Journal of Enterprise Information Management

The role of Digital Twin capabilities in Digital Service Innovation deployment: a multiple case approach

Journal:	*Journal of Enterprise Information Management*
Manuscript ID	JEIM-05-2024-0217.R2
Manuscript Type:	Research Article
Keywords:	Digital Twin, Digital Service Innovation, Capabilities, Product-Service Systems, Digital Services

The role of Digital Twin capabilities in Digital Service Innovation deployment: a multiple case study approach

Purpose - As industries increasingly integrate Digital Twins (DTs) into their operations and service offerings, it becomes crucial to understand the specific technological and organizational capabilities associated with DTs and their role in effective Digital Service Innovation (DSI). This paper contributes to the literature on DSI-enabling factors by examining the role of DT capabilities in driving DSI within organizations, highlighting the areas of interconnection.

Design/methodology/approach - This study adopts a multiple case study approach, examining two organizations with different engagements with DT: a consultancy engineering firm offering DT solutions, and a technology company specializing in DT services for different sectors. These diverse perspectives aim to provide a comprehensive understanding of role of DT in DSI in different organizational contexts.

Findings - The study identifies distinct capabilities needed to develop and exploit DT, as well as new capabilities acquired by organizations through DT deployment. It reveals that several technical and non-technical DT capabilities overlap with established DSI capabilities, illustrating a logical pathway from DT capabilities to DSI. These insights are synthesized into a theoretical framework which illustrate how DT capabilities support and enable DSI.

Practical implications - This research delineates critical DT capabilities and highlights which of these contribute to the effective deployment of DSI. These findings provide actionable strategies for organizations aiming to develop and strengthen DT capabilities to maximize their potential impact on DSI.

Originality/value - This paper expands beyond the prevalent technical and engineering emphasis in DT literature by adopting a holistic capabilities-based approach. It provides an in-depth examination of how DT capabilities can drive DSI, delivering valuable insights for both academia and industry practice.

Keywords: Digital Twin, Digital Service Innovation, Capabilities, Product-Service Systems, Digital Services

Paper type: Research paper

1. Introduction

The transformative power of new digital technologies is leading to the development of new service paradigms which fundamentally change how companies interact with their customers and how they orchestrate their value chains (Kamalaldin et al., 2020). In particular, the proliferation of data-driven digital service offerings, underpinned by contextual, environmental, and consumer behavior insights, has generated innovation across industries, allowing organizations to dynamically reconfigure and align their service offerings with evolving customer demands and market conditions (Heller et al., 2021; Opazo-Basáez et al., 2024a). In this context, Digital Service Innovation (DSI) has emerged as a driver of competitive advantage, significantly influenced by the broader phenomenon of digital transformation (Barrett et al., 2015). Rooted in the trends of servitization and digitalization, DSI represents a fundamental shift whereby digital technologies transition from supplementary roles to central components of service innovation (Opazo-Basáez et al., 2024b).

The growth of digital service innovations reshapes competitive dynamics, marking the shift from traditional product-oriented strategies to integrated digital solutions (Vendrell-Herrero et al., 2017). Nonetheless, deploying DSI remains challenging due to the required complex interactions between organizational, strategic, and technological dimensions (Barrett et al., 2015). Organizations often encounter barriers such as technological incompatibilities, limited customer-oriented capabilities, and deficiencies within innovation processes (Chin et al., 2023; Greenhalgh et al., 2004). In fact, these challenges often arise because of conflicting demands on organizational resources and capabilities (Vial and Grange, 2024). Addressing these challenges requires a deeper understanding of how technology adoption influences service innovation capabilities. Burton et al. (2024) argue that technology integration must extend beyond technical problem-solving to strategically enhance innovation capabilities and drive ecosystem interactions. This underscores the need to align digital technologies strategically with service innovation goals.

DSI emphasizes the interconnectedness of digital technologies and service offerings, requiring continuous adaptation of services and underlying technological infrastructures to enhance customer experiences and operational performance (Opazo-Basáez et al., 2022). It leads to an increased utilization of transformative technologies such as Digital Twins (DTs), Internet of Things (IoT), Big Data, Artificial Intelligence (AI), and Cloud Computing for service offerings (Jamwal et al., 2022; Opazo-Basáez et al., 2022). Among these technologies, DTs uniquely facilitate real-time digital representations of physical systems enhancing predictive capabilities, process optimization, and enabling the provision of highly tailored services (Galera-Zarco, 2024). Indeed, DT is increasingly recognized as a key enabler of innovation, effectively bridging the physical and digital domains (Fukawa & Rindfleisch, 2024; Galera-Zarco, 2024). While initially employed primarily for operational optimization and cost reduction, DTs are now appreciated for their capacity to enhance service offerings and generate new value propositions across sectors such as manufacturing, healthcare, the built environment, and energy (Galera-Zarco & Papadonikolaki, 2023; Meierhofer et al., 2020). Research exploring the role of DTs in value creation highlights their systematic integration into service layers, facilitating value co-creation (Galera-Zarco, 2024; Meierhofer & West, 2019; West et al., 2021). However, existing literature reveals a notable gap regarding the organizational and technological capabilities necessary to effectively leverage DTs within service contexts (Agrawal et al., 2022; Fuller et al., 2020). Predominantly, research has emphasized technical and engineering aspects of DT implementation (e.g. Ferko et al., 2022; Minerva et al., 2020), overlooking its potential in driving broader service innovations as indicated by Fukawa and Rindfleisch (2023).

Based on the above, there exists a gap in fully understanding the integration and operationalization of digital technologies within the framework of service innovation. Traditional service management has often detached technological advancements from service strategies, thus limiting the potential for digital technologies to enable truly innovative service offerings (Kreye, 2022). This oversight necessitates a revaluation of how digital developments, such as DTs, can be strategically employed not only to support but drive service innovation (Barrett et al., 2015; Bustinza et al., 2022; Vendrell-Herrero et al., 2021). Building on research by Burton et al. (2024), there is a pressing need to deepen our understanding of the specific capabilities which lead to more effective DSI. Moreover, it is essential to investigate how capabilities developed for technology adoption and exploitation may play a pivotal role in enabling and scaling DSI.

This study aims to contribute to the understanding of DSI-enabling factors by specifically examining the role of DT capabilities in driving DSI within organizations. Two central research questions guide this exploration: 1) *To what extent do capabilities developed through implementing and using Digital Twins align with those necessary for deploying Digital Service Innovation?* and 2) *In what ways does the implementation and use of Digital Twins enable organizations to leverage their capabilities for the deployment of Digital Service Innovation?* The study initially focuses on identifying and understanding the capabilities essential for developing, utilizing and exploiting a DT, followed by structuring the knowledge on capabilities required for DSI. The ultimate goal is to better understand whether and how DT capabilities influence the ability of organizations to perform DSI.

To address these questions, this study employs a multiple case study methodology, analyzing a multinational consultancy engineering firm specializing in DT technology and a provider of Digital Twin as a Service (DTaaS). By analyzing these two cases, the study captures a broader spectrum of what and how DT capabilities are leveraged for DSI. This research introduces a novel perspective by linking DT capabilities directly with the strategic elements of DSI. Situated at a juncture where businesses increasingly depend on digital technologies to drive service innovation and create competitive advantage, this study provides significant and timely research by examining the impact of DTs in this context.

This research paper is structured into sections to provide a comprehensive understanding of the scope of the study and its contributions. The theoretical background section presents a detailed review of the literature, offering foundational insights on the role of DTs in service provision, identifying essential capabilities related to DTs and DSI, whilst also highlighting key gaps which this research seeks to address. The methodology section outlines and justifies the multiple case study approach, explaining how it supports the research objectives. The results and analysis are then presented and discussed in relation to existing literature in DSI. Additionally, the discussion also provides theoretical and managerial contributions derived from the research findings. Finally, limitations are recognized, and the conclusion highlights key findings and proposes directions for future research.

2. Theoretical background

2.1. Digital Twin conceptualization and its role in service delivery

A Digital Twin (DT) is a comprehensive digital representation of a physical product, system or process, capturing selected characteristics, properties, and behaviors through a dynamic, bidirectional flow of real-time data, enabling continuous feedback and synchronization (Grieves & Vickers, 2016). Tao et al. (2018a) define DT similarly as a digital counterpart of a physical entity, process or system, created by amalgamating data from different sources, enabling replication of process and prediction of performance across different scenarios. A DT is not a simple and individual technology but comprises a coordinated set of digital technologies (Bolton et al., 2018). Primarily, DTs function as tools for monitoring, simulation, and optimization throughout the asset lifecycle (Grieves & Vickers, 2017). Over time their application has expanded beyond operational efficiency towards enabling real-time simulations and scenario testing, significantly enhancing organizational decision making capabilities (Tao et al., 2018b). Supported by advanced technologies such as IoT, AI, and Big Data Analytics (BDA), DT applications span sectors including manufacturing, healthcare, and the built environment (Jones et al., 2020; Kumar et al., 2023; Lu et al., 2020).

To understand the role of DT in service delivery, it is essential to adopt the perspective of Service-Dominant Logic (SDL). SDL reconceptualizes service provision as a collaborative and interactive multi-actor value creation process, emphasizing resource integration as a critical process to generating value (Vargo & Lush, 2004; Edvardsson et al., 2014; Lusch & Vargo, 2014). This approach emphasizes collaboration, interaction, and the combination of efforts to create value, with organizations playing a key role in coordinating these integrations (Edvardsson et al., 2014; Lusch and Vargo, 2014; Vargo, Maglio, and Akaka, 2008). In this context, technology is often seen as a tangible enabler (operand resource) over which intangible skills (operant resource) operate to facilitate value creation (Lusch and Nambisan, 2015). Within this logic, DTs serve as both operand and operant resources in value creation, embodying a dual role that highlights the transformative potential of DTs in enabling continuous value co-creation and redefining service dynamics within digital ecosystems (Galera-Zarco, 2024).

Building on this perspective, the phenomenon of servitization offers a complementary lens through which to examine the role of DTs in service delivery. As businesses increasingly move toward offering "advanced services" which emphasize outcomes and performance, they also shift responsibility for asset maintenance and optimization to service providers (Baines & Lightfoot, 2013; Baines et al., 2024; Opazo-Basáez et al., 2023; Story et al., 2017). In this context, DTs play a dual role here: enhancing performance and efficiency of physical assets involved in service delivery (Nicoletti & Padovano, 2019), and enabling deeper understanding of customer needs and service dynamics through sophisticated data analysis (Galera-Zarco, 2024; Meierhofer et al., 2020; Porter & Heppelmann, 2014). Additionally, DTs create a continuous feedback loop between the physical and digital environments, allowing for real-time adjustments based on precise analytics, thus facilitating dynamic, customized service delivery (Galera-Zarco & Papadonikolaki, 2023; Tao et al., 2018b).

2.2 Digital Twin capabilities

DTs require a balanced combination of technical and non-technical capabilities (Moyne et al., 2020; Tao et al., 2018b). While technical capabilities ensure functionality and operability, non-technical capabilities are essential for organizational readiness and strategic alignment (Fuller et al., 2020; Kritzinger et al., 2018; Lehner et al., 2021). Despite the increasing volume of research into DTs, there is still a variety of perspectives in implementing and using DTs which make the identification of these capabilities complex. Thus, a careful identification and definition of DT capabilities is required.

2.2.1 Essential capabilities for developing and exploiting Digital Twins

Plummer et al. (2021) presented an early attempt at identifying DT-related capabilities through a Skills and Competency Framework tailored for the National Digital Twin project in the UK. However, their focus on integrating DTs systems across various domains to achieve national interoperability may not fully align with capabilities relevant to individual organizations. This study digs deeper in the literature in order to define distinct sets of capabilities that allow organizations of any size, from small enterprises to large corporations, to develop and implement DTs. Firstly, our research reviews specific technical capabilities required to develop and manage DTs. This is then followed by an exploration of the non-technical capabilities that support their strategic and operational integration into business processes.

Firstly, in order to effectively develop and operate DTs, the presence of technical capabilities is crucial. These capabilities must ensure that organizations are able to build DTs which serve as accurate and dynamic representations of physical assets, enabling, among other uses, real-time monitoring, predictive maintenance, and operational optimization (Lehner et al., 2021). Technical capabilities include managing large volumes of data through effective collection, storage, processing, and analysis (Agrawal et al., 2022). Likewise, effective data management and data analytics are essential in DTs to interpret the vast amounts of data generated and derive actionable insights (Tao et al., 2018b). Additionally, integration capabilities enabling interoperability among heterogeneous technologies and legacy systems is fundamental to ensure DT accuracy and functionality (Barricelli et al., 2019, Rosen et al., 2015). Organizations also require modeling capabilities to maintain the accuracy and reliability of DTs (Schleich et al., 2017), as well as simulation abilities to run "what-if" scenarios by recreating potential changes affecting the physical counterpart (Barricelli et al., 2019).

As DTs often involve the management of sensitive data and control of critical operations, ensuring the security and privacy of data and associated systems is mandatory (Jones et al., 2020; Plummer et al., 2021; Agrawal et al., 2022). Thus, effective cybersecurity is necessary to protect against potential threats and vulnerabilities, thereby safeguarding the operational continuity of DTs (Jones et al., 2020). Finally, a DT should seamlessly integrate and communicate with other DTs, systems and components within a digital ecosystem. This involves compatibility with various data formats, external data sources, protocols and interfaces to ensure coherent and uninterrupted work across different platforms and operational technologies (Agrawal et al., 2022). Effective data interoperability facilitates data exchange and system integration, enabling comprehensive DT ecosystems (Barricelli et al., 2019, Plummer, et al., 2021). Table 1 summarizes technical capabilities identified in the literature.

