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From readiness to realization: the role of intellectual capital in industrial metaverse adoption

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1. Introduction

In interconnected industrial environments, an organization's competitive advantage depends on its ability to mobilize and reconfigure intangible knowledge resources across organizational boundaries (Ivens *et al.*, 2024; Pagani and Pardo, 2017; Wieland *et al.*, 2024). This challenge becomes particularly relevant in the context of the Industrial Metaverse (IM), where organizations must coordinate advanced digital technologies and diverse ecosystem actors. The IM can be conceptualized as a sociotechnical ecosystem that integrates technologies, including digital twins and artificial intelligence (AI) to enable real-time coordination, simulation, and optimization across interconnected industrial systems (Dincelli and Jafarian, 2025; Endres *et al.*, 2024; Guo *et al.*, 2024; Jacobides *et al.*, 2018; Jauhiainen, 2024; Weinberger and Holl, 2026).

However, its implementation poses challenges, including regulatory uncertainty, embedded legacy systems, and a "lack of skilled workforce" (Tantawi *et al.*, 2024, p. 1469), suggesting that technological readiness alone is insufficient. While prior research has shown that organizations adopt these technologies for reasons such as expected competitive advantage (Bekos *et al.*, 2025) and that their use can reshape intellectual capital (IC) (Weinberger and Holl, 2026), less is known about the IC configurations required for successful IM adoption. This gap is particularly relevant because IM adoption remains predominantly technology-centered and underexplored as an organizational process (Bamberger *et al.*, 2025; Kour *et al.*, 2025).

Technology adoption studies cannot be directly transferred to the IM context. First, IM adoption follows a data-centric logic integrating physical assets, industrial processes, and cross-organizational collaboration across value chains. This differs from existing Metaverse research, which has mainly focused on nonindustrial (e.g., Gupta *et al.*, 2024) or application-specific (e.g., Jacquemin *et al.*, 2026; Zhang *et al.*, 2025) contexts. Second, unlike conventional enterprise systems, the IM aims to coordinate processes across connected value chains. Third, successful IM adoption is knowledge centric, as it depends on the mobilization and reconfiguration of intangible resources. Therefore, integrating an IC perspective enables us to move beyond technology-centric explanations and consider how intangible resources enable, constrain, and are reconfigured throughout the adoption process.

Therefore, we address the following questions:

- (1) What are the key success factors that influence the adoption of IM within organizations?
- (2) How do these factors dynamically shape organizational readiness across the different adoption stages?

(3) How do these factors relate to, and reconfigure human, structural, and relational capital throughout IM adoption?

To answer these questions, we integrate diffusion of innovation (DOI) theory (Rogers, 2003), the Technology–Organization–Environment (TOE) framework (Tornatzky and Fleischer, 1990), and an IC perspective to examine IM adoption across different stages. We draw on qualitative interviews with 33 IM experts to identify 16 IM success factors and their implications for IC.

This study makes three contributions. First, it conceptualizes IM adoption as an ecosystemic embedded coordination process shaped by interorganizational dependencies and pressures rather than a discrete adoption decision. Second, it develops a processual perspective on IM adoption by demonstrating how success factors and IC configurations shift across adoption stages. Third, it advances an IC perspective on technology adoption by showing how human, structural, and relational capital are continuously reconfigured across adoption stages.

The remainder of this article is structured as follows: Section 2 presents the conceptual background, including the origin of the IM and the role of IC; Section 3 outlines the research design; Section 4 reports the empirical findings structured along the DOI stages and maps the identified success factors to the three IC dimensions; Section 5 discusses the findings and contributions; and Section 6 concludes.

2. Theoretical background

2.1 The Industrial Metaverse as a sociotechnical ecosystem

Originating in business–to–consumer (B2C)–oriented research, the Metaverse has commonly been conceptualized as a user–centric virtual environment focused on individual experiences and interactions (Dolata and Schwabe, 2023; Hollensen *et al.*, 2023; Rauschnabel *et al.*, 2022). In industrial contexts, however, the Metaverse focuses on operational integration, real–time data continuity, and cross–organizational collaboration rather than immersive user experiences (Bamberger *et al.*, 2025; Henkel and Ivens, 2025; Jacquemin *et al.*, 2025; Nleya and Velempini, 2024).

From a managerial perspective, the IM refers to a multilayered sociotechnical system in which actors interact across interconnected architectural layers ranging from data infrastructure and connectivity to integration, application, and interaction (Bamberger *et al.*, 2025; Guo *et al.*, 2024; Henkel and Ivens, 2025). These layers build upon one another and form a digital ecosystem with continuous data exchange between physical environments and their digital representations (Tantawi *et al.*, 2024). This sociotechnical ecosystem enables cross–organizational coordination, collaboration, and process synchronization across industrial networks (Nleya and Velempini, 2024).

From a technological perspective, the IM is an umbrella concept that integrates heterogeneous technologies such as “sensing technology, XR, interactive technology, three–dimensional (3D)

modeling, real-time rendering technology [...], and data perception technology” (Lyu and Fridenfolk, 2024, p. 32) into a unified and interoperable industrial environment (Kshetri, 2023). Technically, it is characterized by the convergence and synchronization of these technologies, enabling real-time interaction and data exchange between physical and virtual environments (Endres *et al.*, 2024; Park and Kim, 2022; Tu *et al.*, 2024). This ecosystem logic reflects a system-of-systems perspective in which actors collectively enable industrial coordination and value creation across organizational boundaries (Pagani and Pardo, 2017; Pardo *et al.*, 2022).

This convergence within the IM can create value by enabling processes and tasks to be completed more quickly, with less effort, at higher quality, or in more sustainable ways (Henkel and Ivens, 2025; Kshetri, 2023; Mubarak *et al.*, 2025). In this context, applications such as immersive employee training and workforce development (Almeida *et al.*, 2023; Dincelli and Jafarian, 2025; Jacquemin *et al.*, 2025), scenario simulation (Tu *et al.*, 2024), collaborative product and service design (Dolgui and Ivanov, 2023; Jauhiainen, 2024), and supply chain management (Nleya and Velempini, 2024) are frequently discussed. These applications are particularly relevant in knowledge-intensive industrial environments because they rely on the development, sharing, and application of organizational knowledge resources (Zeng *et al.*, 2025) while simultaneously strengthening organizational capabilities for value creation (Jabin, 2025).

2.2 TOE and organizational readiness

To realize the IM’s potential, organizations must adopt and integrate interconnected digital technologies across organizational processes and ecosystems. In this study, adoption refers to the organizational implementation and use of an innovation (Kimberly and Evanisko, 1981; Rogers, 2003); however, adoption is often constrained by barriers such as organizational inertia, employee hesitation, and ecosystem uncertainty (Oliveira *et al.*, 2014; Vial, 2019).

