despite containing the search keywords, addressed the topic from an exclusively computational perspective (e.g., mathematical optimization of processes) or were not relevant to the organizational context were discarded. At the end of the screening process, 55 articles were deemed fully consistent with the research objectives and included in the final dataset. These 55 studies constitute the empirical basis for the thematic analysis presented in the following section.

2.2.5 Data Analysis and Thematic Extraction

The 55 included articles were subjected to a qualitative content analysis. As no standardized taxonomy of competencies for Digital Twins currently exists, an inductive approach was adopted to categorize the competencies emerging from the literature.

Through an in-depth review of abstracts, discussion sections, and conclusions, the competencies cited by the authors were coded and grouped into four homogeneous macro-dimensions, which structure the presentation of results:

1. Technical Proficiency: Skills related to the direct use of technology and IT/OT integration.
2. Cognitive Skills: Mental capabilities related to data processing, analysis, and sense-making.
3. Soft and Relational Skills: Behavioral abilities required for collaboration in hybrid environments.
4. Managerial and Strategic Skills: Leadership, governance, and organizational change management capabilities.

This categorization provides the conceptual framework for the discussion of results in Section 2.3.

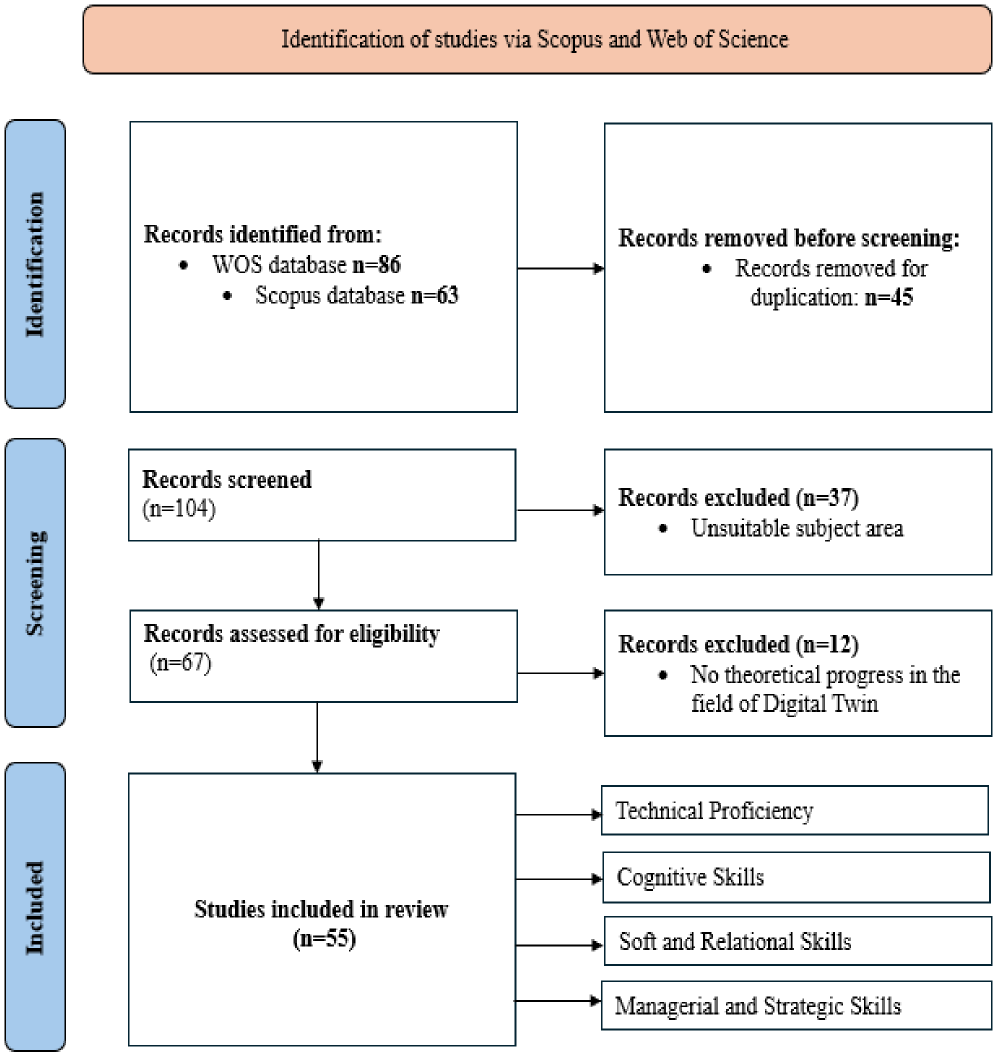

Fig. 2: PRISMA protocol. Source: Author's elaboration

2.3 Descriptive Analysis of the Sample

This section provides a quantitative and qualitative overview of the 55 selected studies, with the aim of highlighting their macro-level characteristics before delving into the thematic results. In particular, the chronological distribution of publications and the relevant application sectors are analyzed. This descriptive analysis serves to "give weight" to the data and to contextualize the current literature on human competencies in Digital Twins.

2.3.1 Temporal Distribution

The analysis of the temporal distribution confirms the strong topicality of the subject under investigation. As illustrated by the collected data, the number of publications addressing the skills gap in Digital Twins has shown an exponential increase starting in 2023. In particular, a significant peak is observed in the most recent two years: more than 70% of the studies considered were published in the 2024–2025 biennium. This sharp increase indicates that the academic debate on the competencies required for Digital Twins is currently in a phase of rapid expansion and remains far from saturation. After sporadic initial contributions in the 2021–2022 period, the volume of publications grew rapidly, with 12 articles published in 2024 and as many as 27 in 2025.

The body of research published prior to 2023 was predominantly focused on the technological validation of the Digital Twin concept, emphasizing prototypes and technical-engineering dimensions, such as Virtual Reality (VR) and Augmented Reality (AR) interfaces within Cyber-Physical Systems (CPS) architectures designed for shop-floor operations (Yun & Jun,2022). During the 2021–2022 biennium, scholarly investigation was primarily concerned with demonstrating the technical feasibility of Digital Twins and engineering experimental tools for operational training, such as virtual simulators for specific industrial tasks (García et al., 2022; Kumar et al., 2021).

Only recently has a significant paradigm shift occurred: alongside the consolidation of the Industry 5.0 paradigm, the scholarly emphasis has transitioned from pure technological efficiency to the organizational, managerial, and training-related implications of Digital Twins (Massaro et al., 2025). Recent literature now positions the technology as an essential component of Knowledge Management (KM) frameworks and human-centric decision-making systems, focusing on how these replicas can support the development of an interdisciplinary workforce (Li et al., 2025; Massaro et al., 2025).

Starting in 2023, the academic discourse has witnessed a significant paradigm shift toward a human-centric orientation and the development of workforce competencies, aligning with the core pillars of Industry 5.0: sustainability, resilience, and human centrality (Liu et al., 2022; Signorini & Pomè, 2025). This transition marks a departure from pure technological automation toward a co-evolution of data-driven intelligence and human-centered approaches (Li et al., 2025).

A prominent example is the work of Longo et al. (2023), who proposed a cognitive "prescriptive training" approach for the workforce of the future, effectively transitioning the training philosophy from "preparing for the unknown" to "training for what is exactly coming" by utilizing Digital Twin (DT) data to simulate specific upcoming non-routine tasks (Longo et al., 2023). Similarly, the recently developed Sim2Know framework by Li et al. (2025) emphasizes the design of human-centric knowledge systems that leverage DT-generated synthetic data to capture both explicit and implicit expert knowledge, thereby facilitating more natural human-machine interactions (Li et al., 2025).

These trends confirm that, although the Digital Twin concept originated in technical-engineering domains decades ago (Grieves, 2014), scholarly reflection on the associated human agency and cognitive skills has primarily intensified over the last two to three years (García et al., 2022; Nielsen & Tambo, 2025). The temporal trajectory of the literature reveals an initial phase of technological exploration, focused on technical feasibility and 3D visualization, followed by an increasing prioritization of the human factor (Akpan & Offodile, 2024; García et al., 2022). This signals the maturation of the field toward a comprehensive socio-technical perspective, where human expertise is recognized as a critical success factor for governing the variability and complexity of modern manufacturing lines (Longo et al., 2023; Nielsen & Tambo, 2025).

2.3.2 Distribution by Application Sector

Numerous contributions within the selected literature investigate how Digital Twins (DT) can simultaneously catalyze operational efficiency and provide robust support for human personnel in their professional routines (Li et al., 2025; Timperi et al., 2023). Specifically, Perno et al. (2025) evaluate the deployment of Augmented Reality (AR) architectures synchronized with Digital Twins for the instruction of production operators, highlighting significant advantages in real-time machine data visualization and the facilitation of "on-the-job" training (Perno et al., 2025). This technological integration effectively mitigates the necessity for operators to frequently access centralized control rooms, thereby streamlining decision-making processes directly at the physical equipment (Perno et al., 2025).

Congruently, other industrial-focused studies emphasize the role of DT in advancing maintenance training and integrating decision-support systems that empower technicians through enhanced situational awareness and predictive insights (Longo et al., 2023; Timperi et al., 2023). In summary, the manufacturing context remains the dominant domain of application in the literature, with a recurring emphasis on smart maintenance protocols, high-fidelity process simulations, and intuitive human–machine interfaces (HMI) designed to optimize the performance of shop-floor workers (Li et al., 2025; Liu et al., 2022; Perno et al., 2025).

A further significant group (approximately 25% of the total) originates from the Education sector, confirming that the need for new digital competencies also affects academic and training contexts. Several studies analyze the use of Digital Twins and immersive technologies as levers for innovating university teaching methods and training programs for future engineers. Within this cluster, attention is focused on bridging the educational gap between theory and practice, preparing students and recent graduates to face the challenges of Industry 4.0 and Industry 5.0.

Several studies analyze the use of Digital Twins (DT) and immersive technologies as levers for innovating university teaching methods and training programs for future engineers (Bělohlav et al., 2024; Omrany et al., 2025). Within this research cluster, attention is focused on bridging the educational gap between theory and practice, preparing students and recent graduates to face the challenges of Industry 4.0 and the emerging Industry 5.0 paradigm (Omrany et al., 2025). For example, Nithyanandam et al. (2022) propose redefining engineering curricula by introducing "digital literacy" and experiential learning pathways based on factory pilot-demonstrators, thereby developing competencies aligned with the needs of modern smart factories (Nithyanandam et al., 2022). Other contributions present virtual learning environments, such as those described by Darejeh et al. (2025), who explore the integrated use of Virtual Reality (VR) and Digital Twins in mechanical engineering laboratories to enhance the learning of complex manufacturing processes, specifically the hand lay-up process in composite fabrication (Darejeh et al., 2025). Similarly, studies addressing training in chemical and bioengineering through digital simulators, which serve as virtual replicas of actual production plants, allow students to gain knowledge in control, process optimization, and problem solving under nonstandard operating conditions (Bělohlav et al., 2024).

Furthermore, since 2023, analyses have increasingly explored the potential of the Metaverse as an integrated virtual-physical ecosystem for innovative blended education and training, utilizing 3D immersive technologies to overcome the engagement limitations of traditional 2D web-based platforms (Mitra, 2023; Chamola et al., 2025). These initiatives within the education sector confirm the urgency of updating training methods at both academic and professional levels to address the significant digital skills gap, which currently acts as a primary bottleneck for the large-scale adoption of digital transformation (Nithyanandam et al., 2022). In conclusion, the reviewed literature spans multiple application sectors, from manufacturing and construction to higher education, demonstrating the pervasive nature of the Digital Twin phenomenon. The need for new competencies thus emerges as transversal and not limited to the factory floor: while smart manufacturing remains the leading field, construction, infrastructure asset management, and university education are also increasingly experimenting with the adoption of Digital Twins. This reinforces the argument that Digital Twins represent a systemic innovation, whose full implementation requires a broad *upskilling* and *reskilling* strategy at the level of the entire socio-economic system. In other words, transforming the technological potential of Digital Twins into real value fundamentally depends on sustained investment in the development of appropriate human competencies across all relevant economic and educational domains.

2.4 Results Analysis: A Competency Framework

The systematic analysis of the 55 selected studies unequivocally confirms the initial hypothesis: success in the adoption of Digital Twins is not solely correlated with the technological maturity of the infrastructure but depends critically on the availability of human capital endowed with multidimensional competencies.

The analyzed literature marks a clear departure from the technocentric vision of Industry 4.0, fully embracing the human-centric paradigm of Industry 5.0. In this new scenario, competencies are no longer isolated silos (e.g., IT-only or engineering-only skills), but hybrid and interconnected sets.

From the thematic synthesis, four fundamental macro-dimensions of competence emerge, which are discussed in the following sections: Advanced Technical Competencies, Cognitive Competencies, Soft Skills and Managerial Competencies.

2.4.1 Technical Competencies: IT/OT Convergence

Although the Digital Twin is a digital artifact, recent literature highlights that the required technical competence is evolving from vertical specialization (e.g., the ability to program in Python) toward horizontal integration capabilities. The dominant theme is the convergence between Information Technology (IT) and Operational Technology (OT).

The selected studies identify three priority technical clusters:

- *Data Literacy and Analytics:* It is no longer sufficient for data scientists alone to manage data; shop-floor operators and managers are also required to possess the ability to read, clean, and interpret data streams generated by IoT sensors. The capability to transform "Big Data" into "Smart Data" is consistently cited as a fundamental prerequisite (Longo et al., 2023; Cimino et al., 2023; Zhang et al., 2023; Fan et al., 2024; Perno et al., 2025; Timperi et al., 2023). Furthermore, the rise of Large Manufacturing Decision Models (LMDM) underscores the necessity for personnel to interact with generative pre-trained models to convert massive data streams into actionable reconfiguration strategies (Li et al., 2025). This competency also involves utilizing Natural Language Processing (NLP) to extract valuable insights from unstructured textual records and previous maintenance reports (Xiahou et al., 2025).
- *Immersive Interaction (XR Skills):* With the advent of the industrial metaverse, interaction with the Digital Twin increasingly occurs through Augmented Reality (AR) and Virtual Reality (VR) interfaces. Several authors emphasize the need to train

the workforce in the use of head-mounted displays and haptic tools for remote maintenance and simulated training (Kan & Anumba, 2019; Kritzinger et al., 2018; Bao et al., 2019; Meierhofer et al., 2020). This paradigm shift requires operators to manage bi-directional communication platforms where holographic projections and spatial computing facilitate intuitive human–robot interaction (Yin et al., 2024; Tran et al., 2025). Mastery of these environments allows for virtual pick-and-place teaching and the deployment of virtual human trajectories directly to physical robotic systems (Yun & Jun, 2022; Guo & Chen, 2023).

- *Hybrid Modeling and Simulation:* There is a growing need for professional profiles capable of understanding both software logic and the physical behavior of machinery. Knowledge of the engineering domain (e.g., thermodynamics, mechanics) remains indispensable to validate the coherence of the virtual model (Kritzinger et al., 2018; Tao et al., 2019; Cimino et al., 2023; Zhang et al., 2023; Perno et al., 2025; Rasheed et al., 2020). Modern mechatronic configurations require the ability to bridge mechatronic design with virtual commissioning to optimize the performance of complex machinery (Cremonini et al., 2025). Moreover, engineers must now incorporate metrological traceability into their models, ensuring that digital twins can quantify measurement uncertainty to improve positioning precision in collaborative robotics (Maculotti et al., 2025).

2.4.2 Cognitive Competencies: "Human-in-the-Loop"

A relevant and rapidly growing stream of literature focuses on the role of the human operator as the final decision-maker (*human-in-the-loop*). In contexts where artificial intelligence can suggest optimizations, responsibility for decisions remains human, requiring an enhancement of cognitive capabilities.