------ Insert Table 1 here ------

Beyond the technical requirements, non-technical capabilities are equally critical for the successful development and exploitation of DTs (Crespi, 2023). These capabilities involve organizational and human factors, allowing organizations to align DT with business objectives. These capabilities are also required to manage the cultural and operational shifts needed for digital transformation (Raj et al., 2020). Moreover, the presence of strong leadership from executive teams is vital for the successful integration and utilization of DTs within an organization (Negri et al., 2017; Martinez & Huss, 2022). Leaders must recognize the strategic value of data and ensure that DT initiatives are aligned with overarching business objectives (Plummer et al., 2021). Additionally, DTs can also alter existing workflows and roles, so the implementation of DTs requires effective management of organizational change to navigate these transitions smoothly, minimizing disruption while maximizing positive outcomes (Kritzinger et al., 2018).

The creation of effective communication and a collaborative environment are of great importance for the success of DT development. Communication and knowledge sharing is essential between different departments, including IT, operations, and engineering (Uhlemann et al 2017; Plummer et al 2021). Moreover, stakeholder management, which includes transparency, reliability and ensuring security protocols, is of particular importance especially when stakeholders from different domains must collaborate and share sensitive data in the DT (Tripathi, et al, 2024). Overall, building and maintaining trust is fundamental to achieving user acceptance and ensuring effective use of DTs within an organization. In the DT context, trust involves confidence in the data integrity, system reliability, and the overall performance of the technologies (Broo et al., 2022, Plummer et al 2021; Trauer et al., 2022). Finally, as noted by Tao and Qi (2019), organizations implementing DTs must cultivate a culture of continuous learning and adaptation. Such a capability allows firms to effectively integrate new insights and data streams provided by DTs, thereby maintaining competitiveness and responding proactively to emerging challenges and opportunities. Table 2 integrates the collection of these non-technical capabilities as presented in the literature.

------ Insert Table 2 here ------

2.2.2 Capabilities enabled through Digital Twin usage

In the exploration of DT capabilities and to better understand the potential of DTs as enablers of DSI it is pivotal to examine the capabilities achieved by organizations through their use. DTs not only require specific technical and organizational competencies for implementation and exploitation, they also enable the emergence of new capabilities.

A widely acknowledged technical capability enabled through DT usage is real-time monitoring and control of operational processes. This allows organizations to respond promptly to system changes and anomalies (Galera-Zarco, 2022; Tao & Qi, 2019; Uhlemann et al., 2017). By providing accurate, real-time representations of physical assets and systems, DTs contribute to operational optimization, enhancing efficiency and minimizing resource wastage (Galera-Zarco, 2022; Uhlemann et al., 2017). Another core technical capability is predictive analytics: by leveraging data-driven insights, DTs support the early identification and prevention of potential equipment failures, thereby reducing downtime and maintenance costs (Agrawal et al., 2022; Grieves, 2014). Additionally, DTs enable scenario-based simulations which facilitate "what-if" analyses, equipping organizations with the ability to assess risks, forecast outcomes, and make informed decisions (Schleich et al., 2017; Tao & Qi, 2019). The final technical capability identified in the literature relates to the ability of DTs to support seamless data exchange and interoperability. This enables the integration of heterogeneous digital infrastructures and underpins the development of interconnected service ecosystems (Agrawal et al., 2022; Uhlemann et al., 2017). Table 3 encapsulates this set of technical capabilities.

------ Insert Table 3 here ------

In addition to technical capabilities, DT usage also enables a broad spectrum of organizational and strategic competencies. One key non-technical capability is the ability to support strategic decision making by enabling organizations to test and predict outcomes in virtual environments, thereby avoiding risks to physical assets (Broo et al., 2022; Rosen et al., 2015). DTs also enhance design an development processes by facilitating rapid prototyping and iterative design testing. This can reduce time-to-market and improve product or service quality (Schleich et al., 2017). Furthermore, DTs contribute to sustainability goals by optimizing resource utilization, minimizing waste, and promoting environmentally conscious practices (Galera-Zarco, 2022). In educational and training contexts, DTs provide realistic, risk-free environments for skills development and operational training, which is crucial for preparing a skilled workforce in different industrial sectors (Beloglazov et al., 2020; Kang et al., 2016). DTs also allow collaboration among different actors by providing a unified platform for real-time information sharing across departments. This capability extends to cross-organizational collaborations within ecosystems (Tao et al., 2019, Uhlemann et al. 2017). Finally, by simulating customer experiences and enabling the co-creation of tailored solutions, DTs enhance the personalization of service interactions and improve customer engagement (Barricelli et al., 2019; Broo et al., 2022; Galera-Zarco, 2024). Table 4 summarizes these non-technical capabilities.

------ Insert Table 4 here ------

2.3 Conceptualizing Digital Service Innovation and its enabling capabilities

DSI refers to the process of creating, improving, or transforming services through the strategic integration of digital technologies, reshaping value propositions, delivery mechanisms, and customer experiences (Barrett et al., 2015; Opazo-Basáez et al., 2022). As part of broader trends in digital transformation and servitization, DSI embodies a shift whereby digital technologies act not as enablers alone but as integral components of innovation logic, enabling continuous adaptation to dynamic market and customer needs (Vendrell-Herrero et al., 2017; Rabetino et al., 2024). As such, successful engagement in DSI requires a robust set of capabilities, both technical and non-technical, which organizations must harness to integrate, adapt, and leverage digital solutions in ways that align with evolving customer needs and strategic goals (Kohtamäki et al., 2020; Rabetino et al., 2024). This section reviews the literature to identify and structure the capabilities that equip organizations to navigate the complexities of DSI.

First, technological capabilities are essential in DSI as they enable organizations to effectively adopt, adapt, and leverage new available emergent technologies within their business models (Bharadwaj et al., 2013; Barrett et al., 2015; Lehrer et al., 2018). To successfully deploy DSI, firms must adopt new technologies, adapt them to their specific operational context, and leverage the technologies to enhance service offerings (Kohtamäki et al., 2020; Rabetino et al., 2024).

Vendrell-Herrero et al., (2017) discuss the strategic application of digital technologies in the context of digital servitization, emphasizing the importance of the integration of technologies to enhance service offerings. Indeed, the interdisciplinary nature of DSI requires the integration of technological advancements such as IoT, AI, and BDA to enable and enhance service offerings, hence the need for continual adaptation and innovation with technology (Kohtamäki et al., 2020; Rabetino et al. 2024). Likewise, the capability to manage data through comprehensive analytics is crucial in extracting actionable insights and supporting decision making processes (Opazo-Basáez et al., 2022). Aligned with this, the importance of data analytics is emphasized for its potential to improve service delivery, create new service opportunities, and to facilitate enhanced customer understanding and service personalization (Barrett et al., 2015; Lehrer et al. (2018); Raddats et al., 2022).

A critical technical capability in DSI is the seamless integration of digital technologies into existing service architectures. This integration forms the backbone of robust digital service systems capable of efficiently meeting diverse and dynamic customer demands (Kohtamäki et al., 2020; Rabetino et al., 2024). The use of digital platforms further enhances this capacity by consolidating and coordinating digital technologies, allowing for scalable and flexible service offerings (Kohtamäki et al., 2022). Finally, data security and privacy represent indispensable technological capabilities within DSI. Protecting sensitive customer data is not only critical for regulatory compliance but also for maintaining trust within digital service ecosystems (Kraus et al., 2021). This imperative is further reinforced by Lusch and Nambisan (2015), who highlight its significance within the service-dominant logic framework. Table 5 synthesizes the key technical capabilities for DSI identified in the literature.

------ Insert Table 5 here ------

Non-technical capabilities play a crucial role in DSI, complementing technological competencies. Organizational learning and adaptation are fundamental to the continuous improvement and successful implementation of DSI (Nylén and Holmström, 2015). This capability allows organizations to evolve in response to technological advancements and changing market conditions (Awad & Martin-Rojas, 2024; Opazo-Basáez et al., 2024c). Moreover, Coreynen et al. (2024) emphasize the iterative learning processes undertaken by organizations to integrate new digital technologies effectively and adapt their business models and strategies to deploy DSI. As highlighted by Sjödin et al. (2020), cultivating a culture of exploration and experimentation, particularly around digital technologies, is essential for successful DSI initiatives.

Organizations engaging in DSI often participate in collaborative ecosystems, increasingly engaging with clients, external partners and other firms to collaboratively co-create value. Effectively managing this value co-creation process is critical, as it serves as a catalyst for the development of innovative digital service solutions (Serrano-Ruiz et al., 2024). Thus, Vargo et al. (2024) point to the significance of engaging in service ecosystems which leverage external capabilities and resources to support the delivery of innovative digital service offerings. An equally critical non-technological capability lies in ensuring strategic alignment between digital initiatives and overarching business objectives. As Awad and Martin-Rojas (2024) argue, such alignment, paired with effective management of the complexities inherent in digital transformation, is vital for realizing the full potential of DSI. In this context, Rabetino et al. (2024) indicate that aligning technological strategies with broader organizational goals ensures coherence in transformation efforts and supports sustained innovation and value creation through digital services.

An additional non-technical capability is resource liquification. This removes barriers and facilitates the flow of information and services across digital platforms, thereby making organizational resources more accessible and responsive, and thus enabling DSI (Vargo et al., 2024). Complementing this capability, the establishment of a customer-centric approach has been identified as fundamental for successful DSI (Lehrer et al., 2018) as it allows the design of personalized services which enhance customer experiences and satisfaction (Soto Setzke et al., 2023). Leveraging customer data to inform service design and delivery ensures alignment with customer expectations and preferences (Lehrer et al. 2018; Soto Setzke et al., 2023). Table 6 summarizes the identified non-technical capabilities essential for effective DSI deployment.

------ Insert Table 6 here ------

2.4 Research gap identification and conceptual framework development

Recent literature has explored the relationship between emergent digital technologies and service innovation, particularly from a capabilities perspective. For instance, studies have proposed frameworks illustrating how AI (Akter et al., 2023) or BDA and digital platforms (Xiao et al., 2020) enable service innovation. However, despite this emerging focus observed in the literature, the role of DTs as enablers of DSI remains notably unexplored.

Previous research has examined the technical and non-technical capabilities required for development and utilization of DTs (Kritzinger et al., 2018; Plummer et al., 2021). In parallel, the service innovation domain has separately identified critical capabilities essential for effective DSI (e.g., Barrett et al., 2015; Lehrer et al., 2018; Kohtamäki et al., 2020). Nonetheless, limited research specifically addresses the intersection and synergies between DT capabilities and those required for enabling DSI. Although existing studies acknowledge the contribution of DTs to enhanced service delivery (Galera-Zarco, 2024), improved operational efficiency (Tao et al., 2018b) and innovation processes (Fukawa & Rindfleisch, 2024), their potential as strategic enablers for DSI remains underexplored. In particular, there is a lack of comprehensive research examining the extent to which capabilities developed through DT implementation and use align or overlap with the capabilities necessary for DSI. Addressing this gap is significant as it can offer valuable insights to organizations seeking to strategically leverage DTs as catalysts for innovation, particularly in industries undergoing servitization. While prior studies recognize the role of DTs in advanced services and value creation (Baines et al., 2024; Story et al., 2017), they do not thoroughly explore how DT-specific capabilities directly enhance an organization's capacity to innovate in digital service contexts.

This research hypothesizes that the implementation and use of DTs, through the specific capabilities they both require and enable, position organizations to effectively engage in DSI. Thus, the hypotheses guiding this study are:

- H1: There is a significant overlap between Digital Twin capabilities and those necessary for Digital Service Innovation.
- H2: Organizations that develop and utilize Digital Twins are better positioned to successfully deploy Digital Service Innovation, as the capabilities required and gained through Digital Twins both align with and facilitate the development of Digital Service Innovation.

Addressing this research gap provides an important contribution to the literature on DSI-enabling factors by offering a nuanced understanding of how DT capabilities influence organizational capacity for DSI and help to achieve competitive advantages. Based on a comprehensive literature review and synthesis, this study develops two conceptual frameworks (Figures 1 and 2) to illustrate the interrelationships and overlaps among technical (Figure 1) and non-technical (Figure 2) capabilities involved in DT development and exploitation, capabilities gained through DT usage, and capabilities essential for deploying DSI.

------ Insert Figure 1 and Figure 2 here ------

3. Methodology

In order to investigate how DT capabilities influence DSI within organizations, this study adopts an exploratory qualitative research design grounded in a multiple case study approach. Case study methodology is particularly well suited for examining contemporary phenomena within their real-life contexts, especially when addressing complex "how" and "why" questions which are central to the understanding of phenomena (Yin, 2017). The exploratory nature of the study enables the generation of new theoretical insights without being restricted to the validation of pre-existing frameworks (Rothenberger & Srite, 2009). Employing multiple case studies further strengthens the analytical depth by allowing cross-case comparisons, thereby enhancing the robustness and potential generalizability of the findings (Eisenhardt, 1989).

The case population of this study comprises organizations specializing in the development, exploitation, and strategic utilization of DTs. These organizations not only provide expertise in implementing and operating DTs but also support clients in strategic alignment and in leveraging the potential capabilities enabled through DT usage to achieve operational efficiency, strategic alignment, and DSI. The selection followed a purposive sampling strategy (Patton, 2015) aimed at capturing variation in organizational size, technological focus, and service models within the DT landscape. The first case study involves a large multinational engineering consultancy with a dedicated DT department, providing expertise on how established firms integrate DTs into complex, asset-intensive environments. The second case study features a smaller, technology-native company offering DTs as a service (DTaaS) illustrating agile, innovation-driven applications of DT technology. Beyond their internal expertise, both organizations work with a diverse range of clients across industries and project types, supporting digital transformation efforts, strategic alignment, and innovation initiatives. Together, these organizations span a broad range of DT implementation contexts.

To maintain anonymity, the two organizations are referred to as CompA and CompB. An overview of each case is presented below to contextualize their positioning and relevance in exploring DT capabilities in relation to DSI.