To analyze these dynamics, we combine the TOE framework (Tornatzky and Fleischer, 1990) with DOI theory (Rogers, 2003), building on Cobos *et al.* (2016). Unlike individual-level models like TAM (Davis, 1989) and UTAUT (Venkatesh *et al.*, 2003), this approach captures organizational and environmental adoption dynamics in B2B industrial environments (Hameed *et al.*, 2012; Slappendel, 1996).

The TOE framework categorizes IM adoption success factors into three dimensions:

- technological: Metaverse attributes (e.g., technical maturity, usability, system integration);
- organizational: organizations’ internal characteristics (e.g., resources, leadership, digital capabilities);
- environmental: external forces (e.g., standards, competitive pressure, regulatory landscape).

DOI theory conceptualizes adoption as a staged process comprising knowledge, persuasion, decision, implementation, and confirmation (Rogers, 2003). While TOE helps identify “what” factors

matter in adoption, DOI theory explains “how” adoption unfolds over time. Combining these perspectives enables us to examine how different success factors shape organizational readiness across different stages of IM adoption, thereby addressing DOI theory’s limited consideration of organizational and environmental influences (Chau and Tam, 1997; Gangwar *et al.*, 2014). We use the term *success factors* to emphasize that these conditions must be actively managed throughout the adoption process.

2.3 Intellectual capital and technology adoption

From a resource– (RBV) and knowledge–based (KBV) perspective, knowledge and knowledge–related capabilities constitute strategic resources for organizations (Barney, 1991; Grant, 1996; Nonaka and Takeuchi, 1995; Teece *et al.*, 1997; Wernerfelt, 1984). These resources enable organizations to build competitive advantages by, for example, better fulfilling customer requirements or designing value chains more efficiently (Gupta *et al.*, 2000). In the technology adoption context, knowledge becomes increasingly important, as organizations often face uncertainty, complex decision–making processes, and evolving technological and organizational requirements (Gangwar *et al.*, 2014; Oliveira *et al.*, 2014; Vial, 2019). Consequently, successful technology adoption largely hinges on an organization’s ability to develop, integrate, and apply relevant knowledge resources and capabilities (Alavi and Leidner, 2001; Attewell, 1992).

IC can thus be understood as a conceptualization of organizational knowledge resources, operating as a central mechanism through which organizations translate technology adoption into organizational performance (Bekos *et al.*, 2025; Nahapiet and Ghoshal, 1998; Subramaniam and Youndt, 2005). IC describes the intangible resources and capabilities that enable knowledge–based value creation within organizations (Bontis, 1998; Stewart, 2010). Consequently, it has frequently been identified as a central determinant of organizational innovation, technological progress, and long–term competitive advantage (Keong Choong, 2008; Kianto *et al.*, 2014; Subramaniam and Youndt, 2005). IC is commonly divided into human, structural, and relational capital, with each contributing differently to an organization’s readiness and capability to adopt new technologies (Konno, 2025; Ståhle and Hong, 2002).

Human capital comprises the skills, knowledge, and experiences within an organization (Pyatt, 1966; Schultz, 1961), whereas *structural capital* refers to institutionalized knowledge embedded in organizational routines, infrastructures, culture, and processes (Stewart, 2010). *Relational capital* reflects trust–based relationships, network ties, and knowledge exchange processes that facilitate collaboration and value creation (Nahapiet and Ghoshal, 1998; Pagani and Pardo, 2017; Subramaniam and Youndt, 2005). Thus, it captures the value embedded in relationships with customers, suppliers, employees, and partners (Harrison and Sullivan, 2000; Petty and Guthrie, 2000).

Human capital fosters awareness, learning, and acceptance of innovative tools, while immersive environments may strengthen problem–solving abilities and accelerate skill development (Bekos *et al.*,

2025; Suh, 2024). Structural capital supports digitalization through knowledge codification, cross-departmental knowledge transfer, and generative AI systems (Edvinsson and Malone, 1997; Stewart, 2010). Relational capital further influences knowledge diffusion, user acceptance, and cross-organizational collaboration, with immersive environments supporting trust, shared understanding, and collaborative performance (Nahapiet and Ghoshal, 1998; Suh, 2024; Wieland *et al.*, 2024; Zhang *et al.*, 2025).

Adopting IM technologies in itself does not guarantee successful organizational value creation, since value is only generated if these technologies effectively contribute to the development and mobilization of human, structural, and relational capital (Bekos *et al.*, 2025). Conversely, inadequate IC development may result in fragmented knowledge silos, limited interoperability, or insufficient skill bases, thereby constraining organizational readiness (Alavi and Leidner, 2001; Gangwar *et al.*, 2014). Accordingly, IC constitutes a key determinant of organizational readiness by shaping the organization's ability to absorb, integrate, and leverage technological innovations (Cohen and Levinthal, 1990). From this perspective, successful technology adoption depends on an organization's ability to continuously renew, recombine, and mobilize these resources (Konno, 2025; Stähle and Hong, 2002).

3. Methodology

3.1 Research approach and data collection

To address our research questions, this study adopts an exploratory research design, drawing on primary data collected through semi-structured qualitative interviews (Eisenhardt, 1989; Kumar *et al.*, 1993). This approach is appropriate for generating in-depth insights into an emerging and complex phenomenon (Bamberger *et al.*, 2025), thereby contributing to theory building in an underexplored IM adoption field (Beverland and Lindgreen, 2010; Stake, 1995).

The semi-structured interview guide was designed to ensure comparability and flexibility in exploring context-specific insights and comprised several thematic sections. Given the still-evolving understanding of the IM (Dolata and Schwabe, 2023), no standardized definition was provided prior to the interview, allowing informants to articulate their own interpretation and practical understanding of the phenomenon. During data analysis, however, recurring conceptual patterns enabled the development of a shared analytical understanding of the IM (see Section 4). Following introductory questions on each informant's role and professional background, the discussion focused on: (1) conceptual understanding and perceived relevance; (2) current and potential use cases; (3) technological and organizational integration; (4) adoption drivers and barriers; and (5) required resources and competencies. The interviews concluded with reflections on broader societal implications.

Data were collected by the first author between late 2024 and spring 2025. Informants were purposefully selected according to predefined recruitment criteria. Specifically, individuals were eligible if they: (1) had professional experience with the IM, either in development, implementation, or

operational use; (2) were employed in a business-to-business (B2B) context; and (3) held a role with operational or strategic responsibility for IM adoption. Informants were recruited through professional networks (e.g., LinkedIn) and industry contacts. To ensure data quality, all eligibility criteria were screened ex ante during initial contact and ex post after the interview had been conducted.

The final sample comprised 33 interviewees from 20 B2B organizations, most of which were headquartered in Europe while operating globally. The organizations' headquarters were located in Germany (15), Switzerland (3), the United States (1), and Malta (1). To capture diverse perspectives on IM adoption, the sample included organizations of varying sizes and industry backgrounds (see Table 1). In particular, smaller and more agile organizations often approach emerging technologies differently than large, established corporations (Felicetti *et al.*, 2024).