Emerging cognitive competencies include:

- *Complex Sense-Making:* Faced with dashboards aggregating thousands of real-time variables, operators must possess the ability to "make sense" of anomalies, distinguishing between false positives and actual critical issues. This skill goes beyond technical problem-solving and involves systemic diagnosis (Longo et al., 2023; Cimino et al., 2023; Fan et al., 2024; Timperi et al., 2023; Zhang et al., 2023). The implementation of Large Manufacturing Decision Models (LMDM) further demands that operators refine system configurations through natural language inquiries and iterative feedback, transforming the Digital Twin into an active reasoning partner (Li et al., 2025). Moreover, the use of Vision Language Models (VLM) enables humans to cross-validate automated assessments with domain-specific knowledge, ensuring that decisions are grounded in actual manufacturing contexts rather than confidently generated "hallucinations" (Fan et al., 2024).

- *Systems Thinking:* The ability to visualize not only individual components but also the interdependencies of the entire production ecosystem. The Digital Twin represents a system of systems; understanding its ramifications requires a holistic approach (Longo et al., 2023; Cimino et al., 2023; Zhang et al., 2023; Perno et al., 2025; Timperi et al., 2023). This competency is increasingly linked to the paradigm of Cyber-Physical Social Systems (CPSS), where Human Digital Twins (HDT) model individual cognitive and physiological states to enable "sliding work sharing", a dynamic allocation of tasks between humans and AI based on real-time confidence levels (Karapanagiotis et al., 2025). Such a systemic view allows operators to serve as the "intelligent activity world" within a Digital Triplet framework, governing the co-evolution of physical and digital artifacts (Sato et al., 2024; Liu et al., 2022).
- *Cognitive Load Management:* Several studies highlight the risk of information overload. The ability to filter information and maintain selective attention is identified as a crucial meta-competency to avoid operational errors (Cimino et al., 2023; Longo et al., 2023; Fan et al., 2024; Timperi et al., 2023; Perno et al., 2025). Recent findings suggest that well-designed Mixed Reality (MR) interfaces and skill-based low-code programming can significantly reduce extraneous cognitive load by replacing device-level primitives with high-level semantic instructions (Yin et al., 2024; Darejeh et al., 2025). By providing intuitive visual cues and "cognitive echo" reflections, these systems help trainees focus on essential problem-solving strategies while minimizing

the mental fatigue associated with managing complex, unstructured data streams (Zheng et al., 2025; Bělohlav et al., 2024).

2.4.3 Soft Skills and Interdisciplinary Collaboration

The analysis reveals that the Digital Twin acts as a *boundary object*, forcing historically separate departments (e.g., Maintenance and IT) to collaborate on a daily basis. Consequently, soft skills cease to be ancillary and become operational prerequisites.

- *Cross-Functional Collaboration:* This is the most frequently cited relational competency. Engineers, data scientists, and business managers must develop a shared language to work in agile and integrated teams (Cimino et al., 2023; Longo et al., 2023; Timperi et al., 2023; Perno et al., 2025; Massaro et al., 2025). Furthermore, this collaboration hinges on shared semantics and robust communication protocols that ensure signals are both machine-readable and intuitively understandable by humans, facilitating coordinated interaction among human workers, AI systems, and legacy infrastructure (Karapanagiotis et al., 2025). In high-complexity settings such as megaprojects, these integrated practices act as a strategic "glue" to break down information silos and foster shared accountability (Halder, 2025).
- *Adaptability and Continuous Reskilling:* Given the rapid obsolescence of digital tools, the ability to “learn how to learn” and mental flexibility are considered more valuable than static technical knowledge (Massaro et al., 2025; Lossie et al., 2025; Chaddad & Jiang, 2025; Pacheco-Velazquez et al., 2024). This necessity for lifelong learning is increasingly dependent on the rapid digital changes that redefine working methods, requiring workers to be adaptable problem-solvers and strategic decision-makers (García et al., 2022; Dua, 2025). The shift toward a co-evolution of operator skills and digital tools emphasizes that training must move beyond mere repetition toward managing the inherent complexities of augmented manufacturing systems (Nielsen & Tambo, 2025).

- *Communication and Translation:* The literature highlights the need for “bridging” figures capable of translating the technical outputs of the Digital Twin into information that creates business value, facilitating dialogue between technical experts and top management (Massaro et al., 2025; Pacheco-Velazquez et al., 2024; Lossie et al., 2025; Chaddad & Jiang, 2025). Collaborating in groups requires specific communication skills to share changes and observations effectively, fostering the collective spirit necessary for Industry 5.0 (Bělohlav et al., 2024). Moreover, managerial success involves the institutionalization of "process translators", senior operators or engineers, who are specifically tasked with mediating between digital model developers and shop-floor realities during the design and rollout phases (Nielsen & Tambo, 2025).

2.4.4 Managerial Challenges and Educational Gaps

Finally, a significant portion of the included articles shifts the focus from the individual level to the organizational level, highlighting how the lack of a coherent managerial strategy represents one of the primary causes of failure in Digital Twin projects.

- *New Organizational Roles:* The literature increasingly codifies emerging professional roles, such as the *Digital Twin Manager* or the *Digital Thread Architect*, responsible for governing the entire data lifecycle. These roles require a strategic vision that goes well beyond traditional IT management (Speicher et al., 2025). The transition to Industry 5.0 further necessitates specialized figures like Knowledge Managers to oversee digital knowledge flows and Energy Managers to maintain energetic balance through DT simulations (Massaro et al., 2025). Moreover, organizations increasingly need "process translators", senior operators or engineers, tasked with mediating between digital model developers and the practical realities of the shop floor to ensure system actionability (Nielsen & Tambo, 2025). A failure to clearly define these roles often leads to organizational ambiguity regarding who "owns" the digital twin and who is accountable for decisions based on its analytical outputs (Timperi et al., 2023; Massaro et al., 2025).

- *The Educational Gap:* Many studies report a mismatch between traditional university curricula and industry needs. Universities continue to teach siloed disciplines, whereas Digital Twins require an interdisciplinary pedagogical approach. The use of the Digital Twin itself as a teaching tool (e.g., virtual laboratories) is proposed as a solution to accelerate learning (Pacheco-Velazquez et al., 2024; Lossie et al., 2025; Chaddad & Jiang, 2025, 2025; Massaro et al., 2025). This "Digital Twin Learning Ecosystem" (DTLE) facilitates mutual learning patterns where researchers and specialists collaborate to empower workforce competencies (García et al., 2022). For instance, the use of Operator Training Simulators (OTS) serves as a digital twin of production plants, allowing students to gain adequate knowledge for process optimization under non-standard operating conditions (Bělohlav et al., 2024). Furthermore, the integration of advanced Vision Language Models (VLM) within DT frameworks offers immersive training specifically designed to make complex industrial operations accessible to non-expert users (Fan et al., 2024). Student internships in Small and Medium Enterprises (SMMs) represent a critical roadmap for bridging this gap, providing the technical skills necessary to adopt innovative technologies cost-effectively (Speicher et al., 2025). A new educational gap identified concerns affordability and physical accessibility. Taylor et al. (2024) demonstrate how the Digital Twin can serve as a tool for democratizing technical education, allowing students and workers to interact with prohibitively expensive digital replicas of machinery (over $10,000) with minimal investment in VR headsets. In parallel, management must integrate psychophysical health as a KPI: the WEM (Workforce Ergonomics and Management) platform proposed by Battini et al. (2022) integrates biometric data (heart rate and respiratory rate) into the Digital Twin to prevent musculoskeletal disorders and cognitive overload stress, transforming DT into a guardian of organizational well-being.
- *Change Management and Organizational Culture:* Cultural resistance and the fear that the Digital Twin may replace human labor are frequently cited barriers. Managerial capability to guide change and promote a data-driven culture therefore becomes critical (Massaro et al., 2025; Lossie et al., 2025; Chaddad & Jiang, 2025).

> High initial investment costs and potential over-dependence on technology often lead to dissatisfaction among veteran executives, reinforcing a preference for conventional procedures (Dua, 2025). Organizations may fall into a "vicious cycle" of digital implementation if initial trust in a model is breached by its failure to capture physical complexity, requiring urgent human mitigation and improvisation (Nielsen & Tambo, 2025). Additionally, the adoption of professional avatars, conceptualized as “professional digital twins”, introduces psychological resistance among users who perceive these virtual representations as a threat to their professional authenticity (Kondrateva et al., 2025). Effective digital leadership must therefore balance technological advancements with human oversight to mitigate safety hazards and build long-term trust in hybrid work environments (Dua, 2025; Park et al., 2025).

Beyond the definition of new roles, managers are increasingly required to justify substantial investments to ensure the long-term success of digital initiatives (Saari et al., 2024). However, as highlighted by Timperi et al. (2023), this significant economic potential risks remaining unrealized in the absence of adequate human capital and skilled personnel capable of governing the technological and organizational complexity associated with these systems (Timperi et al., 2023). Recent literature converges on the idea that the return on investment (ROI) of Digital Twins does not depend solely on the availability of advanced hardware and software infrastructures, but on the organizational maturity and the effectiveness with which companies adopt new decision-making models, governance structures, and managerial competencies (Nielsen and Tambo, 2025; Saari et al., 2024).

Within this framework, a substantial share of the studies included in the systematic review shifts attention from individual competencies to the broader organizational structure, highlighting how the lack of a coherent managerial strategy constitutes one of the main causes of failure in Digital Twin initiatives. Several studies stress that the adoption of Digital Twins cannot be regarded as a simple IT project or a narrowly defined technological initiative but must be understood as a process of deep organizational transformation involving governance, roles, decision-making processes, learning systems, and organizational culture (Massaro et al., 2025; Chaddad & Jiang, 2025).

A first critical area concerns the definition and institutionalization of new organizational roles dedicated to Digital Twin management. The literature indeed begins to codify emerging professional figures, such as the Digital Twin Manager or the Digital Thread Architect, responsible for supervising the entire data lifecycle and the integration between physical and digital systems (Speicher et al., 2025). These roles occupy an intermediate position between technology, business, and strategy, requiring competencies that go far beyond traditional IT management.

Speicher et al. (2025) highlight that the *Digital Twin Manager* is not merely a technical coordinator, but a role required to make strategic decisions regarding the collection, quality, use, and valorization of data generated by the digital twin. This role entails the ability to understand simulation models, interpret analytical outputs, and translate them into operational and strategic guidance for management. In the absence of a clear attribution of responsibilities, Digital Twin initiatives tend to remain confined to pilot experiments or isolated projects, failing to generate systemic benefits for the organization.

Several articles emphasize that one of the main obstacles to the large-scale adoption of Digital Twins lies precisely in organizational ambiguity: it is often unclear who "owns" the digital twin, who governs its evolution, and who is accountable for decisions based on its outputs (Timperi et al., 2023; Massaro et al., 2025). In many organizations, Digital Twins are initially developed within IT or engineering functions, but their true value emerges only when they are integrated into business decision-making processes. Without a dedicated managerial role capable of acting as a bridge between technology and strategy, there is a significant risk that the digital twin will remain a sophisticated but underutilized tool.

In this respect, the literature suggests the need for a redefinition of governance structures, whereby Digital Twins are recognized as strategic assets rather than mere operational support systems. This implies the introduction of roles with an end-to-end vision, capable of coordinating interdisciplinary teams and aligning technological objectives with organizational goals (Speicher et al., 2025; Massaro et al., 2025).

A second central stream of managerial challenges concerns the so-called *Education Gap*, namely the structural misalignment between traditional educational curricula and the competencies actually required by industry for the adoption of Digital Twins. Numerous studies report that universities and training systems continue to privilege siloed disciplinary approaches, whereas Digital Twins demand interdisciplinary competencies integrating engineering, data science, information systems, management, and cognitive sciences (Pacheco-Velazquez et al., 2024; Lossie et al., 2025).

Pacheco-Velazquez et al. (2024) emphasize that traditional academic pathways tend to produce highly specialized profiles that are poorly prepared to operate in complex and integrated environments such as those enabled by Digital Twins. This mismatch translates, for organizations, into the need to invest heavily in internal upskilling and reskilling programs, with significant costs and learning timelines that are not always compatible with the pace of technological innovation.

Lossie et al. (2025) further point out that the educational gap does not concern technical competencies alone, but also cognitive and managerial ones. In particular, the lack of training in areas such as systems thinking, the ability to interpret complex models, and the management of data-driven decision-making processes is highlighted. These competencies are rarely addressed explicitly in university curricula, yet they are fundamental to fully exploiting the potential of Digital Twins in real organizational contexts.

In response to this misalignment, several studies propose the use of the Digital Twin itself as a pedagogical tool. The adoption of virtual laboratories, immersive simulations, and learning environments based on digital twins is presented as a promising solution to accelerate learning and foster the development of interdisciplinary competencies (Chaddad & Jiang, 2025; Massaro et al., 2025). These approaches allow students and workers to experiment with complex scenarios in controlled environments, thereby reducing the gap between theory and practice.

However, the literature also highlights that such solutions remain largely experimental and are often limited to pilot contexts. Timperi et al. (2023) observe that, despite growing consensus on the usefulness of Digital Twins as training tools, systematic evidence of their effectiveness at scale and of their stable integration into educational and professional pathways is still lacking. As a result, the educational gap remains an open challenge, requiring closer coordination among universities, firms, and policy makers.

The third axis of managerial challenges concerns *change management* and organizational culture. Numerous articles underline that cultural resistance represents a significant barrier to the adoption of Digital Twins, often more critical than technical difficulties (Massaro et al., 2025; Chaddad & Jiang, 2025). In particular, there is a widespread fear that the digital twin may replace human labor, reducing operators' decision-making autonomy or threatening certain professional roles.

Massaro et al. (2025) note that such fears are often fueled by inadequate communication and insufficient involvement of employees in digital transformation processes. In the absence of a structured change management strategy, Digital Twins risk being perceived as control mechanisms rather than as tools supporting human work. This perception can generate resistance, slow down adoption, and ultimately undermine the return on investment (ROI).

Timperi et al. (2023) stress that the success of Digital Twin projects largely depends on managerial ability to promote a data-driven culture oriented toward learning and collaboration. This requires not only the availability of technical skills, but also the creation of an organizational climate in which the use of data and simulations is encouraged, understood, and shared. Lossie et al. (2025) add that organizational culture plays a crucial role in determining the speed at which new technologies are accepted and integrated into everyday decision-making processes.

Chaddad et al. (2025) show that organizations that successfully adopt Digital Twins tend to invest in parallel in transformational leadership, internal communication, and continuous training programs. In these contexts, change management is not treated as a peripheral activity, but as a core component of the implementation strategy. Conversely, in organizations where change is imposed top-down without adequate cultural support, Digital Twins often remain underutilized or are abandoned after initial experimentation phases.

Overall, the literature converges on the idea that managerial and organizational challenges constitute a decisive factor for the success or failure of Digital Twin projects. The definition of new roles, the reduction of the educational gap, and the effective management of cultural change emerge as interconnected elements requiring a long-term strategic vision. Without an integrated managerial approach, even the most advanced technologies risk failing to deliver the expected benefits, confirming that the Digital Twin is, before being a technological innovation, an organizational and cultural challenge.

A further recurring theme in the literature concerns organizations' difficulty in transforming Digital Twin initiatives from pilot projects into structural components of business processes. Several studies observe that many implementations remain confined to technological demonstrators or proof-of-concept stages, never reaching organizational scalability (Massaro et al., 2025; Timperi et al., 2023). This phenomenon is often attributed not to intrinsic technological limitations, but to the absence of a clear managerial integration strategy.

The literature highlights that Digital Twins introduce a new decision-making logic based on simulations, predictive scenarios, and real-time analytics, which may come into tension with traditional decision-making models often grounded in individual experience and consolidated hierarchical processes (Chaddad & Jiang, 2025). Without alignment between technology and governance, managers may perceive the digital twin as a marginal support tool rather than as a central element of the decision system. Consequently, decisions continue to be made according to pre-existing logics, drastically reducing the potential value added of Digital Twins.