CompA is a multinational consulting engineering firm with over 6,000 professionals operating across multiple countries. The organization addresses complex global challenges in sectors such as aviation, energy, and urban development. This study focuses on the firm's Digital Twin consultancy department, which plays a pivotal role in supporting clients through the design and operational phases of projects by offering innovative DT solutions. Their core expertise lies in leveraging DTs to address issues such as inefficiencies, sustainability and data complexity, while also enhancing stakeholder engagement and articulating the value of DTs across asset lifecycle. The primary informant for this case was a Digital Twin consultant and

Business & IT architect, selected due to extensive experience in managing DT-related projects across multiple industries, their involvement in strategic initiatives related to digital transformation, and comprehensive understanding of organizational capabilities required for effective DT implementation and use.

CompB is a boutique firm based in Canada, specializing in Digital Twin as a Service (DTaaS) and recognized for its innovative approach to delivering DT solutions. The company employs approximately 70 professionals and integrates diverse technological services to transform organizational operating models through highly tailored DTs. Its strategic focus centers on fostering agility, innovation, and data-driven decision making. The firm collaborates closely with client organizations to articulate and realize their digital ambitions, developing roadmaps for both value strategy and technical implementation. The key informant interviewed was the co-founder and chief growth officer, whose strategic leadership role and direct involvement in client engagement across multiple sectors provided valuable insights. The informant was selected due to a deep understanding of the technical, strategic, and organizational capabilities required for DT development and their alignment with broader goals such as DSI.

Data were primarily collected through semi-structured interviews supplemented by secondary sources, including internal company documentation, presentations provided by the interviewees, and publicly available material from organizational websites. Interviewees' experience, their central roles and comprehensive knowledge of both technical and organizational dimensions enabled the collection of rich and detailed data directly relevant to the study's objectives. Interviews took place in March and April 2024 via video conferencing platforms, each lasting between 60 and 90 minutes. An interview guide (see Appendix A) was developed to maintain consistency across cases while allowing flexibility to explore emergent themes (Myers & Newman, 2007).The interviews addressed five areas: 1) capabilities required to develop and exploit DTs, 2) capabilities achieved through DTs, 3) the role of DTs in deploying DSI, 4) organizational culture, and 5) DT implementation goals. After covering the first two areas, the researchers presented the capability tables (Tables 1–6) and initial versions of capability interrelationship frameworks (Figures 1 and 2) which were developed by the authors through a combination of literature review and the authors' interpretive analysis of existing research. Participants were invited to validate these findings and contribute additional insights. After incorporating their inputs, the interrelationship figure was sent back to the interviewees via email for final feedback to ensure accuracy and completeness. All interviews were video-recorded with the consent of the participants and transcribed verbatim for analysis.

A systematic analytical strategy was employed, integrating both within-case and cross-case analysis techniques (Eisenhardt, 1989). In the first phase the transcribed interview data were analyzed on a case-by-case basis to construct a detailed understanding of DT and DSI capabilities within each organizational context. This was followed by a cross-case analysis aimed at identifying shared patterns, divergences, and overarching themes across the two cases.

The qualitative data analysis followed an iterative coding process. Initial coding drew upon the capability sets identified from the literature while remaining open to new insights through inductive open coding. These initial codes were then refined through axial coding, which facilitated the clustering of themes into broader categories relevant to the study's focus on capabilities (Corbin & Strauss, 2015). This approach enabled a structured yet flexible examination of both theoretically grounded and emergent capabilities. To strengthen the validity and reliability of the findings, two strategies were employed. Triangulation was achieved by incorporating the previously mentioned secondary data to corroborate and contextualize the interview data (Denzin, 1978). Additionally, reflexivity was maintained throughout the research process. The researchers engaged in continuous critical reflection on their assumptions, interpretations, and potential biases to ensure a more objective and nuanced analysis (Finlay, 2002).

4. Findings and analysis

This section presents the findings and analysis of the empirical data structured to address the two research questions guiding this study. The first subsection validates the DT capabilities identified from the literature and introduces any new capabilities emerging from the cases. The subsequent subsection explores the role of these DT capabilities in enabling DSI, specifically examining the alignment between DT capabilities and the requirements for successful DSI, as well as the way in which organizations leverage DT capabilities to facilitate DSI deployment.

4.1 Empirical validation and extension of Digital Twin capabilities

The analysis of CompA and CompB provided robust validation of the technical Digital Twin (DT) capabilities identified in the literature, as summarized in Table 7. Both organizations validated Data Management and Analytics as a foundational technical DT capability, particularly emphasizing robust IT infrastructure and metadata management to address complex and large-scale data requirements. Integration of Heterogeneous Systems and Technologies was similarly affirmed, with both organizations highlighting the necessity of comprehensive technical stacks capable of aggregating diverse data sources tailored to specific business objectives. Modeling received partial validation; CompA supplemented this capability through the identification of two additional capabilities, namely Knowledge Graphs and Ontology Management. CompB notably pointed out the necessity of tailored AI and Machine Learning models to effectively operationalize DTs in various use cases. Simulation Ability was jointly validated, reflecting the strategic utilization of DTs for scenario analysis. While CompB explicitly validated Cybersecurity & Data Privacy as critical, particularly regarding the secure integration of external data, CompA did not initially include this capability; however, its importance was subsequently acknowledged following the interviewee's review of Figure 1. Furthermore, Data Interoperability and Digital Platforms was recognized as crucial: CompA highlighted interoperability standards, whereas CompB emphasized data governance to facilitate external data integration.

Both organizations confirmed significant technical capabilities achieved through DT use, notably Operational Optimization, Predictive Analysis, Scenario Analysis for Decision Making, and Data Interoperability. Operational Optimization was explained differently, with CompA providing examples of DTs enabling optimized operations in complex environments (e.g., real-time adjustments in complex water systems), whereas CompB contextualized it as part of a broader evolution from initial cost reduction toward sustained efficiency improvements. Predictive and Scenario Analyses were similarly validated, with both organizations recognizing the integration of AI-driven foresight into DTs and the ability to test scenarios and decisions before implementation as central benefits. However, perspectives diverged regarding Real-time Monitoring and Control: CompA strongly supported this capability, reflecting its operational focus, while CompB provided only partial support, noting the potential of DTs primarily for decision support and simulation scenarios rather than for explicit real-time applications. This divergence suggests varying organizational priorities: CompA's emphasis on immediate operational outcomes aligns with the nature of its clients, whereas CompB focuses more on a strategic planning orientation.

------ Insert Table 7 here ------

In the sphere of technical DT capabilities, each case contributes distinctively to the identification of novel capabilities (Table 8), clearly reflecting their organizational context and strategic focus. CompA introduced the capabilities of Knowledge Graphs and Ontology Management. Knowledge Graphs was highlighted as an essential capability for effectively modeling complex relationships, while Ontology Management was identified as vital for ensuring data consistency and interoperability. These capabilities are particularly relevant given CompA's involvement in large-scale engineering projects, where managing multi-dimensional and domain-specific information is critical. In contrast, CompB highlighted Edge Computing and Advanced Visualization (e.g., AR/VR). Edge Computing emerged as significant for addressing challenges associated with large-scale data processing, enhancing real-time analytics, and reducing latency. Advanced Visualization emerged as a distinct capability, referring to the ability of organizations to adopt and effectively utilize technologies such as Augmented Reality (AR), Virtual Reality (VR), and tools like HoloLens. This capability was recognized for its potential to enhance user experience, support intuitive data exploration, and improve training as well as decision-related processes in DT applications. The identification of these new capabilities aligns with CompB's position as a boutique Digital Twin-as-a-Service provider, where scalability, real-time responsiveness, and user engagement are central to delivering adaptable and client-oriented solutions.

------ Insert Table 8 here ------

Non-technical DT capabilities were consistently validated across cases, as indicated in Table 9. Strategic Alignment and Complexity Management were crucial for both organizations, though articulated differently. CompA discussed the importance of enterprise architecture integration to connect DT initiatives with broader organizational objectives and value chains, whereas CompB associated these capabilities with the necessity of leadership vision and organizational maturity to drive digital transformations such as DT development. Effective Collaboration emerged as critical, with both cases emphasizing Stakeholder Management as essential for aligning technical initiatives with business ambitions, thereby requiring iterative change management to ensure successful adoption. Indeed, insufficient collaboration was identified as a common reason for the failure of many DT initiatives. Organizational Learning and Adaptation was highlighted through the importance of understanding internal barriers, organizational culture, and cross-departmental collaboration before implementing technical solutions. CompA introduced the concept of a DT maturity matrix as a means of guiding organizations through the technological and business transformation processes necessary for developing and utilizing a DT. The capability of Building and Maintaining Trust was partially validated by both organizations. The interviewee from CompA described efforts to address internal resistance by educating teams and demonstrating the advantages of DTs through tangible examples. In contrast, CompB linked this capability closely with Governance, emphasizing trust-building as crucial due to the potential of DTs to enable secure and relevant data sharing. These differences reflect variations in organizational scale and project complexity. CompA's emphasis on internal education and stakeholder engagement underscores the importance of managing resistance and aligning interests within large, complex engineering environments. Conversely, CompB's focus on governance and secure data sharing likely stems from its frequent collaborations with diverse clients who rely on external data sources across distributed ecosystems.

Both companies validated the critical role of Strategic Decision Making Support enabled by DT use. CompA recognized the potential of DTs to facilitate scenario-based analyses that explore various options and optimize decision making processes, whereas CompB emphasized their ability to enhance transparency and visibility into operations. Likewise, improved Collaboration Across Departments and Ecosystem was consistently recognized, emphasizing the role of DTs in reducing organizational silos and enhancing cross-organizational communication. Optimization of Design and Development Processes was fully supported by CompA, highlighting the benefits of virtual scenario testing, while CompB's validation was partial, primarily addressing operational automation without explicit connections to design processes. Similarly, Educational and Training Applications were strongly confirmed by CompA, which emphasized DTs as tools for organizational knowledge transfer and workforce upskilling. This capability was not supported by CompB, possibly indicating this is not a primary area of focus in their projects, where formal training mechanisms may be less prominent. Regarding the Customer-Centric Approach, CompA provided partial validation, primarily within the context of servitization strategies, viewing DTs as aids in transitioning to servitization and enhancing customer value through tailored services. In contrast, CompB placed stronger emphasis on the role of DTs to better serve customers by providing operational transparency. This aligns with their observation that the market is increasingly leveraging DTs to innovate and enhance customer satisfaction. Finally, Sustainable Practices and Waste Reduction received partial and no validation, respectively. CompB touched on sustainable practices and waste reduction indirectly by discussing cost reduction and operational efficiencies but did not explicitly link these to sustainability goals. CompA, although not initially mentioning these capabilities in response to the first block of questions, later supported them during discussions of the non-technical capability interrelationship model (Figure 2).

------ Insert Table 9 here ------

In terms of additional non-technical DT capabilities, both organizations agreed on the importance of Bridging Technical and Business Domains. CompA described this capability as essential for aligning technical DT capabilities with strategic business goals, ensuring that projects involving DTs deliver meaningful value. CompB focused on the formation of multidisciplinary teams capable of effectively communicating and integrating expertise from both domains to ensure that DT solutions align with business objectives and deliver measurable outcomes. Change Management and Overcoming Organizational Resistance also emerged as critical capabilities in both cases, reflecting the importance of managing cultural and operational shifts through stakeholder involvement and gradual implementation strategies. Distinctively, CompA introduced the importance of integrating Domain Knowledge to ensure DT relevance, illustrating the critical role of specialized industry expertise in large-scale, sector-specific DT projects, where accurate contextualization of DT solutions is essential. CompB underlined Skill Development and Talent Management, advocating investment in training to build balanced technical and business expertise. Finally, Resource Liquification was uniquely identified by CompB as a non-technical capability, referring to the enhanced mobility and accessibility of information and services enabled by DT platforms. This capability supports greater agility and responsiveness in DSI, particularly in environments requiring dynamic resource allocation and real-time adaptability. The capabilities emerging from the cases are presented in Table 10.

------ Insert Table 10 here ------

4.2 Understanding the role of DTs in DSI deployment

4.2.1 The extent to which DT capabilities align with those required for DSI deployment

Case CompA: Consulting Engineering Firm (Digital Twin consultancy department)

The interviewee from CompA validated several technical DT capabilities identified from the literature as crucial for enabling DSI. Specifically, Data Management and Analytics, Integration of Heterogeneous Systems and Technologies, Interoperability, Advanced Visualization, and Cybersecurity were confirmed as technical DT capabilities required for developing and exploiting DTs, which are also essential for DSI, as presented in the initial conceptual framework (Figure 1). Additionally, the interviewee highlighted two supplementary technical DT capabilities enabled through DT use, Scenario Analysis and Predictive Analysis, as significantly overlapping with technical DSI capabilities.

Scenario Analysis, in particular, was recognized for its potential to facilitate service-oriented innovation, as it allows organizations to digitally explore multiple scenarios, thereby reducing costs and enhancing the efficiency of new service development:

"In the design phase, digital twins allow companies to explore all kinds of scenarios and options, helping to create smarter and more optimized services"

"…you can also use digital twins to explore all kinds of options digitally… that is not as expensive as if you start trying to engineer and build it"

Predictive Analysis was also identified as transformative for enabling innovative services, particularly those related to predictive maintenance:

"With AI and machine learning models in digital twins, you can develop better data-driven models and offer better services around predictive maintenance, especially in complex environments…"

From a non-technical perspective, CompA's interviewee affirmed that a set of the DT capabilities outlined in the literature overlapped significantly with capabilities necessary for DSI. Specifically, Strategic Alignment and Complexity Management, Effective Communication and Collaboration, Organizational Learning and Adaptation, and a Customer-Centric Approach were validated as essential capabilities for DSI. Furthermore, three of the newly identified capabilities. Bridging Technical and Business Domains and Domain Knowledge emerged as critical for aligning DT capabilities with DSI objectives. The interviewee emphasized the necessity of integrating business understanding and context-specific knowledge to enhance services through DT initiatives:

"...(to offer services)..you want to understand the value chain of the company, the business capabilities, not just the capabilities to build digital twins...understand the ecosystem done by enterprise architecture, to identify what exists and what needs to be connected."