+++ INSERT TABLE 1 ABOUT HERE +++

The study comprised both male (27) and female (6) informants. On average, informants had 4.6 years of experience in their current role, 9.7 years of organizational tenure, and 13.7 years of industry experience. A detailed overview of all interviews and informant characteristics is provided in Table 2.

+++ INSERT TABLE 2 ABOUT HERE +++

One-to-one interviews were conducted online, recorded, transcribed, and analyzed using MAXQDA. Interviews lasted from 26 to 90 minutes ($M_{\text{length}} = 55$ minutes). The number of interviews was determined by theoretical saturation—that is, the point at which no substantially new theoretical insights emerged (Guest *et al.*, 2006). During data collection, we observed recurring patterns within the data. After 12 interviews, the emergence of new codes became less frequent, indicating code saturation (Hennink *et al.*, 2017). After approximately 26 interviews, few additional insights emerged, indicating meaning saturation. Following interviews with already scheduled experts, data collection concluded after 33 interviews. This sample size is consistent with prior information systems (IS) research suggesting that qualitative-oriented studies commonly reach saturation between 20 and 30 interviews (Marshall *et al.*, 2013).

To enhance trustworthiness, we applied several strategies to ensure credibility, transferability, and confirmability (Lincoln and Guba, 1985). Data triangulation combined interview data with internal documents (e.g., customer presentations) and secondary materials such as corporate reports.

Perspectives across organizational roles, organizations, and industries further supported the validation of emergent themes. Collaborative coding and peer debriefing ensured investigator triangulation.

3.2 Data analysis

Data analysis followed a two-step procedure. First, we inductively developed first-order codes based solely on informants' statements, and second, these emergent codes were deductively organized by aligning them with the TOE and DOI frameworks. We adopted a mixed inductive-deductive analytical strategy consistent with the established Gioia methodology (Gioia, 2021; Gioia *et al.*, 2013).

Thematic coding was applied to organize and interpret qualitative data, following a three-stage procedure. In the first-order analysis, concepts were inductively derived from the interview transcripts, staying close to the informants' original wording and perspectives. In the second-order analysis, related first-order concepts were consolidated into broader second-order themes. In the third-order analysis, these themes were synthesized into aggregate dimensions and classified within the TOE framework and linked to the respective DOI adoption stages. An overview of the Gioia data structure is provided in Appendix A. While the concepts were assigned according to their primary relevance within specific DOI stages, the findings also indicate iterative interdependencies across adoption activities. Factor salience was assessed by the number of interviews in which each factor was mentioned (see Appendix B).

To strengthen analytical reliability, both authors independently developed the initial coding system, before jointly reviewing and refining the coding system. Across the 33 interviews, 1,053 coding references were identified. Prior to consensus building, intercoder reliability reached 82.53% agreement (O'Connor and Joffe, 2020), indicating an acceptable level of consensus (Miles and Huberman, 1994). The iterative refinement process resulted in consolidating the data into 16 second-order themes.

4. Results

During the analysis, a shared understanding of the IM was inductively derived and used as a common analytical reference point. Informants described the IM as “*a further evolutionary stage of the digital factory and the digital twin*” (I-04), and as “*an evolution and convergence of key technologies*” (I-11). Synthesizing these perspectives, the IM can, for the purpose of this study, be defined as:

A sociotechnical, data-centric environment that interconnects multiple digital twins of products, processes, and production systems within a unified, interoperable platform, enabling real-time collaboration, simulation, and optimization across the industrial value chain.

This conceptualization positions the IM as an evolutionary step in digital transformation that connects design, production, and operations through persistent, intelligent, and collaborative digital ecosystems. Based on this understanding, the findings are structured along the five DOI stages and analyzed through the TOE dimensions, identifying 16 success factors shaping IM adoption (see Figure 1).

+++ INSERT FIGURE 1 ABOUT HERE +++

4.1 Technological factors

We identify five technological success factors shaping IM adoption: (1) interoperability & system integration; (2) platform adaptability & modularity; (3) technological orchestration; (4) architectural robustness & security readiness; and (5) advanced simulation & system capabilities.

(1) *Interoperability & system integration* refers to a unified data foundation enabling communication across systems and organizational units. As I-13 noted: “*We need a unified data foundation and interfaces so that all systems can communicate with each other.*” Several interviewees (e.g., I-02, I-22, I-24, and I-27) emphasized that connectivity issues and legacy infrastructures remain major barriers to IM adoption. As I-32 stated, “*Connectivity issues are often the simplest of all the problems we should solve.*” Achieving interoperability requires organizations to standardize and operationalize knowledge across systems and units. This is particularly critical during the knowledge phase, as IM applications depend on an interoperable and standardized data architecture (Henkel and Ivens, 2025).

(2) *Platform adaptability & modularity* refers to IM systems’ ability to combine shared technological standards with flexible configurations. For example, XR-based training applications need to be adapted to department-specific requirements (Dincelli and Jafarian, 2025). As I-15 emphasized:

The tool landscape must be modular—each department needs something different, but on a common basis.

Such adaptability simplifies adoption and enables organizations to align IM applications with varying operational contexts. Within the IM, modularity becomes critical because organizations must integrate heterogeneous technologies, actors, and data standards across boundaries. Modular platform structures therefore enable organizations to connect to evolving ecosystems without redesigning their entire system landscape (Hemonnet-Goujot *et al.*, 2022; Wei and Pardo, 2022).

(3) *Technological orchestration* captures the integration of digital technologies into coherent IM applications. Organizations face the challenge of transforming existing data into value-generating applications by combining different technologies. As I-27 illustrated, “*We already have CAD data—it should just work. But simply transferring CAD data into an AR app is not that easy.*” Several interviewees (e.g., I-10, I-14, and I-21) emphasized that IM adoption depends on integrating immersive and intelligent technologies in a technically feasible and reliable way. As I-04 stated, “*XR, AI—it all gets combined. What matters is that it creates value and runs reliably.*” Interoperable solutions enable visualization, simulation, and process institutionalization capabilities, which are central to advanced digital twin applications (Fang *et al.*, 2022). Achieving this level of integration depends on both

specialized technical expertise (human capital) and robust data governance structures (structural capital), underscoring IC's importance in IM adoption.

(4) *Architectural robustness & security readiness* emerges as a fourth success factor referring to technically robust and reliable IM infrastructures. Several interviewees (e.g., I-02, I-04, I-09, I-14, and I-32) emphasized that stable digital twin architectures form the backbone of IM applications. As I-33 noted, such systems must ensure technical operability, and I-18 emphasized the need for “*massive computing power*”. I-24 also highlighted hardware constraints as a central challenge. Closely related to these requirements are security measures ensuring the trustworthy operation of IM applications:

Cybersecurity is nonnegotiable—without it, we won't get approval internally or externally. (I-19)

These findings indicate that this success factor extends beyond technical stability and also concerns legitimacy and trust. From an IC perspective, this success factor depends on human (technical expertise), structural (governance routines), and relational (trust-based collaboration between ecosystem partners) capital.