Timperi et al. (2023) emphasize that adoption success depends on management's ability to redefine decision-making processes by clarifying when and how Digital Twin outputs should be used. This entails formalizing new procedures, revising information flows, and, above all, defining clear accountability for data-based decisions. Without these conditions, the digital twin risks producing advanced information that is never truly incorporated into operational and strategic choices.

A closely related issue concerns *digital leadership*. Several articles show that effective adoption of Digital Twins requires leaders capable of understanding not only technological potential, but also the organizational and human implications of digital transformation (Massaro et al., 2025; Chaddad & Jiang, 2025). Digital leadership does not coincide with technical expertise; rather, it involves the ability to orchestrate heterogeneous competencies, facilitate organizational learning, and promote a shared innovation vision.

Speicher et al. (2025) observe that roles such as the Digital Twin Manager assume transversal accountability, as they must ensure coherence between the digital twin, business objectives, operational needs, and organizational constraints. This form of leadership requires a combination of strategic, communicative, and decision-making competencies that are rarely concentrated in a single individual within traditional organizations. As a result, many firms struggle to identify suitable profiles or to develop them internally.

The literature suggests that, in the absence of strong and recognized leadership, Digital Twin projects tend to fragment across organizational functions, generating priority conflicts and operational redundancies (Timperi et al., 2023). In particular, a recurring tension emerges between IT functions, focused on system stability and security and, business functions oriented toward decision speed and flexibility. The lack of a strategic coordination role can slow adoption and undermine trust in the technology.

Another central aspect of managerial challenges concerns *data culture*. Numerous studies highlight that Digital Twins presuppose a profound shift in how organizations produce, interpret, and use information (Massaro et al., 2025; Lossie et al., 2025). In contexts characterized by decision-making cultures primarily based on intuition or individual experience, the introduction of predictive models and simulations may encounter strong resistance.

Lossie et al. (2025) argue that data culture cannot be imposed through technological tools alone but must be built over time through organizational learning practices and knowledge sharing. This requires investment in training as well as the creation of spaces for dialogue in which results generated by the Digital Twin can be discussed, interpreted, and related to operators' experiential knowledge. In this sense, the digital twin can become an object of collective learning, fostering reflection on processes and organizational performance.

Chaddad et al. (2025) underline that organizations most mature in Digital Twin adoption are those that manage to integrate the digital twin into continuous learning mechanisms, using it not only to optimize operations but also to develop new competencies and work practices. Conversely, in organizations where data are perceived as tools of control or punitive evaluation, Digital Twin adoption tends to generate distrust and resistance.

The literature also shows that managerial challenges are closely linked to perceptions of risk associated with advanced automation. As systems capable of simulating and recommending decisions, Digital Twins may be perceived as a threat to professional autonomy by both operators and managers (Timperi et al., 2023; Massaro et al., 2025). This perception can hinder adoption, particularly in contexts where human capital is strongly tied to tacit knowledge and experiential know-how.

Timperi et al. (2023) note that one of management's main challenges lies in repositioning the role of humans within Digital Twin systems, clarifying that the digital twin does not replace human judgment but supports and enriches it. This narrative is essential to reduce resistance and foster technology acceptance. Nevertheless, the literature shows that many organizations neglect this communicative aspect, focusing predominantly on technical implementation issues.

Massaro et al. (2025) emphasize that the failure of many digital transformation projects is precisely attributable to inadequate management of expectations and employee perceptions. Without a structured change management strategy, Digital Twins may be interpreted as tools for labor rationalization or cost reduction, fueling fears of job loss. Conversely, the literature suggests that clear and transparent communication, accompanied by targeted training programs, can help transform the Digital Twin into an ally of the human operator.

Overall, the analyzed articles converge on the view that managerial challenges related to Digital Twins cannot be addressed in a fragmented manner. The definition of new organizational roles, the management of the educational gap, the promotion of a data-driven culture, the transformation of decision-making models, and ROI measurement emerge as critical dimensions requiring a systemic and long-term approach (Massaro et al., 2025; Timperi et al., 2023).

The literature suggests that organizations capable of integrating these dimensions develop greater innovation absorption capacity and higher resilience in the face of technological complexity. By contrast, organizations that treat Digital Twin adoption as a set of isolated technical problems tend to experience delays, resource waste, and outcomes below expectations.

In this sense, managerial challenges emerge as a critical success factor for Digital Twin projects. They extend beyond the initial implementation phase and accompany the entire technology lifecycle, influencing its evolution, everyday use, and ability to generate value over time. The literature thus highlights the need to shift attention from the question "which technology should be adopted?" to the more complex question "how should technology adoption be governed within the organization?", placing management and organizational culture at the center of reflection on Digital Twins.

Synthesis

Table 2, summarizes the key competencies identified, mapping them across the four analyzed dimensions.

Table 2: Taxonomy of Digital Twin Competencies. Source: Author's elaboration

Dimension	Competences	Key References (Selected)
Technical	IoT Data Analysis, IT/OT Integration, VR/AR usage, Simulation modeling, Cyber-security awareness	Longo et al., 2023; Cimino et al., 2023; Zhang et al., 2023; Fan et al., 2024; Perno et al., 2025; Kritzinger et al., 2018; Tao et al., 2019; Rasheed et al., 2020; Kan & Anumba, 2019
Cognitive	Systems Thinking, Sense-making, Complex Problem Solving, Cognitive Load Management	Longo et al., 2023; Cimino et al., 2023; Fan et al., 2024; Zhang et al., 2023; Timperi et al., 2023; Perno et al., 2025
Soft	Cross-functional Collaboration, Adaptability, Knowledge Sharing, Interdisciplinary Communication	Massaro et al., 2025; Chaddad & Jiang, 2025; Lossie et al., 2025; Pacheco-Velazquez et al., 2024; Timperi et al., 2023; Cimino et al., 2023
Managerial	Digital Leadership, Change Management, Strategic Vision, Talent Development	Speicher et al., 2025; Massaro et al., 2025; Timperi et al., 2023; Chaddad & Jiang, 2025; Lossie et al., 2025; Pacheco-Velazquez et al., 2024

2.5 Discussion: The Gaps in the Literature (The Missing Links)

The current literature on Digital Twin competencies largely adopts a universalistic approach, implicitly assuming that the skills required are identical across any geographical or organizational context. The analyzed studies often outline sets of competencies considered valid everywhere, without accounting for how local factors may modify their relevance. For instance, García et al. (2022) present a set of priorities and challenges for integrating Digital Twins into manufacturing training as if they were general principles applicable to the entire industry. Similarly, Omrany et al. (2025) propose a conceptual framework for Digital Twin adoption in construction education without differentiating across national contexts. This approach presupposes that competency challenges and training solutions are homogeneous, regardless of the country or cultural environment in which implementation occurs.

In reality, there is an almost complete lack of studies that systematically explore the role of context. None of the 55 articles included in the SLR has examined in depth variables such as national culture, local regulations, the level of technological development of a given territory, or the presence of innovation ecosystems, and how these factors influence the competencies required. This gap is significant: cultural differences such as uncertainty avoidance or varying degrees of organizational hierarchy may affect the soft and managerial competencies needed, yet the literature provides no empirical evidence in this regard. For example, it remains unclear whether an entrepreneurial and agile mindset, often considered fundamental in highly innovative environments such as Silicon Valley, is equally valued in more traditional industrial contexts such as Italian manufacturing. Furthermore, X. Liu et al. (2024) note the absence of a universal maturity model (Maturity Model) for the Digital Twin: without clear parameters to assess the level of development a project is at (from a simple static model to a reconfigurable autonomous system). However, these questions remain unanswered because no comparative study has directly contrasted different socio-economic contexts. A contextual gap therefore emerges competencies are discussed as if they were "one-size-fits-all," without investigating how and to what extent they vary across environments.

Some indications of the relevance of context appear indirectly in the literature, suggesting that this omission should be addressed. Ebiloma and Aigbavboa (2025), for example, in examining barriers to Digital Twin adoption in Nigerian healthcare, recommend intensifying research efforts in developing countries. This recommendation implies that much of the existing literature focuses on advanced contexts, implicitly assuming the availability of infrastructures, resources, and competencies that may be lacking in emerging settings. In the cited study, key obstacles include "insufficient research" on the topic, a problem specific to less technologically mature contexts, alongside issues such as shortages of local technical skills and systemic factors such as corruption.

Such aspects rarely appear in studies conducted in industrialized countries, indicating that the socio-economic context significantly shapes the challenges encountered. The same authors caution that while some aspects of Digital Twins may be universal across cultures, others may not, underscoring the need to validate competencies in multiple contexts. In other words, what holds in one country may not hold in another: for instance, change management practices and communication skills required to implement a Digital Twin may take different forms in a U.S.-based organization compared to an Asian firm, due to differences in cultural values and organizational structures.

The absence of contextual awareness in the literature generates potentially misleading generalizations. The competency taxonomies proposed so far are presented as general and timeless, with limited problematization of boundary conditions. This theoretical gap is particularly critical because digital and managerial competencies do not exist in a vacuum: demand for specific skills may depend on a country's level of digitalization, national training policies, dominant industrial sectors, and prevailing corporate culture. Ignoring these variables implies, erroneously, that training a Digital Twin engineer in Europe entails the same needs and skill sets as training one in Asia or Africa. Ultimately, a perspective integrating environmental differences is missing where and how technologies are adopted may influence what knowledge and capabilities are required. To date, the scientific literature has not explicitly addressed this dimension, instead treating competencies as a static and universal set. This highlights the need for future studies that explicitly examine the impact of context national, cultural, and ecosystemic on Digital Twin competencies, thereby addressing this first missing link.

2.5.1 The Lack of Comparative Perspectives

Closely related to the contextual gap is the comparative gap: the scarcity of studies that directly compare multiple contexts. The SLR reveals that empirical research is fragmented into a series of isolated cases, each confined to a single geographical or sectoral reality. For example, Ebiloma and Aigbavboa (2025) analyze the Nigerian healthcare context; Signorini and Pomè (2025) explore Digital Twin adoption in facility management primarily using European data; other studies focus on manufacturing in Asia or pilot projects in the United States. Each of these works provides valuable local insights, but none is designed to conduct a direct comparison across different contexts. In other words, cross-country or cross-sector studies applying the same methodology to two or more contexts, so as to identify similarities and differences in required competencies, are missing. The existing literature juxtaposes findings from individual cases (China, the U.S., Europe, etc.) without integrating them into a coherent comparative analysis.

This fragmentation makes it difficult to generalize findings at a global level. If one study identifies lack of training as the primary barrier in a Chinese case, while another highlights cultural resistance to change as the main issue in a European firm, how can we determine whether these obstacles are structural (present everywhere) or contingent (specific to a given context)? Without a comparative research design, it remains unclear whether observed differences are attributable to chance, sectoral characteristics, levels of national development, or genuine cultural and environmental specificities. To date, the literature provides no definitive answer.

Available studies suggest that substantial differences may indeed exist. For example, in the Nigerian context, atypical barriers, such as insufficient local research and lack of funding transparency, emerge, which are entirely absent from European studies. In Nigerian healthcare, the main obstacles include lack of research capacity and internal competencies, followed by economic and governmental factors; by contrast, in a European industrial facility management context, the reported challenges mainly concern high costs, technological integration difficulties, and the need for specialized workforce training. These represent distinct landscapes: what is “critical” in one environment (e.g., corruption or weak training infrastructure in an emerging country) may be irrelevant in another, where technological updating and organizational change management are more salient.

These insights from separate studies suggest that context matters, yet the literature has not connected the dots through direct comparative research. Ebiloma and Aigbavboa (2025) explicitly note that while certain aspects of Digital Twins may be universal, others “may not” be across different locations. This statement, derived from a single case study, constitutes an invitation to the scientific community to empirically verify which competencies and approaches are shared and which vary across ecosystems. Similarly, other authors call for expanding the scope of inquiry. In the field of Industry 4.0 and education, for example, some studies mention the lack of a global perspective in their conclusions or encourage replication in additional contexts to validate findings. However, these calls themselves highlight that such comparisons do not yet exist in the published literature.

In sum, the lack of comparative perspectives constitutes a clear gap: to date, knowledge on Digital Twin competencies has been constructed in silos, each tied to a single country or sector, and it remains unclear to what extent findings from one context are applicable elsewhere. This limits both the explanatory and prescriptive power of the literature. Without comparative studies, multinational organizations and international institutions lack evidence on which to base geographically differentiated strategies. Moreover, from an academic standpoint, the opportunity to identify general patterns or systematic differences remains unexplored: for instance, it may emerge that certain competencies (such as critical thinking or interdisciplinary collaboration) are universally important, while others (such as familiarity with specific regulations or safety-culture-related skills) vary significantly by context. Addressing this gap will require purpose-designed studies, such as cross-country research applying the same analytical protocol across multiple countries or sectors, to distinguish what is global from what is local in Digital Twin competencies.

2.5.2 Theory vs. Practice

A third major missing link emerging from the literature is the gap between theory and practice. Many of the works included in the SLR, particularly those of an academic nature and originating from the educational domain, propose theoretical models, conceptual frameworks, or prototypes to define and develop Digital Twin-related competencies, but very few provide empirical evidence of their effectiveness at scale within organizations. In other words, the scientific output excels at outlining what should be done in theory, while remaining limited in documenting what has actually been done in pioneering organizations or the concrete impact of these models in practice.

For example, Omrany et al. (2025) develop a comprehensive framework aimed at “bridging the gap” between theoretical learning and real-world application of Digital Twins in construction education. The very fact that the authors perceive the need to build such a bridge indicates that, to date, the integration between educational concepts and practical implementation remains unresolved. Similarly, Massaro et al. (2025) discuss new managerial roles and competency sets required to oversee Digital Twin and Knowledge Management systems in Industry 5.0 scenarios. These roles, such as hybrid managerial figures combining engineering, analytical, and leadership competencies, are theoretically defined as ideal profiles, yet the authors do not report cases of companies that have already formally introduced such positions. These are therefore theoretical recommendations about what should exist, rather than documentation of best practices already in place. This reflects a broader trend: many publications indicate which competencies are needed and propose training approaches to develop them, but do not verify their adoption in real organizational settings.

Several studies in the educational domain present innovative solutions such as virtual or augmented reality learning platforms, Digital Twin simulators for training, and serious games. These initiatives are often tested in controlled pilot environments, university laboratories, small-scale proof-of-concept projects, or experimental settings, rather than implemented at the level of entire organizations. Longo et al. (2023), for instance, propose a “prescriptive” training system supported by Digital Twins, incorporating prescriptive analytics and immersive simulation, and validate it through a demonstrative case study involving a non-routine task in an offshore plant. Although this represents an advanced contribution, the authors themselves frame it as a proof-of-concept, an experimental feasibility demonstration. No evidence is provided of widespread adoption in operational companies or of long-term performance outcomes for workers. As such, it remains within the realm of academic experimentation, indicating that the field is still in an early stage of theoretical–practical development.

The overall picture that emerges is therefore one of a literature rich in models but poor in consolidated empirical data. Many authors emphasize in their conclusions that their models require testing "in the wild," acknowledging the lack of large-scale practical validation. It is thus unsurprising that Digital Twin adoption in industrial contexts is still described as being at an early stage. García et al. (2022) note that the implementation of Digital Twins in production processes is "still in an early phase," with human and technological challenges yet to be resolved. The same authors point out that, at present, "academic applications and demonstrative scenarios" prevail, while real factory use cases remain limited. As a result, academic research is anticipating solutions that industry has not yet fully embraced, creating a gap between the two spheres.