Finally, case CompA explicitly linked Change Management to DSI; specifically, overcoming organizational resistance was discussed:

" (about how to promote service innovation through Digital twins)...Maybe that's also an idea to do it, to say, yeah, evangelize based on use cases and services internally and externally."

Case CompB: : Digital Twin as a Service (DTaaS) provider
The interviewee from CompB validated several technical DT capabilities identified in the literature as crucial for enabling DSI, including Data Management and Analytics, Cybersecurity, Interoperability, and Integration of Heterogeneous Systems and Technologies. These capabilities were considered fundamental in supporting service-oriented business transformations. Additionally, the interviewee introduced and identified four further technical DT capabilities as significant for enabling DSI. These include two newly identified capabilities, Edge Computing and Advanced Visualization, and two capabilities - Predictive Analytics and Scenario Analysis - that were previously classified within DT capabilities but were not integrated into the initial framework (Figure 1) as technical DSI capabilities. Among these newly recognized capabilities, some were particularly reinforced during the interview.

Edge Computing was particularly emphasized as essential in scenarios requiring immediate data handling and rapid decision making:

“The more data you take on, the more complex the infrastructure management becomes… it takes quite a bit of time to understand the needs, the capacity… that's when we start talking about edge computing...to process massive amounts of data.”

Advanced Visualization was also highlighted as transformative, with its potential to enhance user experience and enable interactive, customer-oriented services:

“What we call the visualization layer... visualization, it could be anything from 3D visualization, AR, VR (HoloLenses)… can enhance the user experience, creating opportunities for tailored and interactive services.”

Similarly, Predictive Analytics and Scenario Analysis were identified as integral capabilities for driving innovation in digital services:

“…the what-if scenarios analysis are quite connected (with innovation)… some organizations use them for the design of new products and services.”

From a non-technical perspective, the interviewee validated several capabilities from the initial framework (Figure 2) as essential enablers of DSI. These included Strategic Alignment and Complexity Management, Organizational Learning and Adaptation, Effective Communication and Collaboration, and Customer-Centricity. In addition, the interviewee contributed to the initial framework by identifying four additional non-technical capabilities - Bridging Technical and Business Domains, Skill Development, Resource Liquification, and Change Management - as critical for supporting DSI initiatives.

In relation to Strategic Alignment and Complexity Management, the interviewee underscored the importance of aligning DT initiatives with strategic objectives, ensuring a comprehensive understanding of organizational processes and their interdependencies:

"We start with conversations about business strategy, objectives, and challenges… This top-to-bottom approach helps create the foundation for digital twins to deliver the business outcomes needed."

The ability to bridge technical and business domains was also strongly emphasized as a key enabler of DSI. According to the interviewee, aligning these domains facilitates the development of services that meet both operational and strategic needs:

"You have to have a business understanding alongside technical knowledge. Digital twin projects focus on a multidisciplinary team… bringing these two worlds together to create innovative business outcomes."

Cross-case analysis

The cross-case analysis revealed a high degree of alignment between the two cases regarding the extent to which DT capabilities overlap with those required for DSI (Figures 3 and 4). Both CompA and CompB identified several key technical capabilities as essential for DSI, including Data Management and Analytics, Cybersecurity, Interoperability, and Integration of Heterogeneous Systems. These capabilities constitute the foundational technical infrastructure necessary for the effective deployment of innovative digital services, as initially outlined in the literature. Additionally, both organizations expanded upon the initial model by emphasizing the critical role of two DT-enabled capabilities - Scenario Analysis and Predictive Analytics - in supporting DSI. Furthermore, both cases introduced the newly identified capability of Advanced Visualization, which was viewed as instrumental in enhancing user experience, enabling interactive scenario exploration, and supporting innovative service offerings. CompB uniquely stressed the importance of Edge Computing in addressing real-time data processing challenges within dynamic environments.

The cross-case analysis revealed substantial alignment between both organizations around the extent to which DT capabilities overlap with those required for Digital Service Innovation (DSI). Key technical capabilities recognized by both CompA and CompB as essential for DSI include Data Management and Analytics, Cybersecurity, Interoperability, and Integration of Heterogeneous Systems.

The analysis also revealed convergence in relation to non-technical capabilities. Both CompA and CompB emphasized the importance of Strategic Alignment and Complexity

Management, recognizing these as fundamental to the successful DSI. Similarly, capabilities such as Effective Communication and Collaboration, Organizational Learning and Adaptation, and Customer-Centricity were consistently recognized as overlapping capabilities between DT and DSI. In addition, newly identified non-technical DT capabilities such as Bridging Technical and Business Domains and Change Management were reinforced across both cases as playing a critical role in enabling DSI. This alignment underscores the need for organizations to strategically connect DT-related competencies with business and innovation objectives to support effective DSI deployment.

The analysis also demonstrated convergence in relation to non-technical capabilities. Both CompA and CompB emphasized the importance of Strategic Alignment and Complexity Management, recognizing these as fundamental to the successful integration of DT initiatives within broader organizational strategies, including DSI. Similarly, capabilities such as Effective Communication and Collaboration, Organizational Learning and Adaptation, and Customer-Centricity were consistently validated. In addition, newly identified non-technical DT capabilities such as Bridging Technical and Business Domains and Change Management were reinforced across both cases as having an important role for DSI as well. This alignment highlights the need for organizations to strategically connect DT-related competencies with business and innovation objectives in order to enable effective DSI deployment.

Nevertheless, the analysis revealed notable distinctions in the specific DT capabilities each organization associated most closely with DSI requirements. For example, CompA uniquely emphasized the integration of Domain Knowledge to tailor DT solutions to industry-specific contexts. This emphasis reflects CompA’s role as a consulting engineering firm engaged in large-scale infrastructure projects, where deep sectoral expertise is essential for ensuring that DT applications are relevant, accurate, and aligned with complex technical and regulatory environments. In contrast, CompB identified Skill Development, enabled through DT use, and Resource Liquification as distinctive non-technical capabilities supporting DSI. The focus on these capabilities reflects CompB’s need to navigate the dynamic ecosystems of their clients, often operating with partners across varied sectors and digital infrastructures.

------ Insert Figure 3 and Figure 4 here ------

4.2.2 Leveraging DT capabilities for DSI deployment

Case CompA: Consulting Engineering Firm (Digital Twin consultancy department)

CompA’s interviewee provided valuable insights into how DT capabilities are actively leveraged in practice to support the deployment of DSI. The interviewee discussed the role of Change Management, particularly strategies for overcoming organizational resistance, as a DT capability that critically enable successful DSI. In Case A, a clear connection was made between DT capabilities related to knowledge management, domain expertise, and customer-centric approaches and their relevance in supporting servitization and knowledge-based service offerings. These capabilities were recognized for enabling a shift from product-based models to service-oriented ones, with DTs seen as key tools for capturing organizational expertise and facilitating this transition:

"I'm convinced that with the help of digital twins, the servitization of products and selling services instead of hardware will enormously grow."

"You can also use them (digital twins) to catch and capture the knowledge about all those assets, especially when you fill in or when you set up digital trends based on knowledge graphs…"

The interviewee further explained how DTs enable dynamic, real-time representations of physical systems, thereby enhancing the ability of firms to provide performance-based and innovation-driven services:

"[Talking about performance-based services] …You can do that much better if you have digital twins because then you have the physical dynamic representation of part of the company."

In this context, DTs were identified as drivers of continuous improvement and optimization across operational and engineering processes, highlighting their transformative potential for traditional service delivery:

"Most of the time, you improve operational or engineering processes and use digital twins to optimize, improve, and do smarter optimization of operational processes … Can we call that innovation? Maybe we can."

These findings highlight the active role of DT capabilities in facilitating not only the initial deployment but also the ongoing evolution of innovative digital services.

Case CompB: : Digital Twin as a Service (DTaaS) provider

CompB's interviewee and secondary data provided insights into how DT capabilities are actively leveraged to support the deployment of DSI. Effective Change Management was highlighted as a crucial capability, particularly in facilitating successful DT adoption and sustained innovation. The interviewee advocated for iterative implementation strategies to enhance organizational acceptance and alignment with evolving service goals:

"You don't overwhelm the organization with automation; you do it in small pieces to increase adoption… This approach helps align digital twin capabilities with evolving service goals."

Skill Development also emerged as a key enabler of DSI, emphasizing the critical role of DTs in supporting training and developing operational and business understanding of assets. This capability was seen as essential for equipping teams with the expertise needed to effectively apply DTs in innovative digital service offerings:

"This takes a lot of time from a business to train people and provide the right understanding… but these skills are essential for creating solutions that connect data, processes, and business insights."

Resource Liquification was uniquely emphasized, highlighting the potential of DTs to enable dynamic utilization of internal and external resources. This capability supports innovative forms of collaboration across organizational ecosystems:

"When you negotiate governance methods to acquire external data, it provides a huge business advantage... Digital twins help simulate scenarios and understand impacts, enabling better collaboration and innovative solutions."

In addition to the interview findings, secondary sources reinforced CompB's perspective of DTs as orchestrators that support enhanced decision making, resource optimization, and the development of innovative value propositions. The strategic vision of CompB positions DTs as integrative frameworks that bridge technical and business domains, enabling service innovation, operational excellence, and the creation of new service models, such as data monetization:

"We are helping [customers] leverage their own data to create new revenue streams... helping them package and sell their existing technology ... now I see new needs come up with customers such as data monetization... this is a new service that never existed before."

In conclusion, CompB regards DT capabilities not merely as technical tools, but as strategic enablers that bring together diverse competencies to support DSI. In this view, DTs are instrumental in generating new value through service innovation, bridging internal silos, and fostering agile responsiveness within evolving digital ecosystems. As the interviewee summarized:

"Digital twins allow different types of services to play a part at the same time... they bring these two worlds [physical and digital] together and enable organizations to speak the same language."

This perspective also reflects the integration of knowledge across organizational boundaries, whereby companies use digital twins as shared models to integrate data and simulate common and interconnected activities.

Cross-case analysis

Both organizations demonstrated how DT capabilities are leveraged to facilitate and accelerate the deployment of DSI, though they emphasized distinct strategic orientations and responded to different market-driven considerations.

CompA primarily leveraged DT capabilities to support its clients' transition toward servitization, transforming traditional product-based offerings into innovative, service-oriented business models. DT-enabled capabilities such as Scenario Analysis and Predictive Analytics were specifically recognized as means to test, optimize, and improve new services in virtual environments, thereby reducing costs and associated risks. In addition, CompA highlighted the use of DTs for capturing and sharing critical organizational knowledge, as well as supporting educational and training applications aimed at workforce upskilling and continuous adaptation, which are key enablers of effective DSI.

In contrast, CompB emphasized leveraging DT capabilities around value creation and orchestration. The company identified the capability of Resource Liquification, which allows enhanced mobility and accessibility of data and services across platforms, as pivotal in enabling highly responsive and flexible service innovation. CompB also illustrated how capabilities such as Advanced Visualization and Edge Computing are applied to create tailored digital services that support real-time decision making and strengthen customer engagement. Notably, CompB's strategic use of DTs to facilitate new services for their clients, such as data monetization and productization, exemplifies how DT capabilities can support the development of novel business models and revenue streams.

Overall, this cross-case analysis illustrates that, while both cases explain how DT capabilities support DSI, their distinct industry contexts shape the specific manner in which these capabilities are employed by their clients to facilitate DSI.

5.- Contributions and Implications

5.1 Theoretical contributions

This study advances the literature on service innovation and DT by illuminating how DT capabilities can serve as strategic enablers of DSI. Existing research in DT has predominantly focused on the technical aspects of DTs (e.g., Kritzinger et al., 2018; Fuller et al., 2020) but has rarely integrated the service innovation perspective to explore their broader impact on DSI. By contrast, this study systematically maps DT capabilities, both those required to develop and exploit DTs and those achieved through DT use, against essential capabilities for DSI (Figures 3 and 4), demonstrating concrete overlaps and synergies between these domains.

First, the study identifies a set of novel DT capabilities emerging from the empirical analysis that had not been previously recognized. These include the technical capabilities of Knowledge Graphs, Ontology Management, Edge Computing, and Advanced Visualization, as well as the non-technical capabilities of Change Management, Bridging Technical and Business Domains, Domain Knowledge, Skill Development, and Resource Liquification. These newly identified technical DT capabilities enable more sophisticated DT functionalities, such as real-time data processing and immersive user experiences, while non-technical capabilities extend beyond the traditional engineering focus of DT by enhancing organizational functions such as knowledge sharing, strategic alignment, and agile resource deployment. These functions influence service innovation by fostering greater agility, co-creation, and user-centric design (Lusch & Nambisan, 2015; Vargo et al., 2024). Furthermore, these results extend existing discussions on the transformative potential of DTs (Fukawa & Rindfleisch, 2024; Galera-Zarco, 2024), underscoring that their value is not limited to operational optimization alone but also encompasses broader innovation and service ecosystems. Additionally, these findings emphasize the importance of organizational and strategic capabilities in digital transformation and service innovation contexts, and expand upon previous studies in this area (Kohtamäki et al., 2020; Rabetino et al., 2024).

Second, the integration of DT capabilities with DSI frameworks constitutes an important theoretical contribution. Findings demonstrate that many DT capabilities, both technical (Data Management and Analytics, Cybersecurity, Interoperability, Integration of Heterogeneous Systems, Scenario Analysis, Predictive Analysis, Edge Computing, and Advanced Visualization) and non-technical (Strategic Alignment and Complexity Management, Domain Knowledge, Change Management, Organizational Learning and Adaptation, Bridging Technical and Business Domains, Effective Communication, Customer-Centricity, Skill Development, and Resource Liquification) overlap significantly with those required for DSI. This convergence supports a synergistic pathway through which DTs act as catalysts for DSI, aligning technical infrastructure with organizational and strategic imperatives. In this vein, these results underscore the importance of aligning technological initiatives with business objectives in a continuous process of learning and alignment (Coreynen et al., 2024), driving a culture receptive to innovation, resonating with previous studies (e.g., Barrett et al., 2015; Opazo-Basáez et al., 2022 - 3).