(5) *Advanced simulation & system capabilities* concerns the value realization of IM applications. Within the layered IM architecture proposed by Henkel and Ivens (2025), these capabilities unfold at the application layer, where underlying technological infrastructures are translated into processes, enabling organizations to visualize workflows, test scenarios, and anticipate disruptions before implementation. However, these capabilities depend on interoperable and usable data from PLM systems and digital twins (I-13). I-08 explained that “*bringing these worlds together and finding a workable consensus for our software is a real cultural and technical challenge.*” Realizing these simulation capabilities therefore requires aligning different data logics and professional practices. Once established, these capabilities enable value-generating IM applications such as immersive training (I-05, I-20) and virtual factory tours (I-11). As I-32 described, such simulation functions are a “*real game changer*” for organizational transparency.

4.2 Organizational factors

The analysis revealed seven key organizational factors: (1) perceived strategic value; (2) leadership & strategic alignment; (3) standardized reference framework; (4) workforce readiness & training; (5) process institutionalization & automation; (6) collaborative organizational culture; and (7) agile innovation structures.

(1) *Perceived strategic value* refers to the anticipated and socially constructed value associated with IM adoption. Interviewees highlighted expected benefits like lower operating costs (I-04), reduced planning efforts (I-28), and improved value chain transparency (I-06, I-25). As I-11 noted, “*We look at ROI and efficiency gains first—if those aren't there, it becomes difficult.*” Several interviewees indicated that recognizing these opportunities often requires “*intensive interdisciplinary dialogue*” (I-

23) among internal functions and external partners to identify relevant use cases, articulate value propositions, and align expectations (I–29, I–30).

(2) *Leadership & strategic alignment* relates to articulating a clear strategic vision, legitimizing IM initiatives across the organization, and mobilizing resources. Several informants (e.g., I–03, I–07, and I–20) stressed that IM adoption must be embedded within a “*broader organizational transformation agenda*” (I–32) rather than remaining confined to isolated initiatives. Since IM adoption demands substantial financial, technological, and organizational investments, top–management support becomes essential. One informant noted that “*without support from management, the introduction of such a technology simply doesn’t work*” (I–01). Similarly, I–26 remarked that “*if management does not act, nothing really happens.*” From an IC perspective, this success factor depends on human (managerial expertise), structural (strategic roadmaps), and relational (alignment across stakeholders) capital.

(3) A *standardized reference framework* refers to an organization’s ability to establish a reusable IM–grounded basis that can be connected to different processes, products, or client interfaces. As I–03 illustrated, this includes the implementation of an administration shell that consolidates product– and process–related information, thereby serving as the foundation for digital twin–based visualizations. This success factor governs how information is categorized, maintained, and accessed within and across organizations, institutionalizing a shared data logic. Establishing this framework enables the creation of a “*single source of truth*” (I–24), ensuring that stakeholders rely on consistent and validated information. Without such a framework, conflicting information, coordination errors, and decision inconsistencies may emerge, undermining trust and reducing the effectiveness of simulation and collaboration processes.

(4) *Workforce readiness & training* captures the individual and collective competencies required to meaningfully engage with all IM applications. Echoing prior research on technology adoption (e.g., Bekos *et al.*, 2025; Chau and Tam, 1997; Gangwar *et al.*, 2014), interviewees emphasized the importance of “*human aspects*” (I–11), including shortages of qualified experts (I–17), uncertainty in using new applications (I–21), insufficient qualifications (I–04), fears of job displacement (I–18), and inadequate intuitive understanding during system development (I–02, I–09). To overcome these obstacles, organizations emphasized long–term training and employee development initiatives, requiring “*patience and perseverance*” (I–01). Several informants (e.g., I–06 and I–31) stressed that training efforts should extend beyond initial onboarding programs:

We even established specific formats in this direction, such as a digital twin initiative and later a digital twin academy, to systematically educate and upskill our employees. (I–14)

From an IC perspective, workforce readiness primarily reflects human capital development, while relational capital supports employee acceptance and adaptation through trust and communication.

(5) *Process institutionalization & automation* focuses on an organization's ability to embed IM technologies into organizational processes and governance structures to sustain their associated value. Rather than remaining isolated projects, IM applications must be integrated into everyday organizational routines and standards. This integration includes workflow redesigns, formal operating guidelines, and new monitoring and control mechanisms. Several organizations have deliberately discontinued legacy systems to ensure that IM applications are consistently used and not bypassed (I-25). As I-10 remarked:

All solutions and all data we have should ultimately be integrated into the IM and made digitally available there, instead of being hidden in isolated dashboards or standalone solutions.

These findings indicate that process institutionalization requires more than technological availability; it also involves aligning processes, standards, and responsibilities. By embedding simulation results and real-time data flows into standardized routines, organizations translate technological potential into operational practice.

(6) *Collaborative organizational culture* concerns shared norms, values, and behavioral routines that foster cross-functional cooperation and joint value creation. Sustained IM adoption depends less on technical feasibility than on an organization's ability to coordinate heterogeneous expertise across departments. Interviewees (e.g., I-04, I-09, I-16, and I-22) commented that collaboration between functions such as manufacturing, planning, and IT accelerates the maturation of IM initiatives: "*When engineering and service work together, things move much faster—but it does require coordination*" (I-23), enabling "*a more agile form of planning*" (I-15). These insights demonstrate that collaborative culture reshapes coordination and decision-making processes while increasing the need for stronger cross-functional alignment to prevent fragmented implementation (I-20). Such collaboration reinforces relational capital through trust-based cooperation while enabling human capital development through shared learning and cross-functional knowledge exchange.

(7) The success factor *agile innovation structures* relates to flexible organizational arrangements that support decentralized decision-making, iterative experimentation, and rapid implementation. Prior research on technology adoption indicates that agile structures are better equipped to respond to rapidly changing external conditions (Merhi, 2023), which is consistent with our findings in the IM context. Several informants emphasized that short iteration loops and organizational flexibility are essential for experimenting with IM technologies and translating early pilot ideas into scalable operational solutions. As I-08 explained: "*We intentionally created agile structures so that new ideas can be implemented more quickly.*" These practices institutionalize continuous learning and iterative adjustment, reinforcing structural capital through flexible routines and relational capital through cross-functional collaboration.

4.3 Environmental factors

Our findings reveal four key environmental success factors shaping IM adoption: (1) market & competitive dynamics; (2) environmental & sustainability drivers; (3) customer expectations & value integration; and (4) policy & regulatory pressures.