A specific aspect of this theory–practice gap is the lack of metrics and performance data on the actual outcomes of Digital Twin-related reskilling and upskilling initiatives. The literature abounds in qualitative assumptions about the importance of certain competencies but offers few quantitative indicators of how improvements in these competencies affect organizational outcomes (e.g., productivity, safety, innovation). The lack of sector-specific Key Performance Indicator frameworks makes it difficult to evaluate and implement Digital Twin solutions. Translated to the present context, this means that shared systems of indicators to measure the effectiveness of training programs and newly acquired competencies are lacking. For example, how much downtime reduction or efficiency gain results from training an operator via Digital Twin simulation? How many errors are avoided by introducing Digital Twin-based training compared to traditional methods? Such questions remain largely unanswered in the analyzed studies. Without metrics, even the few documented practical attempts cannot be generalized in terms of ROI or tangible benefits, further widening the gap with managerial needs, which require numerical evidence and proof of effectiveness before large-scale investment.

Another sign of the theory–practice divide is the scarcity of studies on complex, real-world corporate cases. None of the reviewed contributions, for instance, provides a detailed account of how a major multinational (e.g., IBM, Siemens, GE) has addressed workforce reskilling to adopt Digital Twins. The literature frequently discusses what global players should do, but not what they are actually doing, likely due to limited access to corporate data or because such programs are ongoing but not yet scientifically documented. Consequently, the field offers a substantial body of theoretical knowledge, on competency models, Digital Twin-based training architectures, and new professional roles, but little evidence of how these ideas have been translated into operational practice within organizations.

This theory–practice gap has important implications. From a scientific perspective, it signals the need for more extensive and longitudinal empirical studies to test existing frameworks in real organizational contexts, measure their effects over time, and refine theoretical models based on practical feedback. From a managerial perspective, the lack of concrete evidence may generate uncertainty or skepticism: decision-makers may question whether the models proposed by academics are truly applicable and profitable in their specific contexts. For example, knowing that the literature recommends creating a “Digital Twin Manager” role is useful, but organizations would also want to see documented success cases, actual responsibilities assigned, competencies measured, and benefits achieved before investing in such a position. At present, such information remains scarce.

In conclusion, bridging the gap between theory and practice will require a joint effort. On the one hand, research must embrace empirical methodologies, such as in-depth case studies, industrial surveys, field experiments, and analysis of organizational metrics, to validate and quantify the impact of proposed frameworks. On the other hand, industry must become more open to sharing data and results from its Digital Twin-related upskilling initiatives. Only by integrating the conceptual and applied dimensions will it be possible to develop truly reliable and generalizable knowledge, and to provide concrete guidance for organizations planning workforce development in the era of Digital Twins.

2.6 Conclusions

The systematic literature analysis conducted in this chapter has made it possible to deconstruct the complexity of the Digital Twin, shifting the focus from technology to people.

The findings confirm the existence of a significant skills gap: while the technologies themselves are mature, organizations struggle to identify hybrid profiles capable of governing them effectively. The literature consistently agrees that the Digital Twin professional is not a “super-technician,” but rather a versatile figure combining hard skills (such as data analytics and simulation) with strong cognitive and soft skills (including systems thinking and collaboration).

However, a fundamental theoretical gap emerges, which this study aims to address. The vast majority of the analyzed studies treat competencies as a universal set, without considering how contextual factors, such as national culture, the innovation ecosystem, or attitudes toward risk, may influence the definition and development of these competencies. For example, it remains unclear whether the upskilling challenges faced by a company operating in Silicon Valley are the same as those encountered by a company operating in Italy.

This lack of comparative studies justifies the need for the empirical investigation presented in the following chapter (Chapter 3), which will examine, through the IBM case study, how context actually influences talent management in the era of Digital Twins.

Chapter 3. Methodology and Empirical Analysis: The IBM Case

3.1 Introduction

The preceding chapters have established the theoretical framework of digital transformation and, through a systematic literature review, have highlighted a significant skill gap in the adoption of Digital Twins. State-of-the-art analysis confirms that the primary barrier to large-scale implementation is not strictly technological in nature but rather resides within human and organizational dimensions. In this study, a conceptual distinction is maintained between 'adoption', the strategic decision to embrace the technology and 'implementation', the operational process of integrating it into industrial routines. However, both are treated as part of a single continuous cycle of organizational transformation. This characterizes what management literature defines as a "wicked problem", a challenge that transcends disciplinary boundaries and involves multiple stakeholders with divergent interests. Despite the relevance of this topic, current research exhibits a marked "contextual blindness"; specifically, there is a dearth of studies investigating how cultural and ecosystemic dynamics influence the very definition of the competencies required to govern these technologies. This chapter establishes the methodological foundation of the study and provides an in-depth description of the research context (the IBM case). While it serves as the empirical backbone, the final synthesis of findings and the resulting competency framework will be formally presented and discussed in Chapter 4, allowing this section to focus on the 'how' and 'why' of the research design. This moves the inquiry toward an empirical dimension to explore how contextual and cultural dynamics affect the definition of such skills. The primary objective is not a mere phenomenological description, but a quest for a profound understanding aimed at identifying the conditions underlying differences in technological adoption, seeking explanations for the "how" and "why" of managerial practices (Flick, 2013; Yin, 2018). The choice of research strategy fell upon a single critical case study, identified in the technology giant IBM. This methodological option is justified as the case study is the instrument of choice for addressing "how" and "why" questions, allowing for an in-depth exploration of contemporary phenomena within their real-life context, especially when the boundaries between the phenomenon and its environment are not clearly distinguishable (Yin, 2018). IBM is analyzed here not merely as a technology provider, but as an "orchestrator" of skills within complex ecosystems, acting as a catalyst for the integration of digital models into consolidated industrial routines. In particular, the adoption of platforms such as the *IBM Maximo Application Suite* and the integration of artificial intelligence services like Watson Studio and Watson Machine Learning necessitate a radical reconfiguration of human labor. The investigation aims, therefore, to overcome the "contextual blindness" of traditional models by adopting an interpretivist paradigm, which posits organizational reality as a social construct produced by the interactions and meanings attributed by actors (Bell et al., 2019; Corbetta, 2014). The research design adopts a transatlantic comparative perspective, contrasting the global strategic vision originating in Silicon Valley (USA) with the application challenges encountered at the IBM hub in Bari, Italy. This approach allows for an observation of how Digital Twin models are "translated" and adapted across contexts characterized by different institutional logics (Flick, 2013; Yin, 2018). While a logic of hyper-growth prevails in the U.S. context, the managerial challenge in the Bari hub confronts the "wall of complexity" typical of Southern Italy's industrial fabric, operating in synergy with the objectives of the National Recovery and Resilience Plan (NRRP/PNRR). In conclusion, the qualitative analysis presented here, supported by in-depth interviews with IBM Executive Architects, aims to trace a "chain of evidence" linking the original research questions to the empirical results (Yin, 2018). This data collection technique is considered particularly effective for exploring complex phenomena through the lived experiences of key protagonists, providing rich contextual details that quantitative surveys would be unable to capture. Through this trajectory, the chapter intends to provide a framework of skills that is not merely technical but reflects the hybrid capabilities required to govern the Digital Twin era. These are defined as the critical intersection between deep technical mastery (Cyber-Physical Systems architecture) and soft-managerial skills, such as sense-making and cultural mediation. This positioning draws upon Zuboff's (1988) paradigm of 'informating' the organization, where technology demands new forms of authority based on data-driven insight and Lee et al.'s (2015) framework for cyber-physical integration. Methodological rigor and transparency in the coding and analysis procedures ensure compliance with the academic standards required for peer review, offering an innovative contribution to the understanding of organizational management in the era of digital transformation.

3.2 The Qualitative Research Paradigm: Ontological and Epistemological Foundations

The empirical investigation presented in this work is firmly anchored in the qualitative research paradigm, which should not be understood merely as a non-numerical alternative to quantification, but as a coherent system of assumptions that redefine the very object of managerial knowledge (Bell et al., 2019). This paradigm responds to the need to transcend the natural science model applied to social phenomena, recognizing that institutions and individuals are fundamentally different from objects in the physical world (Bell et al., 2019; Corbetta, 2014). Within the context of Digital Twin adoption, this methodological choice is crucial for understanding how the meanings attributed by social actors are not mere ancillary variables but constitute the very essence of the organization and its transformation processes (Flick, 2013). From an ontological standpoint, the research adopts the perspective of social constructionism (or constructivism), challenging the objectivist view that conceives social reality as a set of external facts independent of the observer (Bell et al., 2019; Corbetta, 2014). In this study, organizations are not interpreted as inert structures or static "containers," but as "negotiated orders", that is, the dynamic outcomes of continuous interactions and shared meanings among members (Strauss et al., 1973). This assumption is fundamental to the analysis of the IBM case: Digital Twin technology is not analyzed as a "given" object acting externally upon the actor, but as an entity that is "made real" and continuously reshaped by the sense-making practices of Executive Architects and the stakeholders involved (Bell et al., 2019). A constructivist ontology thus allows for the capture of the fluidity of these "multiple realities," where the meaning of a cutting-edge technology necessarily varies according to organizational cultures and reference ecosystemic contexts (Corbetta, 2014; Flick, 2013). The IBM case analysis directly embodies this perspective by comparing the Silicon Valley and Bari hubs. This design does not treat the Digital Twin as a universal 'fact', but explores how its 'reality' is constructed differently: as a tool for hyper-growth and risk-taking in the US, and as a medium for institutional resilience and cultural mediation in Italy. Regarding the epistemological profile, the study is situated within the tradition of interpretivism, centering on the objective of understanding (*Verstehen*, or the sociologically grounded 'empathic understanding' of the meanings actors attach to their actions) rather than the mere causal explanation typical of positivism (Bell et al., 2019; Corbetta, 2014). Interpretivism recognizes that human action is intrinsically endowed with meaning; therefore, the researcher's task is not to observe from the outside to formulate universal laws, but to access the "common-sense thinking" of the actors involved (Schutz, 1962). This perspective requires an "empathic interpretation" approach, aimed at amplifying and illuminating the manifest and implicit meanings contained in the protagonists' accounts, rather than subjecting them to predefined hypothesis testing (Willig, 2012). By adopting this paradigm, the research aims to decode the structures of meaning that motivate managerial behavior in the face of the algorithmic challenge, assuming that social reality is the product of a co-construction between the researcher, the participants, and the institutional context (referring to the set of norms, regulatory frameworks like the GDPR and strategic mandates such as the PNRR that shape the environment in which actors operate) (Charmaz, 2006; Flick, 2013). The integration of these theoretical pillars transforms the data analysis phase into a "sense-making" challenge (Flick, 2013), meaning that the researcher must not merely categorize data, but interpret the cognitive processes through which actors give meaning to technological change. Consequently, the research logic is not linear or sequential, but circular and reflexive, aimed at constantly connecting the empirical level of observations with the theoretical level of abstractions (Bhattacherjee, 2012). The rigor of the interpretative research proposed here is not measured through statistical parameters, but through the criteria of credibility, transferability, and confirmability (Lincoln & Guba, 1985). Providing a "thick description" of the IBM case and the human-algorithm interactions mediated by platforms such as IBM Maximo thus becomes the only path to ensuring scientific knowledge that is both authentic and sensitive to the complexity of the real-world context (Yin, 2018).

3.3 Research Design: The Critical Case Study

The research strategy adopted in this work is configured as a single-case study of a critical and revelatory nature, centered on the organizational ecosystem of IBM (Yin, 2018). Specifically, the study focuses on two distinct organizational units: the Silicon Valley (USA) strategic core, representing the global innovation source, and the Bari Hub (Italy), serving as the local implementation laboratory. This ecosystem is understood as a complex network where IBM acts as an 'orchestrator' of skills, connecting technological development with diverse industrial routines and institutional frameworks like the Italian PNRR. The choice of the case study as a research model is justified by the need to investigate a contemporary phenomenon within its real-life context, particularly when the boundaries between the phenomenon and the surrounding environment are not clearly distinguishable (Yin, 2018). In this scenario, IBM does not represent a mere sampling unit, but a "critical case" that allows for the testing and extension of theoretical propositions regarding the adoption of Digital Twins and the management of the skill gap (Yin, 2018). The primary objective is to achieve analytical generalization, a logical process in which the findings emerging from the case study are used to enrich or challenge existing theoretical concepts, moving toward a higher level of abstraction compared to the specificity of the empirical data (Yin, 2018). In terms of methodological design, the research adopts an "embedded" structure, characterized by the presence of multiple units of analysis within the same case (Yin, 2018). While the primary case consists of IBM's global strategic vision on technological integration, the Bari hub operates as an embedded unit that allows for a close-range, granular observation of operational practices (Yin, 2018). This configuration avoids an excessively holistic approach, which would risk remaining at too high a level of abstraction; instead, it provides a "thick description" of local dynamics in tension with global standards (Geertz, 1973). The investigation focuses on how algorithmic agency, mediated by platforms such as IBM Maximo, necessitates a reconfiguration of human roles, activating logics of delegation and collaboration that challenge traditional organizational hierarchies (Stelmaszak et al., 2025). The IBM case illustrates this through the shift from traditional maintenance to cognitive maintenance. Within the Maximo suite, predictive algorithms do not merely issue commands; they generate 'choice data' that requires humans to move from executive roles to supervisory ones, engaging in 'distributed delegation' where human discretion is intertwined with automated insights. The scientific rigor of the design is ensured through the application of the principle of triangulation of sources, which is essential for strengthening construct validity (Thurmond, 2001; Yin, 2018). The inquiry is not limited to a single data collection method but integrates in-depth interviews with Executive Architects, the analysis of administrative and strategic documents, and the direct observation of operational routines (Flick, 2014; Yin, 2018). This multi-method approach aims to compensate for the potential deficiencies of any single strategy, allowing for the identification of converging lines of evidence and capturing the complexity of the "multiple realities" perceived by various stakeholders (Bell et al., 2019; Thurmond, 2001). By constantly comparing the data collected in the field with the initial theoretical propositions, which include: 1. the assumption that Digital Twin competencies are not universal but 'situated' and context-dependent; 2. the hypothesis that ecosystem maturity (Early Adopters vs. Conservative SMEs) acts as a primary filter for skill development strategies ; 3. the premise that technological adoption requires cultural mediation rather than simple knowledge transfer, the study aims to build a robust chain of evidence that leads the reader from the research questions to the analytical conclusions in a transparent and replicable manner (Yin, 2018). Finally, the selection of IBM as a "revelatory case" is based on the opportunity to access phenomena previously inaccessible to scientific investigation in the field of management, such as the micro-processes of interaction between algorithmic collectives and human actors (Stelmaszak et al., 2025; Yin, 2018). The research design does not follow a logic of statistical sampling; rather, it is inspired by the replication logic typical of experiments, assuming that the dynamics observed in this specific context can serve as a basis for understanding analogous processes in other high-technology-density ecosystems (Yin, 2018). In this way, the critical case study becomes the instrument of choice for addressing the interpretative challenge posed by digital transformation, illuminating not only "what" is changing in terms of competencies, but "how" and "why" such changes manifest within the fabric of the contemporary business organization (Flick, 2013; Yin, 2018).

3.4 Research Context: A Transatlantic Perspective

The empirical investigation unfolds through a transatlantic comparative perspective, configuring a research design aimed at examining how managerial practices and the competencies required for Digital Twin adoption are modulated and "translated" within divergent institutional contexts. This choice is not driven by mere geographical curiosity, but by the methodological necessity to overcome the "contextual blindness" that often afflicts management studies. Such blindness tends to ignore that cutting-edge technologies do not operate in a social vacuum, but within specific socio-cultural ecosystems that redefine their meaning and impact (Bell et al., 2019; Hofstede, 1984; Yin, 2018). The systematic comparison between the United States and Italy allows for the observation of the dialectical tension between a "global" innovation model and its "local" implementation, making visible the adaptation process necessary to overcome organizational and human barriers (Bell et al., 2019; Usunier, 1998).