Third, comparative insights from CompA and CompB illuminate how organizations leverage DT capabilities to drive DSI in distinct ways. For CompA, DT capabilities (e.g., Scenario Analysis, Predictive Analytics, and Domain Knowledge) serve as conduits for servitization and deeper asset knowledge, aligning with literature emphasizing domain-specific expertise in advanced service offerings (Story et al., 2017). Conversely, CompB recognizes DT capabilities such as Edge Computing, Advanced Visualization, Skill Development, and Resource Liquification as critical for value co-creation (Vargo et al., 2024), enabling agile, data-driven collaboration with clients and partners across diverse ecosystems (Bustinza et al., 2024). Collectively, these findings enhance theoretical understanding of how DTs can function as strategic platforms for DSI, enabling servitization pathways, bridging organizational silos, and facilitating new service models.

Finally, by incorporating the Digital Servitization Pathway (DSP) perspective outlined by Vendrell-Herrero et al. (2024), this study further emphasizes that DT-enabled digital transformation acts as a precursor to advanced service innovation. Accordingly, the integrative framework presented in Figures 3 and 4 provides a structured foundation for understanding how DT capabilities facilitate DSI by supporting both the technological and organizational transformations necessary for successful digital servitization. Taken together, these contributions enrich theoretical discourse on digital transformation and service innovation, demonstrating that DT capabilities can evolve from isolated technical tools into strategic enablers of innovation.

5.2 Managerial contributions

This research offers several practical implications for organizations involved in developing DTs as well as those seeking to deploy DSI. Primarily, the identification and validation of both established and newly emerged DT capabilities across technical and non-technical dimensions offer a comprehensive framework that can guide strategic investments in DT initiatives.

Organizations should adopt a dual-focused approach when investing in DT capabilities. On the technical side, developing robust DT infrastructures able to support advanced digital services. Concurrently, building organizational readiness through effective change management, multidisciplinary collaboration, and continuous skill development is equally important. Aligning technical expertise with business strategy is essential to ensure that DT initiatives are embedded within broader organizational objectives and contribute effectively to service innovation. To this end, organizations should develop multidisciplinary teams that combine technological proficiency with business insight, enabling DT projects to generate concrete value and advance strategic priorities. Such integration supports the translation of technological potential into service innovations that respond to customer needs and reinforce competitive positioning.

Moreover, the integration and overlap of DT capabilities with DSI requirements underscore the existence of strategic pathways for achieving DSI through DTs. First, DTs can facilitate digital servitization by enhancing asset knowledge and enabling virtual scenario simulations and predictive maintenance, thereby reducing associated risks and costs, as evidenced in the findings from CompA. Second, DTs can promote value co-creation through capabilities such as resource liquification, adaptive collaboration, and real-time decision support, as demonstrated by CompB. This dual-pathway perspective provides organizations with a structured approach to transitioning from traditional product-centric models toward innovative, service-oriented solutions.

Lastly, prioritizing data governance and cybersecurity is imperative. Given the substantial volumes of sensitive data managed by DTs, establishing robust data governance frameworks and implementing stringent cybersecurity measures not only mitigate potential risks but also enhance stakeholder trust, thereby supporting sustainable DSI deployment. Proactively investing in these technical and organizational capabilities positions organizations to leverage digital assets effectively, respond adaptively to evolving market conditions, and secure sustained competitive advantage within the digital economy.

6. Limitations

While this study offers valuable insights into the role of DT capabilities in enabling DSI, several limitations must be acknowledged. First, the empirical analysis is confined to two specific organizational contexts: a consulting engineering firm and a Digital Twin as a Service (DTaaS) provider. This sectoral focus may limit the broader applicability of the findings, particularly to organizations operating in industries with distinct technological infrastructures, business models, or regulatory environments. However, it is worth noting that both companies work across a range of client sectors, and the insights presented reflect a cross-industry perspective derived from their cumulative experience.

Additionally, although the multiple-case design supports in-depth analysis and comparison, the limited number of cases restricts the extent to which conclusions can be generalized. This is particularly relevant in relation to the empirical validation of capabilities, the identification of emergent ones, and the proposed pathways linking DT use to DSI. Broader studies including a more diverse range of organizations may reveal additional dynamics not captured here.

Second, data collection relied on a single informant per case. While both individuals held senior roles with extensive visibility over DT-related initiatives and strategic developments, their views inevitably represent individual interpretations. This approach may constrain the depth and diversity of perspectives captured, particularly concerning internal processes and organizational culture.

Finally, the qualitative nature of the study, although well-suited to uncovering complex interrelationships and context-specific mechanisms, does not allow for the quantification of causal effects between DT capabilities and DSI outcomes. The research offers detailed conceptual insights but does not empirically assess the magnitude or statistical significance of the identified capability linkages.

7. Conclusions and future research lines

This study has examined the role of DT capabilities in driving DSI within organizations. The findings reveal a significant overlap between DT capabilities and those required for DSI, thus providing empirical support for the study's first hypothesis. In addressing the alignment between DT capabilities and the needs for effective DSI deployment, the analysis demonstrates robust convergence across both capability sets. Technical and non-technical dimensions essential for DT development and exploitation, as well as capabilities enabled through DT use, substantially correspond to those necessary for deploying innovative digital services (Figures 3 and 4). This alignment indicates that investments in DT capabilities do not merely enhance digital infrastructures but also initiate a transition from conventional digital transformation toward more innovative, service-oriented business models. Consequently, DTs provide a natural bedrock for achieving DSI.

With respect to the second hypothesis - that organizations utilizing DTs are better positioned for successful DSI - the evidence from both cases confirms that leveraging DT-enabled capabilities, such as scenario analysis, predictive analytics, and resource liquification, significantly enhances service design. Specifically, DTs reinforce strategic alignment by demanding coherence between DT initiatives and overarching business objectives, thus enabling effective complexity management. Additionally, through sophisticated data management, advanced analytical capabilities, and a customer-centric approach, DTs facilitate the delivery of personalized services. DT capabilities not only support the initial implementation of innovative digital services but also promote ongoing organizational learning and agile adaptation, thereby strengthening competitive positioning in dynamic digital ecosystems

Furthermore, in exploring how DT implementation and usage drive organizational readiness for DSI deployment, this study identifies critical enabling capabilities facilitated by DTs. On the technical side, DTs bolster digital agility by encouraging the adoption of advanced technological solutions and the integration of complex systems, which enhances data utilization, advanced visualization, and real-time decision making. From a non-technical perspective, DTs enable strategic alignment and effective complexity management, ensuring close integration between digital initiatives and business goals. Importantly, this research highlights two distinct pathways through which DT capabilities drive innovation in digital services: first, DTs facilitate digital servitization by enhancing knowledge of assets and client needs within their operational context.; second, DT capabilities enhance collaboration, interoperability, and resource liquification, resulting in superior and more effective value co-creation processes. This dual-pathway perspective underscores the multifaceted potential of Digital Twins as strategic enablers of DSI.

Future research could broaden the understanding of Digital Twin (DT) capabilities and their role in Digital Service Innovation (DSI) by examining a larger and more varied sample of organizations from different industries. Expanding the empirical scope would enhance the generalizability of the findings and offer deeper insights into industry-specific dynamics influencing the relationship between DT adoption and DSI outcomes. Additionally, incorporating multiple informants representing diverse organizational roles could mitigate potential biases associated with single-informant data and provide richer, more nuanced perspectives on internal processes and capabilities. Quantitative studies would also contribute significantly by empirically validating the extent to which specific DT capabilities directly influence DSI performance. Such studies could quantify relationships identified qualitatively in this research, thereby strengthening the robustness of conclusions drawn about capability impacts. Lastly, investigating manufacturing firms that are pursuing servitization strategies and also deploying DTs would be particularly valuable, as it could further illuminate the role of DTs as value orchestrators, enabling novel business models and fostering ecosystem-based collaboration.

8. References

Agrawal, A., Fischer, M. and Singh, V. (2022), “Digital twin: From concept to practice”, *Journal of Management in Engineering*, Vol. 38 No. 3, p. 06022001.

Akter, S., Hossain, M.A., Sajib, S., Sultana, S., Rahman, M., Vrontis, D. and McCarthy, G. (2023), “A framework for AI-powered service innovation capability: Review and agenda for future research”, *Technovation*, Vol. 125, p. 102768.

Awad, J.A.R. and Martín-Rojas, R. (2024), “Digital transformation influence on organisational resilience through organisational learning and innovation”, *Journal of Innovation and Entrepreneurship*, Vol. 13, p. 69.

Baines, T. and Lightfoot, H.W. (2013), “Servitization of the manufacturing firm”, *International Journal of Operations & Production Management*, Vol. 34 No. 1, pp. 2–35.

Baines, T., Ziaee Bigdeli, A. and Kapoor, K. (2024), “Servitization, advanced services and outcomes”, in Servitization Strategy: Delivering Customer-Centric Outcomes Through Business Model Innovation, Springer Nature Switzerland, Cham, pp. 17-48.

Barrett, M., Davidson, E., Prabhu, J. and Vargo, S.L. (2015), “Service innovation in the digital age: key contributions and future directions”, *MIS Quarterly*, Vol. 39 No. 1, pp. 135-154.

Barricelli, B.R., Casiraghi, E. and Fogli, D. (2019), “A survey on digital twin: definitions, characteristics, applications, and design implications”, *IEEE Access*, Vol. 7, pp. 167653-167671.

Beloglazov, I.I., Petrov, P.A. and Bazhin, V.Y. (2020), “The concept of digital twins for tech operator training simulator design for mining and processing industry”, *Chemical Industries*, Vol. 18, p. 19.

Bharadwaj, A., El Sawy, O.A., Pavlou, P.A. and Venkatraman, N.V. (2013), “Digital business strategy: toward a next generation of insights”, *MIS Quarterly*, Vol. 37 No. 2, pp. 471-482.

Bolton, A., Butler, L., Dabson, I., Enzer, M., Evans, M., Feeney, T., Housley, E., Kilpatrick, A., Luck, H., Pawsey, N., Schooling, J., Sharp, M., Smith, H., Tennison, J. and Whyte, J. (2018), *The Gemini Principles*, Centre for Digital Built Britain, available at: https://www.cdbb.cam.ac.uk [Accessed 18 Nov. 2024].

Broo, D.G., Bravo-Haro, M. and Schooling, J. (2022), “Design and implementation of a smart infrastructure digital twin”, *Automation in Construction*, Vol. 136, p. 104171.

Burton, J., Story, V.M., Zolkiewski, J. and Nisha, N. (2024),** “Digital service innovation challenges faced during servitization: a multi-level perspective”, *Journal of Service Management*, Vol. 35 No. 2, pp. 202-226.

Bustinza, O.F., Opazo-Basaez, M. and Tarba, S. (2022), “Exploring the interplay between Smart Manufacturing and KIBS firms in configuring product-service innovation performance”, *Technovation*, Vol. 118, p. 102258.

Bustinza, O.F., Molina, L.M., Vendrell-Herrero, F. and Opazo-Basaez, M. (2024), “AI-enabled smart manufacturing boosts ecosystem value capture: The importance of servitization pathways within digital-intensive industries”, *International Journal of Production Economics*, Vol. 277, p. 109411.

Chin, H., Marasini, D.P. and Lee, D. (2023), “Digital transformation trends in service industries”, *Service Business*, Vol. 17 No. 1, pp. 11-36.

Coreynen, W., Matthyssens, P., Struyf, B. and Vanhaverbeke, W. (2024), “Spiraling between learning and alignment toward digital service innovation”, *Journal of Service Management*, Vol. 35 No. 2.

Corbin, J. and Strauss, A. (2015), *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory* (4th ed.), SAGE Publications, Newbury Park, CA.

Crespi, N., Drobot, A.T. and Minerva, R. (2023), “The digital twin in action and directions for the future”, in The Digital Twin, Springer, Cham.

Denzin, N.K. (1978), *The Research Act: A Theoretical Introduction to Sociological Methods* (2nd ed.), McGraw-Hill.

Edvardsson, B., Kleinaltenkamp, M., Tronvoll, B., McHugh, P. and Windahl, C. (2014), “Institutional logics matter when coordinating resource integration”, *Marketing Theory*, Vol. 14 No. 3, pp. 291-309.

Eisenhardt, K.M. (1989), “Building theories from case study research”, *Academy of Management Review*, Vol. 14 No. 4, pp. 532–550.

Ferko, E., Bucaioni, A. and Behnam, M. (2022), “Architecting digital twins”, *IEEE Access*, Vol. 10, pp. 50335-50350.

Finlay, L. (2002), “Negotiating the swamp: the opportunity and challenge of reflexivity in research practice”, *Qualitative Research*, Vol. 2 No. 2, pp. 209–230.

Fukawa, N. and Rindfleisch, A. (2023), “Enhancing innovation via the digital twin”, *Journal of Product Innovation Management*, Vol. 40 No. 4, pp. 391-406.

Fuller, A., Fan, Z., Day, C. and Barlow, C. (2020), “Digital twin: enabling technologies, challenges and open research”, *IEEE Access*, Vol. 8, pp. 108952-108971.

Galera-Zarco, C. (2022), “Unleashing the potential of digital twin in offering green services”, in *Competitive Advantage in the Digital Economy (CADE 2022)*, Venice, Italy, pp. 158-161.

Galera-Zarco, C. (2024), “Digital twin and services: a theoretical development framework”, *2024 IEEE Technology and Engineering Management Society (TEMSCON LATAM)*, Panama, pp. 1-6.

Galera-Zarco, C. and Papadonikolaki, E. (2023), “Digital twin-based services: a taxonomy”, in *International Conference on AI and the Digital Economy (CADE 2023)*, pp. 98-102.

Greenhalgh, T., Robert, G., Macfarlane, F., Bate, P. and Kyriakidou, O. (2004), “Diffusion of innovations in service organizations: systematic review and recommendations”, *The Milbank Quarterly*, Vol. 82 No. 4, pp. 581-629.