(1) *Market & competitive dynamics* captures the evolving market environment characterized by increasing collaboration and competition among market actors. Organizations are exposed to continuous signals from customers, competitors, and ecosystem partners that shape organizational awareness and trigger early exploration of IM-related technologies. Our findings suggest that this dynamic is driven by two related mechanisms: a fear of missing out (FOMO), which pulls organizations toward emerging technologies, and changing market demands, which push organizations toward IM-related solutions. Reflecting the latter mechanism, one informant noted that “*you push a new technology because you see an opportunity to offer something valuable to customers*” (I-25). External actors such as competitors and ecosystem partners simultaneously shape expectations and exert pressure on organizations to experiment with, and adopt, new technological concepts (Ivens *et al.*, 2024; Pagani and Pardo, 2017). As I-18 explained, “*We see that the market is moving in this direction.*” Identifying and capitalizing on these opportunities relies on the organization’s human capital, particularly employees’ ability to interpret market signals and translate them into technological initiatives. As I-25 summarized, the overarching goal is to become “*future-ready.*”

(2) *Environmental & sustainability drivers* refers to external sustainability expectations and organizational efforts to improve resource transparency, circularity, and operational efficiency through IM technologies. Several interviewees (e.g., I-04, I-09, and I-16) emphasized increasing sustainability requirements from both competitors and suppliers, particularly in supply chain management. These requirements encourage organizations to engage in broader sustainability transformation efforts. In particular, IM applications enable organizations to simulate products, processes, and resource flows before physical implementation, thereby reducing material waste and supporting circularity-oriented decision-making (I-12, I-19). As reflected in I-27’s observation, “*Right now, topics such as sustainability and circularity can first be simulated and tested in the virtual world*”, suggesting that sustainability considerations shape how organizations evaluate the strategic relevance of IM technologies. Consequently, sustainability objectives increasingly influence technology investment priorities and the justification of IM-related initiatives.

(3) *Customer expectations & value integration* refers to customer-driven demands for virtualized processes, interoperable data, and seamless integration across organizational value chains. This development is particularly pronounced in B2B contexts, where organizations increasingly require digital compatibility and integration across value chains (Pagani and Pardo, 2017). Several interviewees (e.g., I-03, I-11, and I-27) emphasized that the initial motivation to engage with IM technologies often originates from customers. I-17 noted:

We already have customers who say they will not start a new production unless it has first been virtualized and can run in parallel in a digital environment.

Suppliers are therefore required to align their systems with customers' value creation processes. I-05 remarked that such expectations are often formalized and enforced through data-sharing requirements: *"Some customers now require us to integrate our solutions into their own Metaverse."* Responding to these expectations requires organizations to mobilize both human and relational capital to interpret customer requirements and coordinate cross-organizational technological integration. As a result, customers increasingly act as co-drivers of IM adoption by influencing technological priorities and integration requirements.

(4) *Policy & regulatory pressures* concerns legal frameworks that require organizations to provide transparent product- or service-related information across supply chains. Here, several informants (I-13, I-28) raised the European Union Digital Product Passport as an example that necessitates interoperable data management practices. Furthermore, I-28 emphasized the influence of regulatory requirements on IM adoption decisions:

Regulations like these have a major influence on how we design our Metaverse and can be a very strong driver for fostering this kind of data exchange.

Such regulatory developments act as institutional pressures shaping organizational structures and technology adoption processes (DiMaggio and Powell, 1983), encouraging organizations to establish digital representations and interoperable data flows (Bamberger *et al.*, 2025). Similar regulatory requirements can be observed in the healthcare industry. Here, device history records enforce traceability and standardized digital documentation practices (I-25), indicating that regulatory pressure acts as an environmental driver in developing an interoperable, data-driven architecture.

4.4 Findings through an intellectual capital lens

Of the 16 success factors, 15 are directly linked to at least one IC dimension, underscoring that IM adoption can be primarily understood as an IC reconfiguration process. Rather than depending primarily on technological solutions, successful IM adoption requires organizations to mobilize, align, and reconfigure IC across adoption stages. Table 3 presents an overview of this mapping.

+++ INSERT TABLE 3 ABOUT HERE +++

In the knowledge stage, *interoperability & system integration* and *market & competitive dynamics* dominate. Organizations rely on human expertise and structural integration capabilities for assessing technological compatibility and ecosystem readiness. *Market & competitive dynamics* further strengthens awareness and technological monitoring.

During the persuasion stage, *perceived strategic value*, *environmental & sustainability drivers*, and *customer expectations & value integration* become central. These factors primarily activate relational capital, as organizations evaluate external expectations and the strategic relevance of IM applications. Customer expectations additionally connect human and relational capital through stakeholder coordination and co-creation opportunities.

In the decision stage, *leadership & strategic alignment* highlights the combined role of human, structural, and relational capital. Managerial competencies, strategic vision, and decision-making capabilities enable organizations to translate evaluations into strategic commitments. At this stage, organizations must reconfigure and align all IC dimensions to support coordinated decision-making and organizational commitment toward IM adoption. While *policy & regulatory pressures* was also identified as a relevant decision-stage factor, it was not linked to IC dimensions, as these requirements primarily constitute external pressures rather than internally mobilized organizational resources.

The implementation stage concentrates seven IC effects. *Platform adaptability & modularity*, *technological orchestration*, *architectural robustness & security readiness*, and *advanced simulation & system capabilities* mobilize both human and structural capital by embedding expertise into an interoperable architecture. *Standardized reference frameworks* and *process institutionalization* further codify knowledge into organizational routines, while *workforce readiness & training* additionally activates relational capital through collaboration and knowledge exchange. This stage therefore represents the core transformation of IC into scalable operational technological capabilities.

In the confirmation stage, a *collaborative organizational culture* stabilizes adoption by fostering trust, knowledge sharing, and cross-functional cooperation. *Agile innovation structures* combine structural and relational capital by establishing flexible governance mechanisms and innovation routines. At this stage, the mechanism shifts from capability development to routinization and organizational embedding, ensuring that IM technologies become integrated into organizational practices.

5. Discussion

For RQ1, our findings demonstrate that successful IM adoption depends on the simultaneous management of technological, organizational, and environmental conditions. While several success factors are already known from prior technology adoption research (e.g., Chau and Tam, 1997), our findings show that IM adoption involves a distinctive technological configuration shaped by bidirectional data flows (Henkel and Ivens, 2025). This configuration creates interrelated technological and organizational challenges, making *interoperability & system integration* critical for maintaining reliable real-time synchronization. Accordingly, successful IM adoption requires coordinating an interconnected system of technologies, actors, data flows, and environments rather than implementing a single digital solution. These findings challenge linear adoption perspectives by showing that organizational readiness must continually evolve with technological and environmental demands. This

contrasts with prior studies such as Merhi (2023), where environmental factors played a comparatively minor role in technology adoption. In our study, however, environmental influences emerged as key factors in early adoption stages, highlighting the ecosystemic embeddedness of IM adoption.