In the U.S. technological pole, identified with the strategic vision of Silicon Valley, the adoption of advanced platforms like the IBM Maximo Application Suite and the integration of artificial intelligence services such as Watson Studio and Watson Machine Learning is situated within a context dominated by hyper-growth logics and a vision of reality oriented toward technological objectivism (IBM, 2021; Bell et al., 2019; Stelmaszak et al., 2025). This vision treats technological adoption as a rational outcome of hyper-growth logic. It makes sense to compare this 'strategic core' with Bari because they represent two opposite ends of the adoption spectrum: an ecosystem of 'Early Adopters' characterized by a high propensity for risk, versus an SME-dominated fabric requiring cultural mediation and resiliency. In this scenario, IBM acts as an orchestrator of digital ecosystems, defining the standards of human-algorithm interaction that underpin the agency of digital models (IBM, 2021; Stelmaszak et al., 2025). However, the interpretative inquiry reveals that even in this high-technology-density environment, the organizational order is not an inert structure but the result of a continuous process of sense-making and negotiation among social actors, suggesting that Digital Twin integration is, ultimately, a "negotiated order" (Strauss et al., 1973). Even in high-tech environments, rules and procedures are not fixed commands but 'general understandings'. Interpretative inquiry shows that Executive Architects continually renegotiate these meanings in their daily work, making the Digital Twin a dynamic entity that is 'made real' only through these human sense-making practices.

On the other side of the Atlantic, the IBM Bari hub serves as an embedded unit that allows for a granular observation of the reception dynamics of these models within Italian organizational praxis (Yin, 2018). Here, the managerial challenge takes on the characteristics of a "wicked problem," marked by a plurality of stakeholders with divergent interests and influenced by the strategic directives of the National Recovery and Resilience Plan (NRRP/PNRR) and the ICSC National Centre (Bell et al., 2019; Ferraro et al., 2015). In this territory, technological adoption cannot be reduced to a mere software transfer; rather, it requires profound cultural mediation. The analysis of the Bari hub allows for the observation of how local values and the specificities of Southern Italy’s industrial fabric act as critical filters, transforming IBM’s global routines into context-sensitive operational practices (Yin, 2018).

In summary, the choice of a transatlantic research context addresses the need to achieve analytical generalization, where the findings from the IBM case are not used for statistical extrapolation, but to enrich and challenge existing theories on the digital skill gap (Yin, 2018). The research explores the circularity of the innovation process, assuming that organizational reality is co-constructed through the interaction between the researcher, the participants, and the institutional contexts (Charmaz, 2006; Flick, 2013). This approach ensures that the proposed hybrid competency framework, which emerges from the distillation of 1st-order concepts into 2nd-order themes and aggregate dimensions, reflects the relational and hybrid capabilities required to govern the interaction between algorithmic collectives and human actors across heterogeneous contexts, moving from a mere technical description to an idiographic understanding of 'how' and 'why' human-algorithm interaction produces innovation within specific institutional and cultural boundaries. (Stelmaszak et al., 2025; Yin, 2018).

Case Selection Criteria

The selection of IBM as the unit of analysis was not random but guided by the principle of theoretical sampling. IBM was identified as a "critical case" for the investigation based on three fundamental motivations:

1. ***Technological Maturity and Leadership:*** IBM is historically a pioneer in digital transformation and the development of Artificial Intelligence and IoT solutions. Its suite of Digital Twin solutions (particularly IBM Maximo) is among the most mature and widely adopted in the global market. This ensures that the collected data reflects deep and established knowledge of the phenomenon, moving beyond a purely experimental dimension.
2. ***Internal Comparability (Technology as a Constant):*** As a single multinational corporation, IBM shares the same technological platforms, operating procedures, and corporate culture worldwide. This factor is crucial for the internal validity of the research: it allows the technology to remain a constant variable, thereby isolating the analysis of the impact of geographic context and local human capital as independent variables.
3. ***Relevance of Geographical Contrast:*** Comparing the Silicon Valley division with IBM Italy provides an ideal contrast for the study. Silicon Valley represents the ecosystem of *Early Adopters*, characterized by a high propensity for risk. Italy, and specifically the Bari hub, operates within a context characterized by a different industrial fabric (predominantly SMEs), stricter European regulations, and a different risk culture. This gap maximizes the opportunity to observe how environmental factors shape the required competencies.

To bridge the gap between these geographical contrasts, the transatlantic comparison is operationalized through three specific analytical lenses that guide the investigation of both hubs:

- ***Logic of Innovation:*** Contrasting the hyper-growth orientation of the U.S. ecosystem with the resiliency and PNRR-driven transformation objectives characterizing the Italian context.

- ***Organizational Fabric:*** Examining the tension between global standardized ecosystems and the challenges of integrating advanced models within SME-dominated local industrial clusters.
- ***Managerial Culture:*** Analyzing the shift from technological risk-taking and objectivism to a model based on cultural mediation and the management of 'wicked problems' in complex institutional environments.

3.4.1 Strategic Vision from Silicon Valley (USA)

In the present research design, the U.S. technological pole, identified with the Silicon Valley ecosystem, represents the "theoretical plane" where the constructs of digital transformation are originally conceived and formalized. In this context, the adoption of cutting-edge technologies such as Digital Twins is interpreted not merely as a technical choice, but as the outcome of a hyper-growth logic and an orientation toward technological objectivism, where social phenomena are treated as external facts independent of the observer (Bell et al., 2019). The strategic vision emerging from this ecosystem is exemplified by IBM's approach through the IBM Maximo Application Suite, a platform that integrates artificial intelligence, IoT, and predictive analytics (Watson Studio and Watson Machine Learning) to support managerial decision-making in environments characterized by a high rate of change. In such high-velocity environments (HVE), U.S. managerial praxis challenges traditional paradigms: decisional speed is not achieved by reducing information, but by increasing the use of real-time data to identify and respond promptly to threats and opportunities.

Interpreting the IBM case from an organizational perspective, the Silicon Valley vision is configured as a process of transformative strategic planning. As observed in critical case studies on radical corporate transformations, the success of technological integration does not depend on overlaying new systems onto old structures, but on the organization's ability to restructure itself, shifting from a capacity-driven to a customer-driven logic (Markus, 1983; Yin, 2018). This transition reflects the existence of a "nomological network" of constructs, where algorithmic agency is not limited to executing tasks but activates complex processes of human-algorithm interaction (Bhattacherjee, 2012; Stelmaszak et al., 2025). In this perspective, delegation is no longer unidirectional (from human to machine) but distributed: collectives of reflective algorithms collaborate with human actors, influencing professional routines and identities through continuous flows of trace data and choice data (Stelmaszak et al., 2025).

However, even in a context dominated by objectivism, the interpretative inquiry reveals that the organizational order of Silicon Valley is not an inert structure, but rather a "negotiated order." The rules and procedures of platforms like IBM Maximo are not simple commands, but "general understandings" that are continually renegotiated by Executive Architects in their daily work. This strategic vision assumes that social reality is produced through interaction, rendering the Digital Twin a dynamic entity that evolves alongside the sense-making practices of the actors involved. Therefore, the North Atlantic vision serves as a catalyst for the proposed hybrid competence model, formulated in this research through the synthesis of IBM's technical requirements and the relational dimensions identified in the literature (e.g., Stelmaszak et al., 2025; Zuboff, 1988), in which the manager must possess not only technical skills but also the relational capacity to govern the interaction between algorithmic autonomy and human discretion.

In summary, the Silicon Valley vision serves as a "theoretical prism" that deconstructs the complexity of Digital Twins into global standards of efficiency and innovation. This perspective, while rooted in a culture of risk and extreme optimization, implicitly recognizes that digital transformation is an act of "disciplined imagination," where theory serves to guide empirical inquiry toward the discovery of new ways of organizing work in the era of artificial intelligence (Shepherd & Suddaby, 2017; Yin, 2018).

3.4.2 Local Excellence: The IBM Bari Hub in the Southern Italian Context

Within the present research design, the IBM Bari hub represents the fundamental embedded unit for understanding how the global strategic vision collides and integrates with the contingencies of a specific local ecosystem. While the Silicon Valley pole defines the logical architecture of Digital Twins through platforms such as the IBM Maximo Application Suite, the Bari center operates as a "laboratory" of cultural and organizational translation. In this context, technological adoption ceases to be a linear process of knowledge transfer (Mode 1: traditional, academic, and context-free knowledge) and is transformed into a process of co-production (Mode 2: knowledge that is generated within the specific context of application and is socially accountable). In this transition, the 'transfer' of the Silicon Valley model is replaced by a local 're-construction' that requires sensitivity toward the institutional logics of the territory.(Gibbons et al., 1994).

The managerial challenge in Southern Italy, specifically the task of orchestrating advanced Digital Twin adoption within a fragmented fabric of Small and Medium Enterprises (SMEs), is configured as a classic example of a 'wicked problem'. This involves navigating the 'wall of complexity' created by the gap between high-tech requirements and the traditional organizational structures of local firms. (Bell et al., 2019; Ferraro et al., 2015). Consequently, the implementation of Digital Twins does not merely concern the efficiency of technical processes but requires constant political and social mediation. In this scenario, the Bari hub acts in synergy with the directives of the National Recovery and Resilience Plan (NRRP/PNRR) and the ICSC National Centre, configuring an environment in which institutional pressures drive a radical change in business models. To overcome resistance to change, IBM managers utilize 'hooking' (connecting the new technology to existing organizational priorities) and 'anchoring' (rooting the innovation in deeply held local values) strategies. For example, instead of focusing solely on ROI, the Digital Twin is presented as a tool to enhance labor dignity and operational safety, values that resonate more effectively with the local workforce and institutional stakeholders.

Regarding the organization of work, the Bari hub allows for the observation of the reconfiguration of professional routines in the face of algorithmic agency (Stelmaszak et al., 2025). Here, the use of Watson Studio and Maximo’s predictive models is not imposed as a hierarchical command but emerges as a "negotiated order" (Strauss et al., 1973). Local Executive Architects must manage processes of "distributed delegation," in which human discretion is intertwined with the automated decisions of algorithms (Stelmaszak et al., 2025). This dynamic requires a set of hybrid competencies that go beyond mere technical mastery, embracing the relational capacity necessary to navigate the "multiple realities" perceived by the various actors in the territory (Bell et al., 2019; Flick, 2013).

In conclusion, the analysis of the Bari pole offers a "thick description" (Geertz, 1973) that illuminates how global technological excellence is filtered through local culture. This approach allows for the transcendence of the limits of nomothetic explanations, aiming instead for an idiographic understanding that explains "how" the interaction between human actors and algorithmic collectives produces innovative solutions in complex institutional contexts (Stelmaszak et al., 2025). The Bari hub is, therefore, not just an operational site, but a crucial node in which the Digital Twin is "made real" through sense-making practices that account for the socio-economic specificities of Southern Italy.

3.5 The Case Study: The IBM Maximo Project

IBM Maximo stands as one of the world's most advanced Enterprise Asset Management (EAM) solutions, evolving from a traditional maintenance platform into an AI and IoT-driven integrated suite of applications. This evolution reflects the shift toward what Porter and Heppelmann (2014) define as "smart, connected products," which necessitate a radical reconfiguration of operational capabilities and corporate boundaries. With the release of the IBM Maximo Application Suite (v8.0), the platform has become the enabling infrastructure for developing industrial-scale Digital Twins, realizing the model of "co-evolution" between physical and virtual systems theorized by Grieves (2017) to mitigate unpredictable emergent behaviors in complex systems. For the purposes of this research, IBM Maximo is not viewed merely as a software tool but as an enabler of complex organizational routines. According to the evolutionary theory of Nelson and Winter (1985), routines are patterns of behavior that define organizational capabilities. Maximo institutionalizes these patterns by standardizing diagnostic processes, spare parts procurement, and reporting workflows through its integrated suite. It transforms individual 'know-how' into a systemic, data-driven process where the machine triggers the routine (e.g., an automated work order based on sensor data), thereby redefining how the organization 'remembers' and executes its technical operations. Its core functionality lies in its ability to monitor the asset lifecycle in real-time, utilizing predictive analytics to transform raw data into managerial decisions. The IBM Maximo Application Suite (MAS) integrates several core functionalities to support this transition:

Maximo Monitor: provides AI-powered remote monitoring at scale, utilizing IoT sensors to detect anomalies in asset behavior.

Maximo Health: uses sensor data and maintenance history to provide a 'health score' for critical equipment, allowing managers to prioritize interventions.

Maximo Predict: employs Machine Learning models (Watson) to identify patterns that precede failures, shifting maintenance from scheduled to predictive.

A concrete example of this application can be found in the management of a high-speed railway turbine: sensors monitor vibrations and temperature in real-time (Monitor). When the AI identifies a frequency pattern associated with bearing fatigue (Predict), Maximo automatically generates a work order and assigns it to a technician via a mobile device, including the necessary technical manuals and parts list. This process eliminates human delay and ensures the turbine is serviced just before a failure occurs, optimizing both safety and costs. As suggested by Zuboff (1988), such technologies do not merely "automate" tasks but "informate" the entire organization, making previously opaque processes visible and demanding new forms of authority based on data-driven insight rather than traditional hierarchy.

This technology is functional to the study as it redefines the nature of required competencies by demanding hybrid professional profiles capable of managing what Lee et al. (2015) describe as Cyber-Physical Systems architecture; it facilitates bridging the gap between technical and managerial skills while simultaneously providing the necessary tools to overcome the "Wall of Complexity" through the implementation of cognitive maintenance; finally, such an evolution aligns directly with the ICSC Spoke 9 objectives, framing the Digital Twin not merely as a technical asset but as a fundamental pillar for building a more resilient and sustainable digital society.

In detail, this dissertation is the result of a three-year research project that began in 2023, coinciding with the start of the Ph.D. program. From its early stages, the work was framed within the ICSC National Centre, focusing on the organizational challenges posed by Digital Twins within Spoke 9.

A crucial turning point in the research occurred in late 2024, when the first institutional contact was established with the University of Lausanne (UNIL) in Switzerland, within the

SGS Department (Department of Strategy, Globalization and Society), the chosen host for the international visiting researcher period. This opportunity served as the bridge to the global dimension of the case study: upon arriving at UNIL, I was immediately put in contact with IBM Executive Architects. This privileged access was made possible by the long-standing network of relationships and previous scientific collaborations that the SGS Department has established with IBM over the years, facilitating a seamless integration between academic inquiry and corporate strategic vision. The field investigation process was structured according to a logical sequence:

1. ***Documentary Screening Phase:*** while at the SGS Department at UNIL, I conducted an in-depth study of internal documents, strategic reports, and IBM Maximo suite manuals. This phase was essential for building a solid technical knowledge base and identifying gaps in the managerial literature.

2. ***Elite Interviews Phase:*** facilitated by the department's institutional ties, I proceeded with semi-structured interviews with the Executive Architects. This approach allowed for the elicitation of the tension between global strategic vision (Silicon Valley) and operational practice.

3.6 Data Collection and Triangulation

The data collection phase and the corresponding triangulation strategy constitute the methodological centerpiece of this investigation. They are configured not as a mere linear procedure, but as a recursive and reflexive process in which the generation of empirical evidence proceeds in tandem with the refinement of analytical categories (Flick, 2013; Yin, 2018). To ensure scientific rigor and mitigate the limitations of monocular observation, the research applies the principle of methodological and data source triangulation. This approach aims to counterbalance the potential deficiencies inherent in any single method and to strengthen construct validity through the convergence of multiple lines of evidence (Thurmond, 2001; Yin, 2018). According to Yin (2018) and Patton (1999), triangulation involves the use of multiple sources of evidence to study the same phenomenon, allowing the researcher to corroborate findings and mitigate the biases inherent in any single data collection method. In a complex context such as digital transformation, relying on a single source would be limiting; instead, triangulation enables the development of converging lines of inquiry, thereby increasing the scientific value and the "trustworthiness" of the qualitative analysis (Flick, 2013).