Grieves, M. (2014), “Digital twin: manufacturing excellence through virtual factory replication”, White Paper, pp. 1-7.

Grieves, M. and Vickers, J. (2016), “Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems”, in Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches, Springer, Cham, pp. 85–113.

Gummesson, E. (2006), “Qualitative research in management: addressing the complexity of the business reality”, *Management Decision*, Vol. 44 No. 2, pp. 167-179.

Heller, J., Chylinski, M., de Ruyter, K., Keeling, D.I., Hilken, T. and Mahr, D. (2021), “Tangible service automation: decomposing the technology-enabled engagement process (TEEP) for augmented reality”, *Journal of Service Research*, Vol. 24 No. 1, pp. 84–103.

Jamwal, A., Agrawal, R. and Sharma, M. (2022), “Deep learning for manufacturing sustainability: models, applications in Industry 4.0 and implications”, *International Journal of Information Management Data Insights*, Vol. 2 No. 2, p. 100107.

Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. (2020), “Characterising the digital twin: a systematic literature review”, *CIRP Journal of Manufacturing Science and Technology*, Vol. 29, pp. 36-52.

Kamalaldin, A., Linde, L., Sjödin, D. and Parida, V. (2020), “Transforming provider–customer relationships in digital servitization: a relational view on digitalization”, *Industrial Marketing Management*, Vol. 89, pp. 306-325.

Kang, H.S., Lee, J.Y., Choi, S., Kim, H., Park, J.H., Son, J.Y., Kim, H.J. and Noh, S.D. (2016), “Smart manufacturing: past research, present findings, and future directions”, *International Journal of Precision Engineering and Manufacturing-Green Technology*, Vol. 3 No. 1, pp. 111-128.

Kohtamäki, M., Parida, V., Oghazi, P., Gebauer, H. and Baines, T. (2020), “Digital servitization business models in ecosystems: a theory of the firm”, *Journal of Business Research*, Vol. 104, pp. 380-392.

Kohtamäki, M., Parida, V., Rabetino, R., Sjödin, D. and Henneberg, S. (2022), “Framing the digital servitization path towards autonomous solutions”, in *Achieving Net-Zero through Servitization: Proceedings of the Spring Servitization Conference*, Aston Business School, pp. 1-6.

Kraus, S., Palmer, C., Kailer, N., Kallinger, F.L. and Spitzer, J. (2021), “Digital transformation: an overview of the current state of the art of research”, *SAGE Open*, Vol. 11 No. 3, p. 21582440211047576.

Kreye, M.E. (2022), “When servitized manufacturers globalise: becoming a provider of global services”, *International Journal of Operations and Production Management*, Vol. 42 No. 10, pp. 1521-1543.

Kritzinger, W., Karner, M., Traar, G., Henjes, J. and Sihn, W. (2018), “Digital twin in manufacturing: a categorical literature review and classification”, *IFAC-PapersOnLine*, Vol. 51 No. 11, pp. 1016-1022.

Kumar, R., Abrougui, K., Verma, R., Luna, J., Khattab, A. and Dahir, H. (2023), “Digital twins for decision support system for clinicians and hospital to reduce error rate”, in Digital Twin for Healthcare, Elsevier, Amsterdam, pp. 241–261.

Lehner, D., Pfeiffer, J., Tinsel, E.F., Strljic, M.M., Sint, S., Vierhauser, M., Wortmann, A. and Wimmer, M. (2021), “Digital twin platforms: requirements, capabilities, and future prospects”, *IEEE Software*, Vol. 39 No. 2, pp. 53-61.

Lehrer, C., Wieneke, A., Vom Brocke, J., Jung, R. and Seidel, S. (2018), “How big data analytics enables service innovation: materiality, affordance, and the individualization of service”, *Journal of Management Information Systems*, Vol. 35 No. 2, pp. 424-460.

Lu, Q., Parlikad, A.K., Woodall, P., Don Ranasinghe, G., Xie, X., Liang, Z., Konstantinou, E., Heaton, J. and Schooling, J. (2020), “Developing a digital twin at building and city levels: case study of West Cambridge campus”, *Journal of Management in Engineering*, Vol. 36 No. 3, pp. 1–19.

Lusch, R.F. and Nambisan, S. (2015), “Service innovation”, *MIS Quarterly*, Vol. 39 No. 1, pp. 155-176.

Lusch, R.F. and Vargo, S.L. (2014), *Service-Dominant Logic: Premises, Perspectives, Possibilities*, Cambridge University Press, New York, NY.

Martinez, V. and Huss, N.F. (2022), “Digital twins: thought leadership in the satellite industry”, *University of Cambridge*.

Meierhofer, J. and West, S. (2019), “Service value creation using a digital twin”, in *Naples Forum on Service, Service Dominant Logic, Network & Systems Theory and Service Science: Integrating Three Perspectives for a New Service Agenda*, Ischia, Italy, pp. 4-7.

Meierhofer, J., West, S., Rapaccini, M. and Barbieri, C. (2020), “The digital twin as a service enabler: from the service ecosystem to the simulation model”, in Exploring Service Science: 10th International Conference, IESS 2020, Springer International Publishing, pp. 347-359.

Minerva, R., Lee, G.M. and Crespi, N. (2020), “Digital twin in the IoT context: a survey on technical features, scenarios, and architectural models”, *Proceedings of the IEEE*, Vol. 108 No. 10, pp. 1785-1824.

Moyne, J., Qamsane, Y., Balta, E.C., Kovalenko, I., Faris, J., Barton, K. and Tilbury, D.M. (2020), “A requirements driven digital twin framework: specification and opportunities”, *IEEE Access*, Vol. 8, pp. 107781-107801.

Myers, M.D. and Newman, M. (2007), “The qualitative interview in IS research: Examining the craft”, *Information and Organization*, Vol. 17 No. 1, pp. 2-26.

Negri, E., Fumagalli, L. and Macchi, M. (2017), “A review of the roles of digital twin in CPS-based production systems”, *Procedia Manufacturing*, Vol. 11, pp. 939-948.

Nicoletti, L. and Padovano, A. (2019), “Ubiquitous knowledge empowers the smart factory: the impacts of a service-oriented digital twin on enterprises' performance”, *Annual Reviews in Control*, Vol. 47, pp. 221-236.

Nylén, D. and Holmström, J. (2015), “Digital innovation strategy: a framework for diagnosing and improving digital product and service innovation”, *Business Horizons*, Vol. 58 No. 1, pp. 57-67.

Opazo-Basáez, M., Bustinza, O.F. and Molina, L.M. (2024a), “The effect of industrial solution services (ISS) on innovation performance: The moderating role of sustainable development goals (SDGs)”, *Journal of Cleaner Production*, Vol. 455, p. 142265.

Opazo-Basáez, M., Vendrell-Herrero, F., Bustinza, O.F. and Raddats, C. (2024b), “Guest editorial: digital service innovation: ontology, context and theory”, *Journal of Service Management*, Vol. 35 No. 2, pp. 129-140.

Opazo-Basáez, M., Monroy-Osorio, J.C. and Marić, J. (2024c), “Evaluating the effect of green technological innovations on organizational and environmental performance: A treble innovation approach”, *Technovation*, Vol. 129, p. 102885.

Opazo-Basáez, M., Vendrell-Herrero, F. and Bustinza, O.F. (2022), “Digital service innovation: a paradigm shift in technological innovation”, *Journal of Service Management*, Vol. 33 No. 1, pp. 97-120.

Opazo-Basáez, M., Vendrell-Herrero, F., Bustinza, O.F., Vaillant, Y. and Marić, J. (2023), “Is digital transformation equally attractive to all manufacturers? Contextualizing the operational and customer benefits of smart manufacturing”, *International Journal of Physical Distribution & Logistics Management*, Vol. 53 No. 4, pp. 489-511.

Patton, M.Q. (2015), *Qualitative Research & Evaluation Methods* (4th ed.), SAGE Publications, Thousand Oaks, CA.

Plummer, D., Kearney, S., Monagle, A., Collins, H., Perry, V., Moulds, A., Mroczka, M., Robertson, J., Smith, T., Trewavas, S. and Lewis, C. (2021), “Skills and competency framework—supporting the development and adoption of the information management framework (IMF) and the national digital twin”, *Centre for Digital Built Britain*.

Porter, M.E. and Heppelmann, J.E. (2014), “How smart, connected products are transforming competition”, *Harvard Business Review*, Vol. 92 No. 11, pp. 64–88.

Rabah, S., Zacharewicz, G. and Chapurlat, V. (2022), “Digital twin for services (DT4S): conceptual strategy”, *IFAC-PapersOnLine*, Vol. 55 No. 10, pp. 3256-3261.

Rabetino, R., Kohtamäki, M. and Huikkola, T. (2024), “Digital service innovation (DSI): a multidisciplinary (re) view of its origins and progress using bibliometric and text mining methods”, *Journal of Service Management*, Vol. 35 No. 2, pp. 176-201.

Raddats, C., Naik, P. and Bigdeli, A.Z. (2022), “Creating value in servitization through digital service innovations”, *Industrial Marketing Management*, Vol. 104, pp. 1-13.

Raj, A., Dwivedi, G., Sharma, A., de Sousa Jabbour, A.B.L. and Rajak, S. (2020), “Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: an inter-country comparative perspective”, *International Journal of Production Economics*, Vol. 224, p. 107546.

Rosen, R., von Wichert, G., Lo, G. and Bettenhausen, K.D. (2015), “About the importance of autonomy and digital twins for the future of manufacturing”, *IFAC-PapersOnLine*, Vol. 48 No. 3, pp. 567-572.

Rothenberger, M. and Srite, M. (2009), “An investigation of customization in ERP system implementations”, *IEEE Transactions on Engineering Management*, Vol. 56 No. 4, pp. 663–676.

Schleich, B., Anwer, N., Mathieu, L. and Wartzack, S. (2017), “Shaping the digital twin for design and production engineering”, *CIRP Annals*, Vol. 66 No. 1, pp. 141-144.

Serrano-Ruiz, J.C., Ferreira, J., Jardim-Goncalves, R., et al. (2024), “Relational network of innovation ecosystems generated by digital innovation hubs: a conceptual framework for the interaction processes of DIHs from the perspective of collaboration within and between their relationship levels”, *Journal of Intelligent Manufacturing*.

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A. and Calinescu, A. (2022), "Digital twins: state of the art theory and practice, challenges, and open research questions", *Journal of Industrial Information Integration*, Vol. 30, p. 100383.

Sjödin, D., Parida, V., Kohtamäki, M. and Wincent, J. (2020), "An agile co-creation process for digital servitization: a micro-service innovation approach", *Journal of Business Research*, Vol. 112, pp. 478-491.

Soto Setzke, D., Riasanow, T., Böhm, M. et al. (2023), "Pathways to digital service innovation: the role of digital transformation strategies in established organizations", *Information Systems Frontiers*, Vol. 25, pp. 1017–1037.

Story, V.M., Raddats, C., Burton, J., Zolkiewski, J. and Baines, T. (2017), "Capabilities for advanced services: a multi-actor perspective", *Industrial Marketing Management*, Vol. 60, pp. 54-68.

Tao, F., and Qi, Q. (2019), "Make more digital twins", *Nature*, Vol. 573 No. 7775, pp. 490-491.

Tao, F., Zhang, H., Liu, A. and Nee, A.Y.C. (2018a), "Digital twin in industry: state-of-the-art", *IEEE Transactions on Industrial Informatics*, Vol. 15 No. 4, pp. 2405-2415.

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H. and Sui, F. (2018b), "Digital twin-driven product design, manufacturing and service with big data", *The International Journal of Advanced Manufacturing Technology*, Vol. 94, pp. 3563-3576.

Trauer, R., Bravo-Haro, M. and Schooling, J. (2022), "A digital twin trust framework for industrial application", *Journal of Industrial Information Integration*, Vol. 26, p. 100257.

Tripathi, N., Hietala, H., Xu, Y. and Liyanage, R. (2024), "Stakeholders collaborations, challenges and emerging concepts in digital twin ecosystems", *Information and Software Technology*, p. 107424.

Uhlemann, T.H.J., Lehmann, C. and Steinhilper, R. (2017), "The digital twin: realizing the cyber-physical production system for Industry 4.0", *Procedia CIRP*, Vol. 61, pp. 335-340.

Vargo, S.L. and Lusch, R.F. (2004), "Evolving to a new dominant logic for marketing", *Journal of Marketing*, Vol. 68 No. 1, pp. 1-17.

Vargo, S.L., Fehrer, J.A., Wieland, H. and Nariswari, A. (2024), "The nature and fundamental elements of digital service innovation", *Journal of Service Management*, Vol. 35 No. 2.

Vargo, S.L., Maglio, P.P. and Akaka, M.A. (2008), "On value and value co-creation: a service systems and service logic perspective", *European Management Journal*, Vol. 26 No. 3, pp. 145-152.

Vendrell-Herrero, F., Bustinza, O.F. and Parry, G. (2021), "Digital business model innovation in SMEs: leveraging dynamic capabilities and tangible assets through digital technologies", *Journal of Business Research*, Vol. 123, pp. 289-301.

Vendrell-Herrero, F., Bustinza, O.F., Parry, G. and Georgantzis, N. (2017), "Servitization, digitization and supply chain interdependency", *Industrial Marketing Management*, Vol. 60, pp. 69-81.

Vendrell-Herrero, F., Para-González, L., Mascaraque-Ramírez, C. and Freixanet, J. (2024), “The order of the factors matters: how digital transformation and servitization integrate more efficiently”, *International Journal of Production Economics*, Vol. 271, p. 109228.

Vial, G. and Grange, C. (2024), “Conceptualizing digital service: coconstitutive essence and value cocreation dynamics”, *Journal of Service Management*, Vol. 35 No. 3, pp. 408-437.

Wang, Y., Tian, Q., Li, X. and Xiao, X. (2022), “Different roles, different strokes: how to leverage two types of digital platform capabilities to fuel service innovation”, *Journal of Business Research*, Vol. 144, pp. 1121-1128.