For RQ2, our findings reveal that these success factors neither operate in isolation nor exert uniform influence across DOI stages. This sheds light on the processual nature of IM adoption by demonstrating that different success factors vary in their relevance. This extends prior TOE-based research, which has typically treated such factors as relatively static antecedents of adoption (e.g., Hameed *et al.*, 2012), by showing that their salience changes throughout the adoption process.

In addressing RQ3, our findings suggest that the development and mobilization of IC are critical for managing IM adoption across different stages. Organizations need to coordinate and reconfigure IC to navigate technological, organizational, and environmental pathways throughout the adoption process, thereby highlighting the pivotal role of IC in IM adoption. While prior IM research has primarily examined the outcomes of IM adoption (Bekos *et al.*, 2025; Weinberger and Holl, 2026), our findings position IC as a key mechanism through which organizations translate readiness into successful IM adoption.

5.1 Theoretical contributions

First, our findings emphasize that IM adoption is a broader organizational and ecosystemic transformation. By identifying four environmental success factors, we show that organizations must respond to market developments, sustainability directives, and emerging regulatory frameworks that shape adoption priorities and capability requirements (Jacquemin *et al.*, 2025; Weinberger and Holl, 2026). This aligns with recent research by Pardo *et al.* (2022), who demonstrate that digital technologies reshape established business network structures by altering actor relationships, resource ties, and activity links. Our findings similarly show that IM adoption extends beyond organizational boundaries and increasingly embeds organizations within digitally connected industrial ecosystems (Pagani and Pardo, 2017; Tantawi *et al.*, 2024). In doing so, our study extends existing adoption theories by highlighting the institutional and ecosystemic embeddedness of IM adoption and the need to align internal IC resources with evolving market expectations.

Second, by integrating the TOE framework with DOI theory, our study develops a processual perspective on IM adoption that captures the conditions and dynamics of adoption within industrial environments. Our findings show that successful progression across DOI stages depends on the mobilization of human, structural, and relational capital. In doing so, we conceptualize IM adoption as an iterative process requiring evolving organizational capabilities, strategic alignment, and ecosystem coordination. This extends research on IC and digital transformation (Edvinsson and Malone, 1997; Oliveira *et al.*, 2020; Stewart, 2010) by demonstrating that organizations require different IC

configurations to absorb, operationalize, and scale new technologies. More specifically, our findings show *how* different IC configurations become salient across adoption stages.

Third, this study contributes to IM research by demonstrating that IM adoption depends on the mobilization and reconfiguration of IC across adoption stages. The identified success factors reflect critical human, structural, and relational capital resources required to realize IM initiatives, including employee competencies, organizational infrastructures, and interorganizational collaboration capabilities. Our findings therefore extend resource- and knowledge-based perspectives of the firm (Barney, 1991; Grant, 1996; Teece *et al.*, 1997; Wernerfelt, 1984) by showing that IM adoption depends less on isolated technological resources than on the dynamic orchestration of IC, thereby challenging technocentric views of technology adoption.

5.2 Managerial implications

Organizations should view IM adoption as a broader transformation toward digitally connected ecosystems. Our findings show that organizations require IC to manage technological, organizational, and environmental challenges. Consequently, IM initiatives should not remain isolated within individual departments; rather, organizations should establish cross-functional governance structures integrating different functional areas. This may include steering committees, interdisciplinary working groups, or cross-functional transformation teams that align technological development with organizational and ecosystem requirements.

Organizations must recognize that different capabilities become critical at different DOI adoption stages and continuously reconfigure them according to evolving adoption requirements. Managers should therefore define stage-specific capability requirements and align investments in human, structural, and relational capital accordingly.

Finally, organizations should invest in IC before it becomes operationally necessary. Managers should proactively develop employees' digital skills, establish interoperable data systems, and implement governance mechanisms that support future IM integration. In early adoption stages, organizations should focus on experimentation capabilities, digital competencies, and employee change readiness. During implementation, managers should prioritize standardized data models, scalable simulation environments, and modular architectures that facilitate operationalization. In later stages, organizations should strengthen collaboration with external actors to enable coordination within shared digital ecosystems.

5.3 Societal implications

The results highlight a changing work environment in which employees increasingly need to develop capabilities beyond the use of isolated digital tools. As IM technologies evolve into interconnected ecosystems, employees are increasingly expected to engage with digital technologies in strategic ways (Henkel *et al.*, 2025). This shift affects how skills and qualifications are defined, how

professional roles evolve, and how continuous learning is organized. Consequently, educational institutions and industry associations are also challenged to foster openness toward such ecosystem-based technologies and prepare employees for working within dynamic technology-mediated environments.

The findings also point to broader societal implications at the regulatory and governance level. Regulations such as supply chain transparency requirements increasingly shape IM adoption by encouraging interoperable and transparent digital infrastructures. Regulatory actors such as governments should therefore recognize that political decisions can accelerate or hinder IM adoption across industrial ecosystems.

5.4 Limitations and future research

This study is subject to several limitations. First, its exploratory qualitative interview design limits the statistical generalizability of the findings. Although the sample comprises 33 informants from 20 companies and yielded 1,053 coding references, these references reflect qualitative evidence of perceived relevance rather than quantitative effect sizes. Accordingly, quantitative inferences regarding the relative importance, interaction effects, and sequencing of the identified success factors remain beyond the scope of this study. Future research could therefore employ quantitative or configurational approaches, such as qualitative comparative analysis (QCA), to examine (a) which adoption factors are most important, (b) how companies prioritize and sequence these factors across different adoption stages, and (c) which specific factor combinations (i.e., causal configurations) lead to successful adoption outcomes.

Second, our study sheds light on the adoption process but does not capture how external stakeholders respond to IM-enabled changes. Existing research (e.g., Lundin and Kindström, 2024; Wieland *et al.*, 2024) indicates that digital technologies reshape customer touchpoints, interaction patterns, and value co-creation; future research could therefore investigate how IM adoption affects customer experiences, relational dynamics, and expectations to help clarify whether IM technologies primarily enhance internal processes or also transform interactions with external actors.

Third, the interview sample was predominantly male, reflecting the gender composition often observed in technology-related environments (Harmon and Walden, 2021). Although no systematic gender-specific patterns emerged during the analysis, future research could examine whether male and female decision-makers differ in their perceptions of organizational enablers and barriers. This echoes recent calls for gender-sensitive research in B2B contexts (Ivens, 2023).

Finally, our findings are grounded primarily in European industrial contexts, with most participating companies headquartered in Germany, and therefore reflect a specific institutional setting. Although we sought to mitigate this potential bias through data triangulation across companies, industries, and expert roles, future research could examine how different institutional norms, regulatory

frameworks, and industry structures shape IM adoption (DiMaggio and Powell, 1983). Such studies could provide deeper insights into how adoption challenges and enabling conditions vary across industrial ecosystems and how institutional inertia and established organizational structures influence the translation of IM readiness into successful adoption.

6. Concluding remarks

This study examined how organizations develop IM readiness and how IC shapes adoption across different stages. Drawing on 33 expert interviews and an integrated TOE and DOI theory perspective, we identified 16 technological, organizational, and environmental factors influencing IM adoption.