As established in the seminal work of Denzin (1978), there are four primary forms of triangulation in qualitative research:

1. ***Data Triangulation:*** The use of a variety of data sources (e.g., different individuals, groups, or points in time) within the same study.
2. ***Investigator Triangulation:*** The involvement of several different researchers or evaluators in the data collection and analysis process to reduce individual observer bias.
3. ***Theory Triangulation:*** The use of multiple theoretical perspectives or hypotheses to interpret a single set of data.
4. ***Methodological Triangulation:*** The use of multiple methods to study a problem, such as combining interviews, observations, and surveys (within-method or between-method).

Among these forms, this study specifically focuses on Data Triangulation. This choice involves crossing primary data (in-depth interviews) with secondary data (technical documents, strategic reports and field observations) to ensure a holistic understanding of the relationship between technology and organization.

The choice of this specific methodological strategy is driven by the multifaceted and socio-technical nature of the Digital Twin. Since the phenomenon under investigation involves both technical specifications (the software suite) and organizational dynamics (the required competencies), a single-source approach would fail to capture the full picture. Specifically, the rationale for choosing data triangulation in this research is threefold:

Alignment between Strategy and Practice: It allows the researcher to verify if the "official" competencies described in corporate strategic documents align with the actual skills identified by high-level practitioners during interviews.

Mitigation of Subjectivity: By comparing the insights gained from an Elite Interview with technical manuals and institutional reports (ICSC/PNRR), the research provides a safeguard against the potential subjectivity of individual perspectives, ensuring that the findings are grounded in multiple organizational realities.

Contextual Depth: It enables the analysis to distinguish between universal technical requirements (found in documents) and "situated" managerial skills that emerge only through the lived experience of experts working between the Silicon Valley vision and the Italian industrial fabric.

The data collection process was systematically structured to map the competencies required to manage Digital Twin ecosystems, with a specific focus on the IBM Maximo suite. The approach adopted is analytical-interpretive, aimed at reconstructing both the strategic vision and the operational practice through the convergence of three primary sources of evidence:

- *Elite Interview (Primary Data):* Two in-depth, semi-structured interviews were conducted with high-level representatives from IBM's technical and strategic leadership: specifically, the Executive Architect for IBM Italy and the Executive Architect for IBM Silicon Valley. This dual-source approach was essential for capturing the high-level "vision" from both the transatlantic strategic core and the local operational hub. These elite interviews provided "insider" knowledge that is inaccessible through standard surveys, offering a deep dive into the decision-making logic and the evolution of managerial competencies required to orchestrate complex Digital Twin technologies across different institutional contexts.
- *Documentary Analysis (Secondary Data):* A systematic analysis of technical and strategic documents related to the IBM Maximo suite (including technical manuals, corporate white papers, and official case studies) was performed. This source allowed

for the identification of the "hard" technical requirements and platform functionalities that define the objective scope of the necessary skills.

- *Institutional Context and Field Notes (Observation):* Data collection was further integrated with an analysis of strategic reports from ICSC Spoke 9 and the PNRR framework. This allowed the gathered data to be situated within the broader societal and institutional requirements of the "Digital Society," providing a macro-level perspective on the research problem.

By synthesizing these three sources, the research was able to compare the global strategic vision (rooted in Silicon Valley) with the operational reality of the Bari hub. This triangulation was key to identifying the discrepancies and synergies between abstract technological requirements and the actual human capital needs in a specific local context.

3.6.1 Elite Interview: Insights from an Executive Architect

One of the primary data sources utilized for this research consists of semi-structured interviews with elite informants, specifically identified as IBM Executive Architects. Corbetta (2014) defines the qualitative interview as "a conversation provoked by the interviewer, having a cognitive purpose, guided by the interviewer on the basis of a flexible and non-standardized questioning scheme." Qualitative methods, such as interviews, allow for capturing the richness of themes emerging from the respondent's discourse rather than reducing responses to quantitative categories (Smith, 1995). The fundamental objective of this investigation method is to access the subject's perspective, grasping their mental categories, interpretations, perceptions, and the motives behind their managerial and strategic actions. The adopted analysis methodology is particularly suited to the characteristics of the topic at hand, as qualitative interview forms are ideal for complex phenomena not yet clearly defined from an organizational perspective, such as Digital Twin implementation and the mapping of competencies required for their governance. The advantages of the qualitative interview applied to this study reside in the possibility of:

1. giving voice to subjects (Executive Architects) outside of pre-established schemes, allowing for the emergence of a "vision" that transcends technical data;
2. ensuring greater flexibility compared to closed questionnaires, adapting to the varying technological maturity of the observed hubs (Silicon Valley vs. Bari);
3. detecting and exploring non-verbal aspects and leadership nuances fundamental to understanding human capital;
4. quickly grasping the dimensions (strategic, technical, and territorial) that characterize the Digital Twin phenomenon.

The interviewees were selected based on their specific roles and direct experience in Digital Twin or Digital Transformation projects, following a purposive sampling strategy. The sample includes heterogeneous profiles, to ensure a triangulation of perspectives and to capture the complexity of the phenomenon from various organizational angles. Table 3 summarizes the profile of the participants involved in the study, highlighting their location and professional experience.

Table 3: Profile of Elite Informants. Source: Author’s elaboration

ID	Professional Role	Organization	Location	Experience	Time
EA-01	Executive Architect	IBM	Silicon Valley (USA)	22+ Years	120 min
EA-02	Executive Architect	IBM	Bari Hub (Italy)	31+ Years	120 min

Structure of the Interview Protocol

The semi-structured interview protocol was designed not as a rigid list of questions, but as a flexible guide structured into five thematic areas mirroring the research objectives. This framework allowed for the elicitation of the Executive Architect’s "vision" while ensuring data comparability between the U.S. and European technological hubs.

The macro-areas of the protocol are defined as follows:

Area 1: Cultural Dynamics and Innovation Systems (Contextual Mindset): This section explores the dialectical tension between Silicon Valley’s "fail fast" culture and the conservative approach typical of traditional European industry. The objective is to decode how risk aversion influences the speed of Digital Twin adoption and the broader perception of the technology itself. In the case analysis, this area is operationalized by contrasting the Silicon Valley 'fail fast' mindset, observed in the rapid prototyping of AI services, with the conservative resilience of the Bari Hub, where innovation is modulated by the institutional requirements of the PNRR.

Area 2: Mapping Hybrid Competencies (The Skill Gap): Grounded in the analysis of the IBM Maximo suite, the investigation focuses on the "human bottleneck." It examines whether the primary barrier resides in technical coding skills or in the managerial capacity to translate algorithmic data into strategic value, thereby validating the requirement for hybrid professional profiles. The empirical investigation of the IBM Maximo suite highlights this 'bottleneck', showing that technical mastery of the software must be integrated with the managerial ability to interpret 'choice data', effectively validating the need for hybrid profiles.

Area 3: Algorithmic Agency and Human-Centricity: Through the analysis of pioneering projects (such as "JimTwin"), the interview explores the evolution of Digital Twins toward human-centric models. This section aims to understand how technology can augment human decision-making and identifies the new relational capabilities required to interact with "digital doubles." This aspect is specifically addressed through the analysis of the concept of "distributed delegation", exploring how Maximo's predictive models enhance, rather than replace, human decision-making in the industrial routines of the Bari Hub.

Area 4: The Academic and Educational Gap (Education): This area examines the discrepancy between university curricula and the actual requirements of industry leaders like IBM. The goal is to define the ideal profile of a "Digital Twin Manager" and identify the pillars of a potential interdisciplinary Master’s degree. The case study provides evidence for this gap by examining the collaboration between the IBM Bari Hub and the University of Bari, highlighting the need for interdisciplinary 'cross-faculty' programs to bridge the current educational discrepancy.

Area 5: Human Capital Acquisition Strategies (Make vs. Buy): The final section analyzes managerial logic in the face of skill shortages: the choice between internal upskilling and the acquisition of external talent. This comparison highlights the structural differences between the Silicon Valley and Mediterranean labor markets. The analysis contrasts the Silicon Valley

'Make' logic (internal talent development) with the Bari 'Buy/Partner' strategy, where SMEs often acquire competencies through IBM's orchestration or educational prototypes.

Regarding the research instrument, the interviews were conducted synchronously via the Google Meet platform. Each session lasted an average of approximately two hours, a timeframe considered appropriate for delving into the complexity of the topics covered and allowing the Executive Architects to provide articulate responses rich in strategic detail. As these interviews targeted privileged informants within the IBM system, it must be emphasized that they are inherently heterogeneous and not immediately comparable in a quantitative sense. Each interview, conducted with technical leaders from both Silicon Valley and the Bari Hub, can be interpreted as a standalone case, distinguished by specific characteristics linked to the relevant socio-economic context. This reflects the fact that these professionals, while belonging to the same organization, operate in different ecosystems, each having their own personal "technological and managerial history" to recount. This approach is consistent with Patton (1999), for whom the qualitative interview aims to understand how the subjects see the world, learning their terminology and their way of judging. The interviews were conducted based on a guide or interview protocol (see Appendix A), which identified the key topics while leaving the interviewer the task of introducing themes related to strategic vision, competencies, and the relationship with the territory. The interviewer allowed the interviewee to develop their own perspective, pushing for deeper insights whenever topics relevant to the research, such as overcoming the "wall of complexity", emerged. During execution, the interviewer also played a control role, ensuring the conversation did not stray toward topics disconnected from organizational theory. The high degree of detail in the protocol ensured that all relevant themes were addressed while granting both parties the freedom to explore the most effective lines of inquiry for the specific moment. Finally, once the responses were transcribed, the data coding phase (Corbetta, 2014) was implemented, transforming technical discourse into analytical categories useful for the final framework of the thesis.

The results of these five thematic areas, elicited through the elite interviews and documentary triangulation, serve as the foundational data for the coding process described in Section 3.7.

They provide the empirical evidence required to build the second-order themes and the final aggregate dimensions of the situated competency framework.

3.6.2 Documentary Analysis: IBM Maximo Suite and Strategic Reports

To complement the primary data, a systematic Documentary Analysis was conducted. This phase involved the study of secondary data to establish an objective "technical and institutional baseline" for the research. The analysis was performed using Qualitative Content Analysis, a method that allows for the subjective interpretation of the content of text data through the systematic classification process of coding and identifying themes or patterns (Hsieh & Shannon, 2005).

The documentary corpus was categorized into three main pillars:

IBM Maximo Technical Documentation (v8.0): This included technical manuals, integration guides, and functional specifications. The content analysis of these documents aimed to identify the "hard" technical requirements (e.g., IoT connectivity, AI algorithms, and predictive maintenance workflows) that define the objective scope of the necessary skills.

IBM Strategic White Papers and Case Studies: These corporate documents were analyzed to extract the official "strategic vision" of the company. They provided insights into how IBM conceptualizes the ROI of Digital Twins and which managerial leadership models are promoted as benchmarks for digital transformation success.

Institutional Reports and National Frameworks (ICSC Spoke 9 & PNRR): The analysis was extended to the strategic reports of the ICSC National Centre and the programmatic documents of the Italian PNRR. This integration was crucial to situate the technological requirements within the broader "Digital Society" objectives, ensuring the research accounts for the institutional pressures and sustainability goals of the Italian ecosystem.

This documentary foundation provided the necessary "nomological network" of the construct to frame the subsequent in-depth interviews, ensuring that the proposed competency framework is not merely technically accurate, but reflects the relational capacity required to govern contemporary digital transformation (Bhattacherjee, 2012). The understanding of the

Digital Twin thus emerges as a "negotiated order" between what is prescribed within the Maximo manuals and what is daily renegotiated within the organizational fabric (Strauss et al., 1973; Yin, 2018).

3.7 Data Analysis

As highlighted throughout this chapter, qualitative research is profoundly embedded in organizational and social contexts, requiring a rigorous process to translate raw data into theoretical insights capable of generating new knowledge. The analysis conducted in this thesis follows an analytical-interpretative approach aimed at deconstructing the complexity of the Digital Twin ecosystem through the methodological triangulation of multiple sources, ensuring a holistic perspective that captures both global dynamics and local contingencies.

In line with the arguments of Flick (2013) and Bell et al. (2019), data analysis begins in parallel with the research itself, configuring an iterative and recursive process. In this way, the researcher is fully engaged in fieldwork, whether through elite interviews, document analysis, or the interrogation of technical suites, proceeding with systematic readings and re-readings of empirical material to interpret structures of meaning.

In this phase, the primary goal is to understand research findings through a full immersion in the data, treating observations not as isolated variables but as components of a "negotiated order" within the organization. In the present study, this immersion was further strengthened by the manual transcription of interviews, an operation that Kowal and O'Connell (2014) define as a crucial and indispensable step of analysis; it allows for a superior command of discursive nuances, specialized technical terminology, and the strategic visions expressed by Executive Architects.

Interpretative analysis is therefore not limited to mere data reduction; rather, it works to "inform" organizational reality, making visible complex processes and human-algorithm interactions that a purely mechanical coding process would fail to convey in their entirety. Through this constant dialectical shuttling between theory and evidence, the research aims for analytical generalization, where interpretation does not seek a universal truth but a plausible and theoretically grounded explanation of the "how" and "why" of how digital innovation transforms contemporary managerial routines.

Thematic Analysis

The primary method adopted for data processing in this study is Thematic Analysis, an analytical strategy widely utilized in management and business sciences for its capacity to offer a structured yet inherently flexible interpretation of complex organizational phenomena. In alignment with the interpretative approach of this research, thematic analysis is conceived not as a merely mechanical classification procedure, but as an act of meaning production aimed at decoding the latent structures and underlying patterns within the analyzed texts. As highlighted by Bell, Bryman, and Harley (2019), a theme is more likely to be identified the more frequently the phenomenon it refers to recurs during the coding process, thereby providing a "springboard" for the theoretical understanding of the data's generality.

The coding operation was operationalized through the Gioia Methodology (Gioia et al., 2013), a systematic approach designed to enhance the qualitative rigor of inductive research. This process moved beyond simple labeling to build a structured Data Structure, consisting of three distinct levels of abstraction:

1. *1st-Order Concepts: Initially*, the analysis adhered closely to informant-centric terms, identifying raw codes from the interview transcripts and technical documents. Following the coding cycles suggested by Saldaña (2021), this phase captured specific insights into operational frictions, such as 'algorithmic speed' or 'Southern Italy’s industrial fabric complexity'.
2. *2nd-Order Themes:* In this stage, the researcher-centric perspective emerged. The 1st-order codes were distilled into more abstract, theoretically relevant themes, such as 'Algorithmic Agency' or 'Contextual Mediation'. This allowed for the identification of recurring patterns like the Skill Gap and the Context Gap within a broader theoretical framework.
3. *Aggregate Dimensions:* Finally, these themes were synthesized into overarching dimensions that form the pillars of the final competency framework.

This systematic progression ensures that the themes are not merely descriptive but are analytically linked to the data, creating a transparent 'chain of evidence' (Yin, 2018) that leads from the raw interview excerpts to the final theoretical conclusions.

To ensure the transparency of the 'chain of evidence' (Yin, 2018), Table 4 illustrates the hierarchical progression of the analysis. While this Data Structure provides a visual map of the coding process, the exhaustive results, including the 'thick description' (Geertz, 1973) and the supporting informant excerpts for each dimension, are presented in detail in Chapter 4. This allows for a clear separation between the description of the methodological rigor (Chapter 3) and the comprehensive discussion of the empirical findings (Chapter 4).