West, S., Stoll, O., Meierhofer, J. and Züst, S. (2021), “Digital twin providing new opportunities for value co-creation through supporting decision-making,” *Applied Sciences*, Vol. 11 No. 9, p. 3750.

Xiao, X., Tian, Q. and Mao, H. (2020), “How the interaction of big data analytics capabilities and digital platform capabilities affects service innovation: A dynamic capabilities view”, *IEEE Access*, Vol. 8, pp. 18778-18796.

The role of Digital Twin capabilities in Digital Service Innovation deployment: a multiple case study approach

Purpose - As industries increasingly integrate Digital Twins (DTs) into their operations and service offerings, it becomes crucial to understand the specific technological and organizational capabilities associated with DTs and their role in effective Digital Service Innovation (DSI). This paper contributes to the literature on DSI-enabling factors by examining the role of DT capabilities in driving DSI within organizations, highlighting the areas of interconnection.

Design/methodology/approach - This study adopts a multiple case study approach, examining two organizations with different engagements with DT: a consultancy engineering firm offering DT solutions, and a technology company specializing in DT services for different sectors. These diverse perspectives aim to provide a comprehensive understanding of role of DT in DSI in different organizational contexts.

Findings - The study identifies distinct capabilities needed to develop and exploit DT, as well as new capabilities acquired by organizations through DT deployment. It reveals that several technical and non-technical DT capabilities overlap with established DSI capabilities, illustrating a logical pathway from DT capabilities to DSI. These insights are synthesized into a theoretical framework which illustrate how DT capabilities support and enable DSI.

Practical implications - This research delineates critical DT capabilities and highlights which of these contribute to the effective deployment of DSI. These findings provide actionable strategies for organizations aiming to develop and strengthen DT capabilities to maximize their potential impact on DSI.

Originality/value - This paper expands beyond the prevalent technical and engineering emphasis in DT literature by adopting a holistic capabilities-based approach. It provides an in-depth examination of how DT capabilities can drive DSI, delivering valuable insights for both academia and industry practice.

Keywords: Digital Twin, Digital Service Innovation, Capabilities, Product-Service Systems, Digital Services

Paper type: Research paper

1. Introduction

The transformative power of new digital technologies is leading to the development of new service paradigms which fundamentally change how companies interact with their customers and how they orchestrate their value chains (Kamalaldin et al., 2020). In particular, the proliferation of data-driven digital service offerings, underpinned by contextual, environmental, and consumer behavior insights, has generated innovation across industries, allowing organizations to dynamically reconfigure and align their service offerings with evolving customer demands and market conditions (Heller et al., 2021; Opazo-Basáez et al., 2024a). In this context, Digital Service Innovation (DSI) has emerged as a driver of competitive advantage, significantly influenced by the broader phenomenon of digital transformation (Barrett et al., 2015). Rooted in the trends of servitization and digitalization, DSI represents a fundamental shift whereby digital technologies transition from supplementary roles to central components of service innovation (Opazo-Basáez et al., 2024b).

The growth of digital service innovations reshapes competitive dynamics, marking the shift from traditional product-oriented strategies to integrated digital solutions (Vendrell-Herrero et al., 2017). Nonetheless, deploying DSI remains challenging due to the required complex interactions between organizational, strategic, and technological dimensions (Barrett et al., 2015). Organizations often encounter barriers such as technological incompatibilities, limited customer-oriented capabilities, and deficiencies within innovation processes (Chin et al., 2023; Greenhalgh et al., 2004). In fact, these challenges often arise because of conflicting demands on organizational resources and capabilities (Vial and Grange, 2024). Addressing these challenges requires a deeper understanding of how technology adoption influences service innovation capabilities. Burton et al. (2024) argue that technology integration must extend beyond technical problem-solving to strategically enhance innovation capabilities and drive ecosystem interactions. This underscores the need to align digital technologies strategically with service innovation goals.

DSI emphasizes the interconnectedness of digital technologies and service offerings, requiring continuous adaptation of services and underlying technological infrastructures to enhance customer experiences and operational performance (Opazo-Basáez et al., 2022). It leads to an increased utilization of transformative technologies such as Digital Twins (DTs), Internet of Things (IoT), Big Data, Artificial Intelligence (AI), and Cloud Computing for service offerings (Jamwal et al., 2022; Opazo-Basáez et al., 2022). Among these technologies, DTs uniquely facilitate real-time digital representations of physical systems enhancing predictive capabilities, process optimization, and enabling the provision of highly tailored services (Galera-Zarco, 2024). Indeed, DT is increasingly recognized as a key enabler of innovation, effectively bridging the physical and digital domains (Fukawa & Rindfleisch, 2024; Galera-Zarco, 2024). While initially employed primarily for operational optimization and cost reduction, DTs are now appreciated for their capacity to enhance service offerings and generate new value propositions across sectors such as manufacturing, healthcare, the built environment, and energy (Galera-Zarco & Papadonikolaki, 2023; Meierhofer et al., 2020). Research exploring the role of DTs in value creation highlights their systematic integration into service layers, facilitating value co-creation (Galera-Zarco, 2024; Meierhofer & West, 2019; West et al., 2021). However, existing literature reveals a notable gap regarding the organizational and technological capabilities necessary to effectively leverage DTs within service contexts (Agrawal et al., 2022; Fuller et al., 2020). Predominantly, research has emphasized technical and engineering aspects of DT implementation (e.g. Ferko et al., 2022; Minerva et al., 2020), overlooking its potential in driving broader service innovations as indicated by Fukawa and Rindfleisch (2023).

Based on the above, there exists a gap in fully understanding the integration and operationalization of digital technologies within the framework of service innovation. Traditional service management has often detached technological advancements from service strategies, thus limiting the potential for digital technologies to enable truly innovative service offerings (Kreye, 2022). This oversight necessitates a revaluation of how digital developments, such as DTs, can be strategically employed not only to support but drive service innovation (Barrett et al., 2015; Bustinza et al., 2022; Vendrell-Herrero et al., 2021). Building on research by Burton et al. (2024), there is a pressing need to deepen our understanding of the specific capabilities which lead to more effective DSI. Moreover, it is essential to investigate how capabilities developed for technology adoption and exploitation may play a pivotal role in enabling and scaling DSI.

This study aims to contribute to the understanding of DSI-enabling factors by specifically examining the role of DT capabilities in driving DSI within organizations. Two central research questions guide this exploration: 1) *To what extent do capabilities developed through implementing and using Digital Twins align with those necessary for deploying Digital Service Innovation?* and 2) *In what ways does the implementation and use of Digital Twins enable organizations to leverage their capabilities for the deployment of Digital Service Innovation?* The study initially focuses on identifying and understanding the capabilities essential for developing, utilizing and exploiting a DT, followed by structuring the knowledge on capabilities required for DSI. The ultimate goal is to better understand whether and how DT capabilities influence the ability of organizations to perform DSI.

To address these questions, this study employs a multiple case study methodology, analyzing a multinational consultancy engineering firm specializing in DT technology and a provider of Digital Twin as a Service (DTaaS). By analyzing these two cases, the study captures a broader spectrum of what and how DT capabilities are leveraged for DSI. This research introduces a novel perspective by linking DT capabilities directly with the strategic elements of DSI. Situated at a juncture where businesses increasingly depend on digital technologies to drive service innovation and create competitive advantage, this study provides significant and timely research by examining the impact of DTs in this context.

This research paper is structured into sections to provide a comprehensive understanding of the scope of the study and its contributions. The theoretical background section presents a detailed review of the literature, offering foundational insights on the role of DTs in service provision, identifying essential capabilities related to DTs and DSI, whilst also highlighting key gaps which this research seeks to address. The methodology section outlines and justifies the multiple case study approach, explaining how it supports the research objectives. The results and analysis are then presented and discussed in relation to existing literature in DSI. Additionally, the discussion also provides theoretical and managerial contributions derived from the research findings. Finally, limitations are recognized, and the conclusion highlights key findings and proposes directions for future research.

2. Theoretical background

2.1. Digital Twin conceptualization and its role in service delivery

A Digital Twin (DT) is a comprehensive digital representation of a physical product, system or process, capturing selected characteristics, properties, and behaviors through a dynamic, bidirectional flow of real-time data, enabling continuous feedback and synchronization (Grieves & Vickers, 2016). Tao et al. (2018a) define DT similarly as a digital counterpart of a physical entity, process or system, created by amalgamating data from different sources, enabling replication of process and prediction of performance across different scenarios. A DT is not a simple and individual technology but comprises a coordinated set of digital technologies (Bolton et al., 2018). Primarily, DTs function as tools for monitoring, simulation, and optimization throughout the asset lifecycle (Grieves & Vickers, 2017). Over time their application has expanded beyond operational efficiency towards enabling real-time simulations and scenario testing, significantly enhancing organizational decision-making capabilities (Tao et al., 2018b). Supported by advanced technologies such as IoT, AI, and Big Data Analytics (BDA), DT applications span sectors including manufacturing, healthcare, and the built environment (Jones et al., 2020; Kumar et al., 2023; Lu et al., 2020).

To understand the role of DT in service delivery, it is essential to adopt the perspective of Service-Dominant Logic (SDL). SDL reconceptualizes service provision as a collaborative and interactive multi-actor value creation process, emphasizing resource integration as a critical process to generating value (Vargo & Lush, 2004; Edvardsson et al., 2014; Lusch & Vargo, 2014). This approach emphasizes collaboration, interaction, and the combination of efforts to create value, with organizations playing a key role in coordinating these integrations (Edvardsson et al., 2014; Lusch and Vargo, 2014; Vargo, Maglio, and Akaka, 2008). In this context, technology is often seen as a tangible enabler (operand resource) over which intangible skills (operant resource) operate to facilitate value creation (Lusch and Nambisan, 2015). Within this logic, DTs serve as both operand and operant resources in value creation, embodying a dual role that highlights the transformative potential of DTs in enabling continuous value co-creation and redefining service dynamics within digital ecosystems (Galera-Zarco, 2024).

Building on this perspective, the phenomenon of servitization offers a complementary lens through which to examine the role of DTs in service delivery. As businesses increasingly move toward offering “advanced services” which emphasize outcomes and performance, they also shift responsibility for asset maintenance and optimization to service providers (Baines & Lightfoot, 2013; Baines et al., 2024; Opazo-Basáez et al., 2023; Story et al., 2017). In this context, DTs play a dual role here: enhancing performance and efficiency of physical assets involved in service delivery (Nicoletti & Padovano, 2019), and enabling deeper understanding of customer needs and service dynamics through sophisticated data analysis (Galera-Zarco, 2024; Meierhofer et al., 2020; Porter & Heppelmann, 2014). Additionally, DTs create a continuous feedback loop between the physical and digital environments, allowing for real-time adjustments based on precise analytics, thus facilitating dynamic, customized service delivery (Galera-Zarco & Papadonikolaki, 2023; Tao et al., 2018b).

2.2 Digital Twin capabilities

DTs require a balanced combination of technical and non-technical capabilities (Moyne et al., 2020; Tao et al., 2018b). While technical capabilities ensure functionality and operability, non-technical capabilities are essential for organizational readiness and strategic alignment (Fuller et al., 2020; Kritzinger et al., 2018; Lehner et al., 2021). Despite the increasing volume of research into DTs, there is still a variety of perspectives in implementing and using DTs which make the identification of these capabilities complex. Thus, a careful identification and definition of DT capabilities is required.

2.2.1 Essential capabilities for developing and exploiting Digital Twins

Plummer et al. (2021) presented an early attempt at identifying DT-related capabilities through a Skills and Competency Framework tailored for the National Digital Twin project in the UK. However, their focus on integrating DTs systems across various domains to achieve national interoperability may not fully align with capabilities relevant to individual organizations. This study digs deeper in the literature in order to define distinct sets of capabilities that allow organizations of any size, from small enterprises to large corporations, to develop and implement DTs. Firstly, our research reviews specific technical capabilities required to develop and manage DTs. This is then followed by an exploration of the non-technical capabilities that support their strategic and operational integration into business processes.

Firstly, in order to effectively develop and operate DTs, the presence of technical capabilities is crucial. These capabilities must ensure that organizations are able to build DTs which serve as accurate and dynamic representations of physical assets, enabling, among other uses, real-time monitoring, predictive maintenance, and operational optimization (Lehner et al., 2021). Technical capabilities include managing large volumes of data through effective collection, storage, processing, and analysis (Agrawal et al., 2022). Likewise, effective data management and data analytics are essential in DTs to interpret the vast amounts of data generated and derive actionable insights (Tao et al., 2018b). Additionally, integration capabilities enabling interoperability among heterogeneous technologies and legacy systems is fundamental to ensure DT accuracy and functionality (Barricelli et al., 2019, Rosen et al., 2015). Organizations also require modeling capabilities to maintain the accuracy and reliability of DTs (Schleich et al., 2017), as well as simulation abilities to run "what-if" scenarios by recreating potential changes affecting the physical counterpart (Barricelli et al., 2019).

As DTs often involve the management of sensitive data and control of critical operations, ensuring the security and privacy of data and associated systems is mandatory (Jones et al., 2020; Plummer et al., 2021; Agrawal et al., 2022). Thus, effective cybersecurity is necessary to protect against potential threats and vulnerabilities, thereby safeguarding the operational continuity of DTs (Jones et al., 2020). Finally, a DT should seamlessly integrate and communicate with other DTs, systems and components within a digital ecosystem. This involves compatibility with various data formats, external data sources, protocols and interfaces to ensure coherent and uninterrupted work across different platforms and operational technologies (Agrawal et al., 2022). Effective data interoperability facilitates data exchange and system integration, enabling comprehensive DT ecosystems (Barricelli et al., 2019, Plummer, et al., 2021). Table 1 summarizes technical capabilities identified in the literature.