Our findings show that these factors exert stage-specific effects and that successful IM adoption depends on the mobilization of human, structural, and relational capital. Early stages emphasize technological awareness and expertise, while later stages require the institutionalization of knowledge, governance structures, and ecosystem coordination.

Overall, the findings suggest that IM adoption is not primarily a technological challenge but an IC reconfiguration process. Organizations that strategically develop and align their IC are better positioned to move beyond experimentation and realize the operational and strategic value of the IM within industrial ecosystems.

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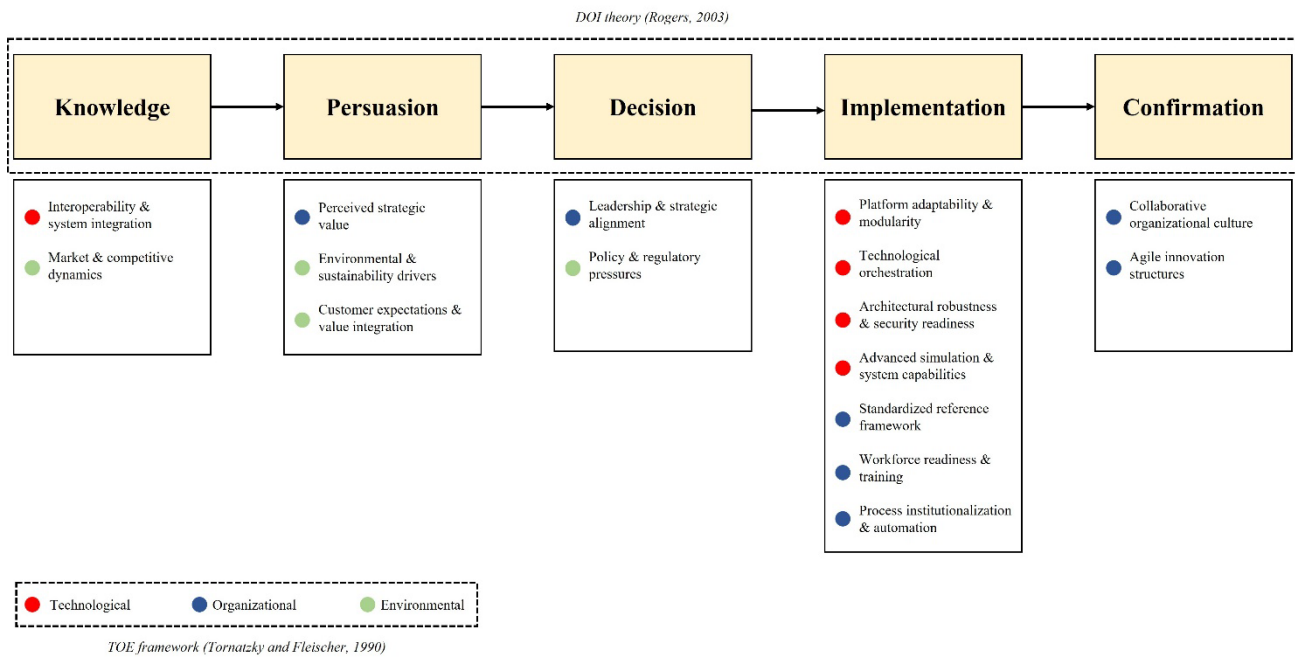


Figure 1. Identified success factors along the adoption journey.

Source(s): Based on Tornatzky and Fleischer (1990) and Rogers (2003)

Table 1. Organizational sample overview

Organizational affiliation	Industrial sector	Headquarters	Company size ¹
C1	Manufacturing industries	Germany	Large-sized
C2	Management and technology consulting	Germany	Small-sized
C3	IT and services	Germany	Medium-sized
C4	Mechanical engineering	Switzerland	Large-sized
C5	Energy and power generation	Germany	Large-sized
C6	Healthcare and medical technology	Germany	Large-sized
C7	Healthcare and medical technology	Germany	Large-sized
C8	Mechanical engineering	Germany	Medium-sized
C9	Manufacturing industries	Germany	Large-sized
C10	IT and services	Germany	Large-sized
C11	IT and services	Germany	Large-sized
C12	Transportation and logistics	Switzerland	Large-sized
C13	Transportation and logistics	Germany	Large-sized
C14	Mechanical engineering	Germany	Large-sized
C15	IT and services	Switzerland	Small-sized
C16	Mechanical engineering	Germany	Large-sized
C17	Manufacturing industries	Germany	Large-sized
C18	IT and services	Malta	Small-sized
C19	IT and services	USA	Small-sized
C20	Automotive	Germany	Large-sized

¹ In terms of number of employees: small-sized ≤ 50, medium-sized 51–500, and large-sized > 500.

Source(s): Authors' compilation

Table 2. Interview sample composition

Identifier	Gender	Role	Role (industry) experience	Organizational affiliation	Organizational tenure
I-01	Male	Solution architect	≈1.5 (6) years	C1	≈1 year
I-02	Male	Chief executive officer	≈1.5 (16) years	C2	≈16 years
I-03	Male	Sales director	≈2 (10) years	C3	≈3.5 years
I-04	Female	Senior digitalization expert	≈2 (24.5) years	C4	≈24.5 years
I-05	Male	Innovation manager	≈4 (23) years	C5	≈10 years
I-06	Male	Digital twin expert	≈7.5 (10) years	C6	≈7.5 years
I-07	Male	Senior XR expert	≈3.5 (10) years	C6	≈10 years
I-08	Male	Senior vice president digital operations	≈7 (29) years	C7	≈29 years
I-09	Male	Chief executive officer	≈18 (18) years	C8	≈18 years
I-10	Male	Digital twin specialist	≈5.5 (14) years	C6	≈10 years
I-11	Female	Project lead immersive systems	≈4 (6) years	C9	≈5 years
I-12	Female	Head of smart factory	≈1.5 (11) years	C6	≈9 years
I-13	Male	Head of innovation and business development	≈3 (27) years	C10	≈6 years
I-14	Male	Product owner immersive systems	≈5 (12.5) years	C6	≈12.5 years
I-15	Male	Chief technology officer	≈8 (13.5) years	C4	≈11 years
I-16	Male	Team lead process and tool	≈6 (16) years	C6	≈6 years
I-17	Male	Chapter lead supply chain	≈6 (12.5) years	C11	≈8.5 years
I-18	Female	Immersive systems development specialist	≈1 (1) year	C20	≈1 year
I-19	Male	Chief technology officer	≈6 (15) years	C12	≈15 years
I-20	Male	Head of life cycle management	≈4 (14) years	C12	≈14 years
I-21	Male	Digital transformation manager	≈2 (2) years	C6	≈2 years
I-22	Male	Senior management consultant	≈7.5 (22) years	C13	≈22 years
I-23	Male	Senior digital twin expert	≈7 (16.5) years	C14	≈16.5 years
I-24	Female	Senior product owner immersive systems	≈2 (2) years	C11	≈2 years
I-25	Male	Supply chain automation specialist	≈5.5 (21) years	C6	≈11 years
I-26	Male	Digital architect	≈7 (30) years	C15	≈7 years
I-27	Male	Group lead data-driven engineering	≈6 (8.5) years	C16	≈8.5 years
I-28	Female	Business development manager	≈2.5 (6) years	C17	≈2.5 years
I-29	Male	Chief executive officer	≈5 (29.5) years	C18	≈5 years
I-30	Male	Business development manager	≈4 (4) years	C6	≈4 years