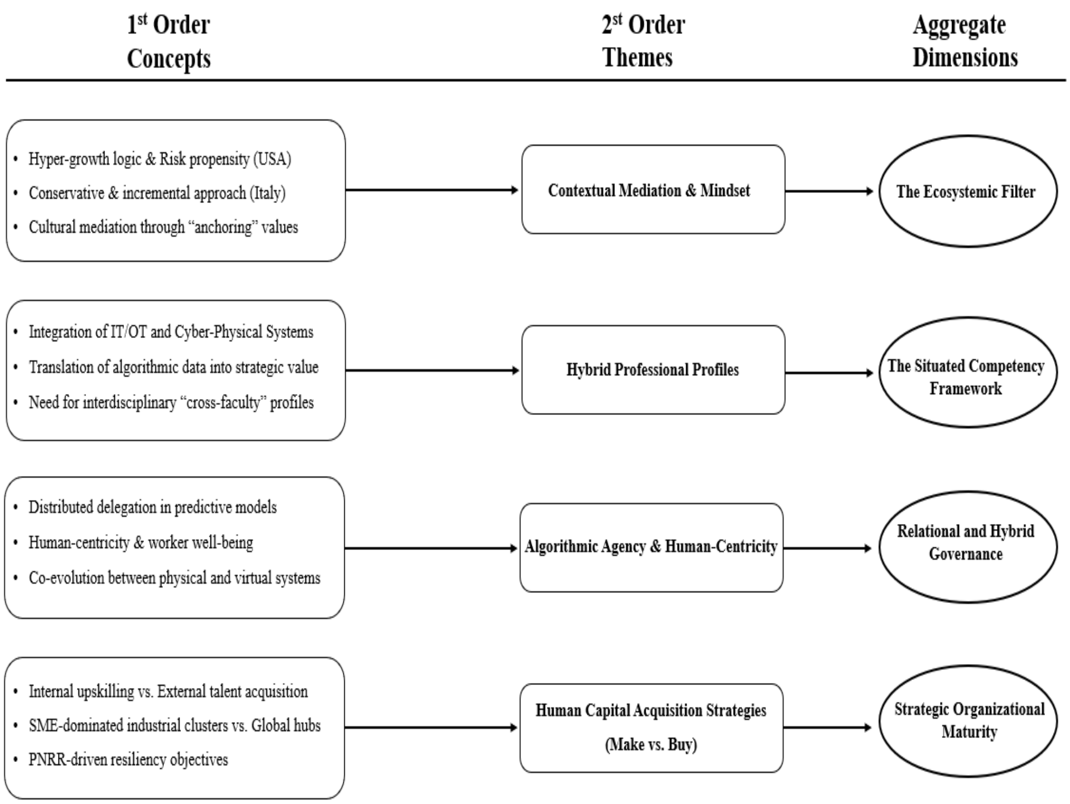

Fig. 3: Data Structure (Source: Author's elaboration based on Gioia et al., 2013).

Following the classic definitions in the literature, the identified themes capture the essence of the participants' reflections regarding the evolution of managerial roles, the socio-technical complexity of Digital Twin ecosystems, and the dialectical tension between global strategic visions and local operational realities. The analysis thus proceeds through a process of data reduction that does not stop at superficial description but aims for a higher-level synthesis performed through the lens of existing literature. This analytical progression, moving from first-order concepts (centered on informant terms) toward second-order themes (centered on researcher constructs), facilitates the construction of a robust data structure and the creation of a comprehensive competency framework for the digital era.Ultimately, the thematic synthesis serves as a bridge between empirical evidence and theoretical development, allowing the research to achieve an analytical generalization capable of challenging and extending established paradigms in contemporary management. For this study, the identified themes capture the essence of what the participants expressed regarding:

1) the evolution of managerial roles;
2) the socio-technical complexity of Digital Twins;
3) the friction between global strategic visions and local operational realities.

By synthesizing these themes through the lens of the existing literature (Chapter 2), the analysis moves beyond mere description to the creation of a comprehensive framework of competencies for the Digital Twin era.

To fulfill the promise of a 'thick description' (Geertz, 1973), the following chapter provides the comprehensive qualitative analysis of the interview transcripts, supporting each theoretical dimension with direct informant excerpts. Furthermore, Chapter 4 integrates these findings with the Systematic Literature Review established in Chapter 2, discussing how the empirical evidence either challenges or extends existing paradigms regarding the Digital Twin skill gap.

3.8 Ethical Considerations, Rigour and Research Limitations

The conduct of the present research was guided by rigorous ethical standards, ensuring that every phase of interaction with elite informants strictly adhered to confidentiality protocols and professional ethics (Bell et al., 2019; ESRC, 2015). Participation in the interviews was strictly voluntary, and each participant was informed in advance of the study's cognitive objectives, ensuring that the informed consent process was not a mere bureaucratic formality but a substantial act of transparency (Bell et al., 2019; ESRC, 2015). Professional anonymity and data processing were guaranteed in compliance with current GDPR regulations, fostering a climate of reciprocity and mutual trust. This was fundamental for accessing high-level strategic information and overcoming the power asymmetries typically found when engaging with powerful institutional actors (Bell et al., 2019; GDPR, 2018). The robustness and trustworthiness of this qualitative research design are ensured through the criteria of credibility, transferability, dependability, and confirmability, as defined by the seminal work of Lincoln and Guba (1985). Specifically, the credibility of the findings is supported by the constant triangulation of data sources (interviews, documents, and technical observations), ensuring that inferences are not the product of a monocular observation but emerge from the convergence of multiple lines of evidence (Lincoln & Guba, 1985; Yin, 2018). Transferability is guaranteed by the production of a "thick description" (Geertz, 1973) of the context regarding the IBM Maximo suite, providing the reader with the necessary elements to assess the degree of "fit" or applicability of the results to similar digital ecosystems (Lincoln & Guba, 1985; Yin, 2018). Dependability and confirmability were further strengthened by the creation of a case study database, which acts as a robust audit trail capable of demonstrating the integrity of the analytical process and the absence of arbitrary researcher influence (Lincoln & Guba, 1985; Yin, 2018). It is, however, necessary to acknowledge certain intrinsic methodological limitations of this study. A noted limitation is the purposive sampling of a small number of elite informants. However, in line with the 'revelatory case' logic (Yin, 2018), the depth of insight provided by Executive Architects, who possess a unique, bird's-eye view of both global strategy and local application, compensates for the lack of statistical breadth. This approach prioritizes analytical density over numerical representation, which is essential for exploring the nascent field of Digital Twin governance. Consequently, the primary objective does not lie in statistical generalization to a population, typical of nomothetic approaches, but rather in analytical generalization, aimed at challenging or expanding theoretical constructs (Yin, 2018). The latter aims to utilize empirical findings to challenge, corroborate, or expand theoretical constructs related to the organizational dynamics of Digital Twins, favoring a situated and profound understanding of digital transformation processes (Bell et al., 2019; Yin, 2018).

From this perspective, the IBM case serves as a "theoretical prism" through which to observe complex phenomena that transcend the specificity of the organization studied (Yin, 2018). In conclusion, this methodological framework, while mindful of its own boundaries, provides a rigorous and transparent foundation for the transition to the next chapter, where the collected data will be translated into the final competency framework for the era of the Digital Twin.

Chapter 4. Findings, Discussion, and Conclusions

4.1 Synthesis of Key Empirical Findings

The present research finds its genesis within the ambitious institutional framework of the ICSC National Research Centre, specifically in the context of Spoke 9, dedicated to the "Digital Society & Smart Cities" and funded by the National Recovery and Resilience Plan (PNRR). The investigation's point of departure is the observation of a fundamental paradox: while computing infrastructure and computational models are rapidly advancing toward exascale capabilities, human and organizational readiness is struggling to keep pace, creating what is defined as the "complexity wall". In this scenario, the Digital Twin (DT) paradigm emerges as the tool of choice for navigating the intricacies of digital societies, offering virtual replicas capable of predicting evolutions and supporting strategic decision-making. However, this research highlights that while the Digital Twin is a technically mature technology, it remains profoundly immature as an organizational practice, as its implementation is often hindered by a significant skill gap and cultural resistance rather than by technological limitations. To deconstruct this complexity, the thesis initially undertook a theoretical trajectory by defining Digital Transformation not merely as technical adoption, but as a process of holistic reinvention of organizational identity. It is essential to distinguish actual transformation from digitization (analog-to-digital conversion) and digitalization (optimization of existing processes). Through a PRISMA compliant Systematic Literature Review (SLR) of 55 selected articles, the necessary competencies were mapped across four interconnected macro-dimensions: technical (IT/OT integration), cognitive (sense-making and systems thinking), soft (cross-functional collaboration) and managerial (leadership and change management). A critical result emerging from the SLR is the identification of a profound "contextual blindness" (Context Gap); the current literature tends to treat competencies as a universal and static set, systematically ignoring how geographical and ecosystemic factors influence talent development. To bridge this theoretical void, the research moved to an empirical plane by adopting a qualitative interpretivist approach, which views the organization not as an inert structure, but as a negotiated order produced by the interactions between actors. The choice of methodology fell upon the critical and revelatory case study of IBM, analyzed not merely as a technology provider but as an “orchestrator” of skills through platforms such as the IBM Maximo Application Suite. The scientific rigor of the analysis is ensured by data triangulation, intersecting elite interviews, documentary analysis and institutional reports and by the application of the Gioia Methodology, which allowed for the transformation of informant-centric concepts into aggregate dimensions through a transparent chain of evidence. The core of the analysis lies in the transatlantic geographical contrast between two IBM centers of excellence: Silicon Valley and the Bari Hub. The interviews reveal a deep cultural divergence: on one hand, the U.S. ecosystem is dominated by a logic of hyper-growth and a “fail fast” culture, where rapid experimentation is seen as the primary vehicle for learning. On the other hand, the Italian reality confronts an industrial fabric of SMEs and a more conservative, incremental approach, where the challenge is not speed for its own sake, but the cultural mediation necessary to overcome resistance to change and translate technological complexity into value for the local business. In conclusion, the thesis demonstrates that skill management for the Digital Twin cannot overlook a situated vision, in which the manager must evolve into the role of a “translator of processes and cultures”. This figure does not merely possess technical abilities but masters hybrid capabilities, understood as the critical intersection between the mastery of cyber-physical systems and sense-making capabilities. Such a synthesis is fundamental for governing new processes of distributed delegation, where algorithmic autonomy does not replace the human but rather enhances strategic discretion. By overcoming the “contextual blindness” identified in the literature, the research moves toward a vision of human-centricity, where the Digital Twin becomes an ally for worker well-being and the resilience of the SME industrial fabric. In this way, the work not only fills an academic gap but provides Spoke 9 of the ICSC with the key to transforming technological acceleration into a sustainable and lasting cultural transformation.

4.2 Mapping Competencies: Evidence from the Systematic Literature Review

The first significant result of this doctoral research emerges from the Systematic Literature Review (SLR) conducted on 55 selected peer-reviewed articles. This theoretical investigation allowed for the deconstruction of the "complexity wall" by identifying a multi-dimensional map of competencies required to govern the Digital Twin (DT) paradigm. Rather than viewing the Digital Twin as a purely technological artifact, the literature, when analyzed through a management lens, suggests that its success depends on a sophisticated "Skills Map" where technical mastery is only the foundational layer.

4.2.1 The Four Pillars of the DT Competency Framework

The SLR findings consolidate the necessary skills into four interconnected macro-dimensions, which collectively address the challenges of digital transformation:

Technical Proficiency and IT/OT Integration: At the base of the framework lies the ability to manage the convergence between Information Technology (IT) and Operational Technology (OT). This goes beyond traditional coding skills; it involves the mastery of Cyber-Physical Systems and the ability to ensure seamless communication between physical assets and their digital replicas.

Cognitive Skills and Sense-making: As the complexity of data grows, the literature highlights Systems Thinking and Sense-making as critical cognitive assets. These skills allow managers to navigate the intricacies of exascale data, transforming raw algorithmic outputs into strategic value and actionable insights.

Soft and Relational Skills as boundary spanning: Because the Digital Twin acts as a "boundary object" that intersects various departmental silos, relational skills are paramount. Cross-functional collaboration is identified as a vital competency for ensuring that the virtual model remains a shared and reliable reference point for all organizational actors.

Managerial Skills and pervasive change: Finally, the framework is orchestrated by managerial capabilities dedicated to leadership and change management. These are required to lead the holistic reinvention of organizational identity, moving the company from simple digitalization to a state of true digital transformation.

A critical synthesis of the 55 analyzed articles reveals a profound theoretical gap, defined in this research as “contextual blindness” or the Context Gap. The existing body of knowledge predominantly treats these four dimensions as a universal and static set of “best practices”. This standardized approach tends to move toward the hypothesis of universal skills, assuming that the requirements for a Digital Twin implementation are identical regardless of the industrial, geographical, or ecosystemic context.

The SLR results suggest that this lack of contextualization is one of the primary reasons for the high failure rate in organizational readiness. By ignoring how local factors, such as the socioeconomic fabric of an industrial cluster or national recovery plans like the PNRR, influence the development of talent, the literature provides a “decapitated” view of competency management.

In conclusion, while the SLR successfully maps the *“What”* (the types of skills needed), it fails to address the *“How”* (the adaptation of these skills to operational reality). This research argues that the transition from a universal model to a *“Situated”* competency framework is necessary to overcome the “complexity wall”. Competencies must be viewed as deeply rooted in operational reality, responding to specific challenges of IT/OT convergence that vary across different ecosystems. This theoretical finding provides the necessary mandate for the empirical investigation of the IBM case study, which seeks to observe how these four macro-dimensions are filtered and redefined by the transatlantic divide between Silicon Valley and the Bari Hub.

4.3 The Ecosystemic Filter: Navigating the Transatlantic Cultural Divide

The empirical analysis reveals that the implementation of Digital Twins is not a culturally neutral process; rather, it is filtered through the specific institutional and economic logics of the territory. This “ecosystemic filter” creates a profound divergence between the Silicon Valley pole and the Bari Hub, highlighting that technological excellence must be “translated” to survive in different environments.

To ensure qualitative rigor and transparency in this interpretative process, the following Data Structure (Figure 4) illustrates the inductive transition from raw informant quotes to the aggregate dimensions that define this transatlantic divide.

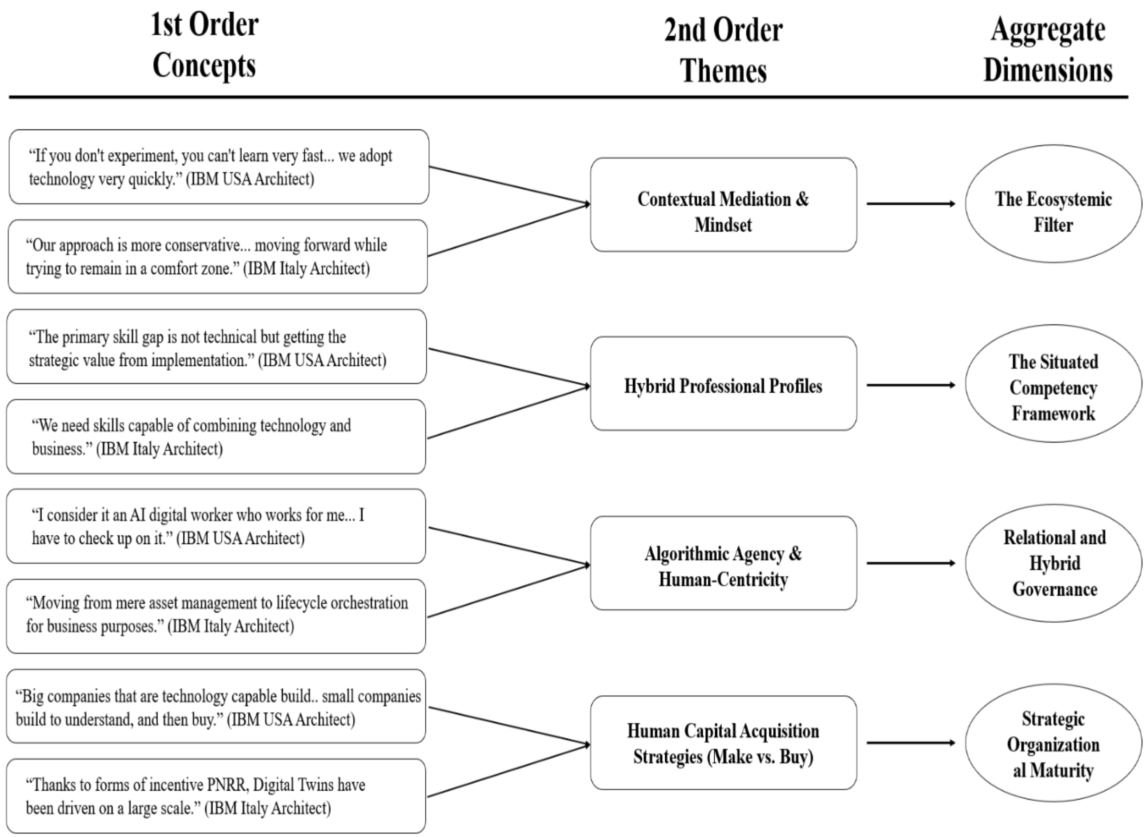

Fig. 4: Data Structure (Source: Author's elaboration based on Gioia et al., 2013).