I-31	Male	Senior manager digital twins	≈2.5 (13) years	C6	≈11 years
I-32	Male	Immersive system onboarding specialist	≈1.5 (1.5) years	C19	≈1.5 years
I-33	Male	Research and development engineer	≈3.5 (8) years	C20	≈8 years

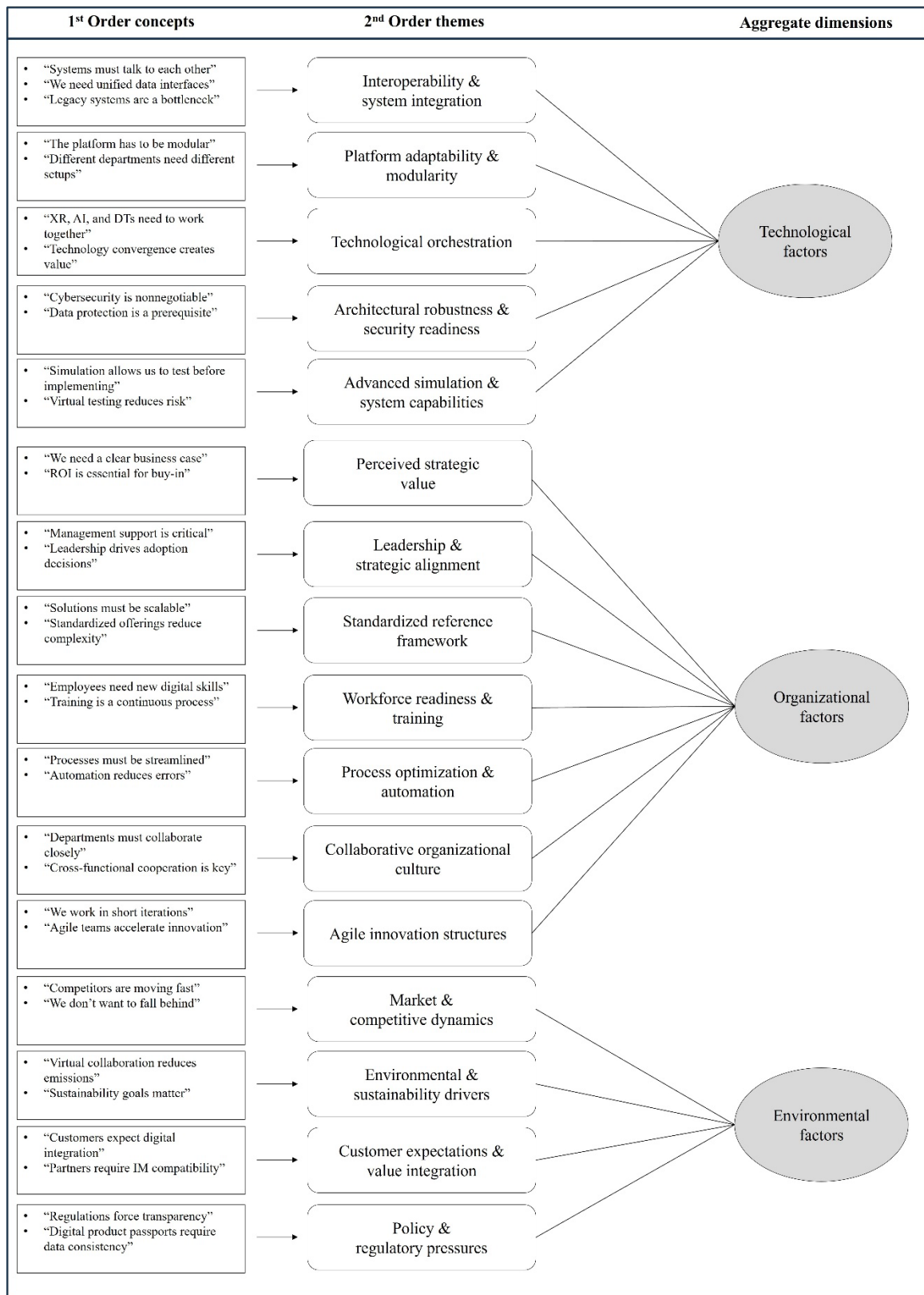
Source(s): Authors' compilation

Table 3. Mapping of TOE-related success factors and IC dimensions across DOI adoption stages

DOI stage	TOE dimension	Success factor	Intellectual Capital (IC)		
			Human	Structural	Relational
Knowledge	Technological	Interoperability & system integration	✓	✓	-
	Environmental	Market & competitive dynamics	✓	-	-
Persuasion	Organizational	Perceived strategic value	-	-	✓
	Environmental	Environmental & sustainability drivers	-	-	✓
		Customer expectations & value integration	✓	-	✓
Decision	Organizational	Leadership & strategic alignment	✓	✓	✓
	Environmental	Policy & regulatory pressures	-	-	-
Implementation	Technological	Platform adaptability & modularity	✓	✓	-
		Technological orchestration	✓	✓	-
		Architectural robustness & security readiness	✓	✓	-
		Advanced simulation & system capabilities	✓	✓	-
	Organizational	Standardized reference framework	-	✓	-
		Workforce readiness & training	✓	-	✓
		Process institutionalization & automation	✓	✓	-
Confirmation	Organizational	Collaborative organizational culture	✓	-	✓
		Agile innovation structures	-	✓	✓

Source(s): Authors' compilation

Appendix A: Gioia coding scheme



Source(s): Authors’ compilation based on Gioia *et al.*, 2013

Appendix B: Identified success factors and frequency of occurrence

Success factor (<i>in ascending order</i>)	Number of interviews mentioning factor (N = 33)
Advanced simulation & system capabilities	14
Agile innovation structures	17
Architectural robustness & security readiness	12
Collaborative organizational culture	11
Customer expectations & value integration	12
Environmental & sustainability drivers	8
Interoperability & system integration	13
Leadership & strategic alignment	24
Market & competitive dynamics	11
Perceived strategic value	7
Platform adaptability & modularity	10
Policy & regulatory pressures	13
Process institutionalization & automation	8
Standardized reference framework	6
Technological orchestration	14
Workforce readiness & training	29

Source(s): Authors' compilation