4.3.1 Silicon Valley: Hyper-growth and the "Fail Fast" Logic

In the North American context, the Digital Twin is perceived through the lens of hyper-growth and rapid experimentation. The interviews with an IBM Executive Architect in the U.S. highlight a mindset where failure is not a terminal state but a fundamental vehicle for learning. In Silicon Valley, the adoption of technology is driven by an experimental urgency that contrasts sharply with the European "precautionary principle".

- The “Fail Fast” Mindset: The interviewee clarifies that in the Valley, the speed of learning is tied to the courage to prototype:

“I think here in Silicon Valley, our view is that [...] if you don't experiment, you can't learn very fast. So, you're right here in Silicon Valley, we tend to adopt technology very quickly”. (IBM Executive Architect, 2025).

- The Skill Gap Paradox: Contrary to the focus on technical coding, the IBM Executive Architect identifies the "bottleneck" in the inability to extract strategic value:

“The primary skill gap tends to be not technical but getting the strategic value from implementation of digital twins. [...] Building [them] can be very, very complex, both to build it and to maintain it. [...] Unlocking the strategic value for predictive maintenance is more mature than unlocking the value of digital twins in general”. (IBM Executive Architect, 2025).

In the managerial logic ecosystem, the main driver is competitive disruption. The “wall of complexity” is addressed by shifting the focus from simple automation to augmentation. The manager's role in Silicon Valley is to act as the “CEO of a startup” (even internally), managing a team composed of both humans and digital workers to ensure that technology serves a precise strategic purpose.

4.3.2 The Bari Hub: Institutional Mediation and the “Wall of Complexity”

In contrast to the North American "Fail Fast" mindset, the Italian context, observed through the Bari Hub, reveals a more conservative and incremental approach to Digital Transformation. The implementation of Digital Twins in this ecosystem is not driven by market disruption but by a logic of Resilience, where technology must be anchored to institutional goals and local industrial traditions.

- The IBM Executive Architect in Italy identifies the primary inhibitor not in the technology itself, but in the psychological and organizational difficulty of trusting a “digital mirror” of reality:

“Our approach is more conservative, incremental... Transposing a techno-organizational complexity into something digital and then trusting the simulations [...] is a complicated thing, even culturally. This is the main inhibitor we have in Italy: moving forward while trying to remain in a comfort zone”. (IBM Executive Architect, Italy, 2024).

- Key Strategic Skill (Cultural Mediation): Given the fragmented industrial fabric dominated by Small and Medium Enterprises (SMEs), the critical skill is the ability to "anchor" global innovation to local values such as safety and sustainability:

*“Transposing a techno-*organizational complexity into something digital and then trusting the simulations [...] is a complicated thing, even culturally”.* (IBM Executive Architect, Italy, 2024).

- Talent Strategy (The “Buy” Strategy): Due to the dimensional constraints of local firms, companies often lack the resources for internal development (“Make”), leading to a preference for external partnerships or educational prototypes:

“Our realities are not comparable to those of North America... and therefore it is difficult to start complex digital projects. [...] Small companies build prototypes to understand and then buy”. (IBM Executive Architect, Italy, 2024).

- Primary Drivers (Institution-Driven): The research highlights how the Digital Twin adoption is heavily influenced by the institutional framework of the (PNRR) and the mission of the ICSC National Centre:

*“In recent years, thanks also to forms of incentives (PNRR), Digital Twins have been pursued on a large scale... providing an initial substrate for complex decision support”. (*IBM Executive Architect, Italy, 2024).

In the managerial logic scenario, the role of the manager shifts from “disruptor” (typical of Silicon Valley) to “inter-faculty orchestrator.” The “complexity wall” is addressed by creating skills, profiles capable of balancing specialized technical depth with the relational breadth needed to connect different disciplines. The educational challenge, as evidenced by involvement in local university programs, is not only about teaching code, but also about "inventing new languages" to transfer knowledge across diverse academic and professional backgrounds.

As illustrated in the Data Structure (Figure 4), the transition from raw interview excerpts to aggregate dimensions reveals a significant divergence in how the Digital Twin is conceptualized. While the Silicon Valley pole emphasizes 'rapid experimentation', the Bari Hub focuses on 'cultural mediation' to bridge the gap between global technology and local business needs.

4.4 Discussion

The empirical results of this research, obtained by triangulating the visionary insights of Silicon Valley with the technical operationality of the IBM Maximo ecosystem, provide a definitive response to the primary research questions. This section synthesizes the evidence to argue that the "complexity wall" identified in the literature is not merely a technical obstacle but a profound managerial gap. The analysis confirms that while computing infrastructures advance toward exascale capabilities, human organizational readiness remains the primary bottleneck, as technological acceleration consistently outpaces the capacity for human absorption and strategic orchestration. Evidence from the IBM Maximo documentation and expert interviews validates that even a robust tool for asset management requires a holistic transformation of organizational identity to be effective; without this reinvention, the Digital Twin remains a sterile technical artifact rather than a strategic practice. Furthermore, the comparative analysis between the transatlantic poles serves as empirical proof that the organizational and ecosystemic context acts as a deterministic "strategic filter". Moving beyond the "contextual blindness" observed in previous literature, this research demonstrates that competencies are not universal but are fundamentally "situated" within the economic and institutional logic of the territory. The divergence is striking while the Silicon Valley ecosystem fosters a market-driven logic of hyper-growth and "fail-fast" cultures that prioritize radical innovation, the European and Italian industrial fabric, specifically within the Bari Hub, demands an institution-driven approach centered on resilience and incremental adaptation. In this Italian context, the manager’s role shifts from a disruptive innovator to a cultural mediator, tasked with anchoring global technological excellence to the local values of safety, sustainability, and SME-specific requirements. This ecosystemic maturity directly influences the talent strategy, where the “Make vs Buy” logic is not a neutral choice but a direct reflection of the surrounding innovation cluster's capacity. Ultimately, the analysis of these findings pushes the boundaries of Industry 4.0 toward a convergence with the emerging principles of Industry 5.0, where the Digital Twin paradigm is no longer confined to the optimization of technical processes but becomes a foundational pillar for human-centricity. This shift in perspective moves the focus from pure automation to augmentation, suggesting that future competencies should no longer be understood as merely technical, but rather as profoundly relational and existential. In this scenario, the manager of tomorrow is called to govern a form of “distributed delegation”, in which algorithmic agency does not replace human discretion but instead enhances it through a synergistic co-evolution between physical and virtual systems. Mastering this new era requires the development of hybrid professional profiles, capable of combining the technical depth necessary to manage cyber-physical systems with a horizontal breadth dedicated to sense-making and interdisciplinary collaboration. By repositioning the Digital Twin as an “intelligent digital worker” (AI digital worker) and a strategic ally for worker well-being, this research outlines a roadmap for the governance of digital societies. Such an approach allows for the overcoming of the “complexity wall”, not through a mere increase in computational power, but through a governance model that is simultaneously technologically advanced and deeply oriented toward the resilience of the social and industrial fabric.

4.5 Theoretical, Managerial, and Social Implications

Theoretical Implications

The synthesis of the empirical findings and the subsequent discussion leads to a multi-layered set of implications that extend the current understanding of Digital Twin governance within complex ecosystems. From a theoretical perspective, this research contributes to the literature by successfully overcoming the “contextual blindness” that has historically characterized competency studies in digital transformation. By identifying the ecosystemic filters that shape skill requirements, the work facilitates a fundamental shift in the primary driver of success: moving away from a narrow focus on “Technological Maturity” toward a more holistic concept of “Organizational Maturity”. In this light, competencies are no longer viewed as a universal or static set of skills but are re-conceptualized as dynamic and situated constructs that evolve in response to the specific institutional and economic logics of the territory.

Managerial Implications

On a managerial level, the research advocates for the formal institutionalization of a new professional figure: the “Digital Twin Manager”, envisioned as a strategic “Process Translator” capable of navigating both technical and organizational complexities. This role is crucial for aligning the *“Make vs. Buy”* logic of talent acquisition with the specific density of the surrounding innovation ecosystem and the dimensional constraints of the firm. Furthermore, the findings suggest that the successful adoption of Digital Twin paradigms requires the active promotion of a “Data-Driven Culture” specifically designed to mitigate human resistance and the pervasive fear of replacement, ensuring that technology acts as a tool for augmentation rather than displacement.

Social and Ethical Implications

Finally, the social and ethical implications of this work underscore the necessity of establishing a framework of Digital Trust and Ethics, ensuring transparency and responsibility in data-driven decision-making processes. The Digital Twin is presented here as a vehicle for “Democratic Learning”, potentially reducing physical and financial barriers to high-level technical education through the use of virtual replicas. This vision culminates in a model of inclusive innovation driven by “cross-faculty” contamination and the invention of new shared languages for knowledge transfer. By bridging diverse academic and professional backgrounds, such an approach ensures that the technological acceleration provided by platforms like IBM Maximo translates into a sustainable and resilient cultural transformation for the entire industrial fabric.

4.6 Limitations and Future Research

Despite the scientific rigor of the analysis, this study presents specific boundaries that open the way for further investigation. First, the adoption of a single critical case study focused on a global technology leader like IBM may limit the immediate generalizability of the findings to smaller or less digitally mature firms. Similarly, the elite purposive sampling prioritized high-level strategic depth through expert informants over statistical breadth, aiming for analytical rather than universal statistical validation. Finally, the qualitative interpretivist approach emphasizes “thick description”, seeking to understand the negotiated order of organizational transformation rather than establishing causal laws.

Future research should therefore aim for a quantitative validation of the proposed competency framework through large-scale surveys across different industrial sectors and SMEs to statistically test the model's robustness. Moreover, the investigation could be significantly enriched by extending the scope from the private sector to the public sector. Given the focus of Spoke 9 on “Smart Cities”, future studies should explore how the “Situated Competency Framework” adapts to the governance of public infrastructures and urban digital ecosystems, where institutional drivers and social value often take precedence over market-driven hyper-growth. Additionally, research could delve into the “Human Digital Twin” dimension, investigating how virtual replicas can specifically support worker safety and well-being within the Industry 5.0 paradigm. Lastly, an educational impact assessment is recommended to monitor the long-term effectiveness of “cross-faculty” interdisciplinary programs in successfully closing the digital skill gap.

4.7 Conclusions

In conclusion, this research has demonstrated that the “complexity wall” hindering the effective adoption of Digital Twins is fundamentally a human and organizational challenge rather than a purely technical one. By deconstructing the “contextual blindness” identified in existing literature, this study has successfully proposed a Situated Competency Framework, proving that the governance of digital societies is deeply rooted in the institutional, cultural, and economic logic of the territory. The research highlights that technology is never a neutral force; instead, it acts as a mirror that reflects the maturity and values of the ecosystem in which it is implemented.

The transatlantic contrast between Silicon Valley and the Bari Hub has highlighted that the manager’s role must evolve from a technical controller to a “Process Translator” and a cultural mediator, capable of anchoring innovation to local values such as sustainability and resilience. This work argues that the true success of the ICSC National Research Centre and Spoke 9 depends on the ability to bridge the gap between exascale computing power and human readiness. It is not enough to build virtual replicas of our cities and industries; we must build the hybrid capabilities necessary to inhabit and govern these digital spaces.

Ultimately, this thesis posits that the Digital Twin is the cornerstone of a new Industry 5.0 paradigm, where technological acceleration is repurposed as an engine for human-centricity and social well-being. By repositioning the human worker at the center of the predictive ecosystem, the research provides a roadmap for transforming the PNRR’s ambitious investments into a sustainable and lasting cultural transformation. In this vision, the Digital Twin ceases to be a mere tool for efficiency and becomes a strategic ally for the resilience of the industrial fabric and the prosperity of the Digital Society, ensuring that we do not just survive the complexity wall, but leverage it to build a more inclusive and technologically conscious future.

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Appendix A

Semi-Structured Interview Protocol

PART I - Introduction and general overview

I would like to thank you for your availability and for the time you are dedicating to this research project. The genesis of this investigation lies within the ambitious institutional framework of the ICSC National Research Centre, specifically in the context of Spoke 9 "Digital Society & Smart Cities", funded by the National Recovery and Resilience Plan (PNRR). The primary objective of this study is to analyze human capital management and the strategic competencies required to navigate what the literature defines as the "complexity wall", the significant gap between rapid technological acceleration toward exascale capabilities and the organizational and human readiness necessary to govern such systems. Specifically, the research seeks to deconstruct the Digital Twin (DT) paradigm not merely as a technical artifact, but as an organizational practice filtered through specific ecosystemic and cultural lenses. For the success of this investigation, which adopts a qualitative interpretivist approach and the Gioia Methodology, it is of fundamental importance to examine your organization's role as an orchestrator of skills. This study focuses on how such an orchestrator mediates between global technological excellence and the unique strategic requirements of diverse innovation hubs, such as Silicon Valley and the Bari Hub.

PART II - Professional background and context

1. Could you describe your current role at IBM and your experience with Digital Twin (DT) implementation projects?

2. How would you define the "maturity" of Digital Twin adoption in your current ecosystem (Silicon Valley vs. Italy)?

PART III - Organizational culture and mindset

3. How does the local organizational culture influence the speed of technology adoption?

4. *Specific to USA:* How does the "Fail Fast" mindset impact the experimentation phase of a DT project?

5. *Specific to Italy:* What are the main cultural inhibitors (e.g., "comfort zones") encountered when introducing complex digital models?

PART IV - The Competency Framework (The Skills Map)

6. In your experience, what is the primary "bottleneck" in DT implementation: the technical software or the human skill gap?

7. How would you prioritize the following macro-dimensions of skills: Technical, Cognitive, Soft, and Managerial?

8. Can you describe the importance of hybrid profiles in bridging the IT/OT (Information Technology/Operational Technology) gap?

PART V - Talent strategy and ecosystemic factors

9. When facing a skill gap, does your organization/ecosystem prefer a "Make" (internal upskilling) or "Buy" (external acquisition) strategy? Why?
10. How do institutional drivers (like the PNRR in Italy) or market drivers (hyper-growth in the US) filter the strategic choice of talent?

PART VI - Future outlook and Industry 5.0

11. How do you envision the evolution of the worker's role when collaborating with an "AI digital worker"?
12. How can the Digital Twin move from being a tool for pure efficiency to a strategic ally for worker well-being (Human-centricity)?

PART VII - Final remarks and acknowledgments

I would like to thank you once again for the time and invaluable expertise you have shared. Should there be any further insights or remarks you wish to add regarding the topics discussed, please feel free to do so.

Information on the processing of personal data (EU Regulation 2016/679 - GDPR and Legislative Decree 101/2018)

Thank you for choosing to participate. Your responses will have the sole purpose of contributing to university research on the management of competencies for Digital Twin implementation within the framework of Spoke 9 – "Digital Society & Smart Cities" of the ICSC National Centre and the PNRR. The personal data provided by you will be treated in absolute compliance with the provisions contained in EU Regulation 2016/679 (GDPR) and Legislative Decree 101/2018. Your personal data will be collected and stored in paper and electronic form not accessible to third parties.