------ Insert Table 1 here ------

Beyond the technical requirements, non-technical capabilities are equally critical for the successful development and exploitation of DTs (Crespi, 2023). These capabilities involve organizational and human factors, allowing organizations to align DT with business objectives. These capabilities are also required to manage the cultural and operational shifts needed for digital transformation (Raj et al., 2020). Moreover, the presence of strong leadership from executive teams is vital for the successful integration and utilization of DTs within an organization (Negri et al., 2017; Martinez & Huss, 2022). Leaders must recognize the strategic value of data and ensure that DT initiatives are aligned with overarching business objectives (Plummer et al., 2021). Additionally, DTs can also alter existing workflows and roles, so the implementation of DTs requires effective management of organizational change to navigate these transitions smoothly, minimizing disruption while maximizing positive outcomes (Kritzinger et al., 2018).

The creation of effective communication and a collaborative environment are of great importance for the success of DT development. Communication and knowledge sharing is essential between different departments, including IT, operations, and engineering (Uhlemann et al 2017; Plummer et al 2021). Moreover, stakeholder management, which includes transparency, reliability and ensuring security protocols, is of particular importance especially when stakeholders from different domains must collaborate and share sensitive data in the DT (Tripathi, et al, 2024). Overall, building and maintaining trust is fundamental to achieving user acceptance and ensuring effective use of DTs within an organization. In the DT context, trust involves confidence in the data integrity, system reliability, and the overall performance of the technologies (Broo et al., 2022, Plummer et al 2021; Trauer et al., 2022). Finally, as noted by Tao and Qi (2019), organizations implementing DTs must cultivate a culture of continuous learning and adaptation. Such a capability allows firms to effectively integrate new insights and data streams provided by DTs, thereby maintaining competitiveness and responding proactively to emerging challenges and opportunities. Table 2 integrates the collection of these non-technical capabilities as presented in the literature.

------ Insert Table 2 here ------

2.2.2 Capabilities enabled through Digital Twin usage

In the exploration of DT capabilities and to better understand the potential of DTs as enablers of DSI it is pivotal to examine the capabilities achieved by organizations through their use. DTs not only require specific technical and organizational competencies for implementation and exploitation, they also enable the emergence of new capabilities.

A widely acknowledged technical capability enabled through DT usage is real-time monitoring and control of operational processes. This allows organizations to respond promptly to system changes and anomalies (Galera-Zarco, 2022; Tao & Qi, 2019; Uhlemann et al., 2017). By providing accurate, real-time representations of physical assets and systems, DTs contribute to operational optimization, enhancing efficiency and minimizing resource wastage (Galera-Zarco, 2022; Uhlemann et al., 2017). Another core technical capability is predictive analytics: by leveraging data-driven insights, DTs support the early identification and prevention of potential equipment failures, thereby reducing downtime and maintenance costs (Agrawal et al., 2022; Grieves, 2014). Additionally, DTs enable scenario-based simulations which facilitate "what-if" analyses, equipping organizations with the ability to assess risks, forecast outcomes, and make informed decisions (Schleich et al., 2017; Tao & Qi, 2019). The final technical capability identified in the literature relates to the ability of DTs to support seamless data exchange and interoperability. This enables the integration of heterogeneous digital infrastructures and underpins the development of interconnected service ecosystems (Agrawal et al., 2022; Uhlemann et al., 2017). Table 3 encapsulates this set of technical capabilities.

------ Insert Table 3 here ------

In addition to technical capabilities, DT usage also enables a broad spectrum of organizational and strategic competencies. One key non-technical capability is the ability to support strategic decision making by enabling organizations to test and predict outcomes in virtual environments, thereby avoiding risks to physical assets (Broo et al., 2022; Rosen et al., 2015). DTs also enhance design an development processes by facilitating rapid prototyping and iterative design testing. This can reduce time-to-market and improve product or service quality (Schleich et al., 2017). Furthermore, DTs contribute to sustainability goals by optimizing resource utilization, minimizing waste, and promoting environmentally conscious practices (Galera-Zarco, 2022). In educational and training contexts, DTs provide realistic, risk-free environments for skills development and operational training, which is crucial for preparing a skilled workforce in different industrial sectors (Beloglazov et al., 2020; Kang et al., 2016). DTs also allow collaboration among different actors by providing a unified platform for real-time information sharing across departments. This capability extends to cross-organizational collaborations within ecosystems (Tao et al., 2019, Uhlemann et al. 2017). Finally, by simulating customer experiences and enabling the co-creation of tailored solutions, DTs enhance the personalization of service interactions and improve customer engagement (Barricelli et al., 2019; Broo et al., 2022; Galera-Zarco, 2024). Table 4 summarizes these non-technical capabilities.

------ Insert Table 4 here ------

2.3 Conceptualizing Digital Service Innovation and its enabling capabilities

DSI refers to the process of creating, improving, or transforming services through the strategic integration of digital technologies, reshaping value propositions, delivery mechanisms, and customer experiences (Barrett et al., 2015; Opazo-Basáez et al., 2022). As part of broader trends in digital transformation and servitization, DSI embodies a shift whereby digital technologies act not as enablers alone but as integral components of innovation logic, enabling continuous adaptation to dynamic market and customer needs (Vendrell-Herrero et al., 2017; Rabetino et al., 2024). As such, successful engagement in DSI requires a robust set of capabilities, both technical and non-technical, which organizations must harness to integrate, adapt, and leverage digital solutions in ways that align with evolving customer needs and strategic goals (Kohtamäki et al., 2020; Rabetino et al., 2024). This section reviews the literature to identify and structure the capabilities that equip organizations to navigate the complexities of DSI.

First, technological capabilities are essential in DSI as they enable organizations to effectively adopt, adapt, and leverage new available emergent technologies within their business models (Bharadwaj et al., 2013; Barrett et al., 2015; Lehrer et al., 2018). To successfully deploy DSI, firms must adopt new technologies, adapt them to their specific operational context, and leverage the technologies to enhance service offerings (Kohtamäki et al., 2020; Rabetino et al., 2024).

Vendrell-Herrero et al., (2017) discuss the strategic application of digital technologies in the context of digital servitization, emphasizing the importance of the integration of technologies to enhance service offerings. Indeed, the interdisciplinary nature of DSI requires the integration of technological advancements such as IoT, AI, and BDA to enable and enhance service offerings, hence the need for continual adaptation and innovation with technology (Kohtamäki et al., 2020; Rabetino et al. 2024). Likewise, the capability to manage data through comprehensive analytics is crucial in extracting actionable insights and supporting decision-making processes (Opazo-Basáez et al., 2022). Aligned with this, the importance of data analytics is emphasized for its potential to improve service delivery, create new service opportunities, and to facilitate enhanced customer understanding and service personalization (Barrett et al., 2015; Lehrer et al. (2018); Raddats et al., 2022).

A critical technical capability in DSI is the seamless integration of digital technologies into existing service architectures. This integration forms the backbone of robust digital service systems capable of efficiently meeting diverse and dynamic customer demands (Kohtamäki et al., 2020; Rabetino et al., 2024). The use of digital platforms further enhances this capacity by consolidating and coordinating digital technologies, allowing for scalable and flexible service offerings (Kohtamäki et al., 2022). Finally, data security and privacy represent indispensable technological capabilities within DSI. Protecting sensitive customer data is not only critical for regulatory compliance but also for maintaining trust within digital service ecosystems (Kraus et al., 2021). This imperative is further reinforced by Lusch and Nambisan (2015), who highlight its significance within the service-dominant logic framework. Table 5 synthesizes the key technical capabilities for DSI identified in the literature.

------ Insert Table 5 here ------

Non-technical capabilities play a crucial role in DSI, complementing technological competencies. Organizational learning and adaptation are fundamental to the continuous improvement and successful implementation of DSI (Nylén and Holmström, 2015). This capability allows organizations to evolve in response to technological advancements and changing market conditions (Awad & Martin-Rojas, 2024; Opazo-Basáez et al., 2024c). Moreover, Coreynen et al. (2024) emphasize the iterative learning processes undertaken by organizations to integrate new digital technologies effectively and adapt their business models and strategies to deploy DSI. As highlighted by Sjödin et al. (2020), cultivating a culture of exploration and experimentation, particularly around digital technologies, is essential for successful DSI initiatives.

Organizations engaging in DSI often participate in collaborative ecosystems, increasingly engaging with clients, external partners and other firms to collaboratively co-create value. Effectively managing this value co-creation process is critical, as it serves as a catalyst for the development of innovative digital service solutions (Serrano-Ruiz et al., 2024). Thus, Vargo et al. (2024) point to the significance of engaging in service ecosystems which leverage external capabilities and resources to support the delivery of innovative digital service offerings. An equally critical non-technological capability lies in ensuring strategic alignment between digital initiatives and overarching business objectives. As Awad and Martin-Rojas (2024) argue, such alignment, paired with effective management of the complexities inherent in digital transformation, is vital for realizing the full potential of DSI. In this context, Rabetino et al. (2024) indicate that aligning technological strategies with broader organizational goals ensures coherence in transformation efforts and supports sustained innovation and value creation through digital services.

An additional non-technical capability is resource liquification. This removes barriers and facilitates the flow of information and services across digital platforms, thereby making organizational resources more accessible and responsive, and thus enabling DSI (Vargo et al., 2024). Complementing this capability, the establishment of a customer-centric approach has been identified as fundamental for successful DSI (Lehrer et al., 2018) as it allows the design of personalized services which enhance customer experiences and satisfaction (Soto Setzke et al., 2023). Leveraging customer data to inform service design and delivery ensures alignment with customer expectations and preferences (Lehrer et al. 2018; Soto Setzke et al., 2023). Table 6 summarizes the identified non-technical capabilities essential for effective DSI deployment.

------ Insert Table 6 here ------

2.4 Research gap identification and conceptual framework development

Recent literature has explored the relationship between emergent digital technologies and service innovation, particularly from a capabilities perspective. For instance, studies have proposed frameworks illustrating how AI (Akter et al., 2023) or BDA and digital platforms (Xiao et al., 2020) enable service innovation. However, despite this emerging focus observed in the literature, the role of DTs as enablers of DSI remains notably unexplored.

Previous research has examined the technical and non-technical capabilities required for development and utilization of DTs (Kritzinger et al., 2018; Plummer et al., 2021). In parallel, the service innovation domain has separately identified critical capabilities essential for effective DSI (e.g., Barrett et al., 2015; Lehrer et al., 2018; Kohtamäki et al., 2020). Nonetheless, limited research specifically addresses the intersection and synergies between DT capabilities and those required for enabling DSI. Although existing studies acknowledge the contribution of DTs to enhanced service delivery (Galera-Zarco, 2024), improved operational efficiency (Tao et al., 2018b) and innovation processes (Fukawa & Rindfleisch, 2024), their potential as strategic enablers for DSI remains underexplored. In particular, there is a lack of comprehensive research examining the extent to which capabilities developed through DT implementation and use align or overlap with the capabilities necessary for DSI. Addressing this gap is significant as it can offer valuable insights to organizations seeking to strategically leverage DTs as catalysts for innovation, particularly in industries undergoing servitization. While prior studies recognize the role of DTs in advanced services and value creation (Baines et al., 2024; Story et al., 2017), they do not thoroughly explore how DT-specific capabilities directly enhance an organization's capacity to innovate in digital service contexts.

This research hypothesizes that the implementation and use of DTs, through the specific capabilities they both require and enable, position organizations to effectively engage in DSI. Thus, the hypotheses guiding this study are:

- H1: There is a significant overlap between Digital Twin capabilities and those necessary for Digital Service Innovation.
- H2: Organizations that develop and utilize Digital Twins are better positioned to successfully deploy Digital Service Innovation, as the capabilities required and gained through Digital Twins both align with and facilitate the development of key Digital Service Innovation capabilities.

Addressing this research gap provides an important contribution to the literature on DSI-enabling factors by offering a nuanced understanding of how DT capabilities influence organizational capacity for DSI and help to achieve competitive advantages. Based on a comprehensive literature review and synthesis, this study develops two conceptual frameworks (Figures 1 and 2) to illustrate the interrelationships and overlaps among technical (Figure 1) and non-technical (Figure 2) capabilities involved in DT development and exploitation, capabilities gained through DT usage, and capabilities essential for deploying DSI.

------ Insert Figure 1 and Figure 2 here ------

3. Methodology

In order to investigate how DT capabilities influence DSI within organizations, this study adopts an exploratory qualitative research design grounded in a multiple case study approach. Case study methodology is particularly well suited for examining contemporary phenomena within their real-life contexts, especially when addressing complex "how" and "why" questions which are central to the understanding of phenomena (Yin, 2017). The exploratory nature of the study enables the generation of new theoretical insights without being restricted to the validation of pre-existing frameworks (Rothenberger & Srite, 2009). Employing multiple case studies further strengthens the analytical depth by allowing cross-case comparisons, thereby enhancing the robustness and potential generalizability of the findings (Eisenhardt, 1989).

The case population of this study comprises organizations specializing in the development, exploitation, and strategic utilization of DTs. These organizations not only provide expertise in implementing and operating DTs but also support clients in strategic alignment and in leveraging the potential capabilities enabled through DT usage to achieve operational efficiency, strategic alignment, and DSI. The selection followed a purposive sampling strategy (Patton, 2015) aimed at capturing variation in organizational size, technological focus, and service models within the DT landscape. The first case study involves a large multinational engineering consultancy with a dedicated DT department, providing expertise on how established firms integrate DTs into complex, asset-intensive environments. The second case study features a smaller, technology-native company offering DTs as a service (DTaaS) illustrating agile, innovation-driven applications of DT technology. Beyond their internal expertise, both organizations work with a diverse range of clients across industries and project types, supporting digital transformation efforts, strategic alignment, and innovation initiatives. Together, these organizations span a broad range of DT implementation contexts.

To maintain anonymity, the two organizations are referred to as CompA and CompB. An overview of each case is presented below to contextualize their positioning and relevance in exploring DT capabilities in relation to DSI.

CompA is a multinational consulting engineering firm with over 6,000 professionals operating across multiple countries. The organization addresses complex global challenges in sectors such as aviation, energy, and urban development. This study focuses on the firm's Digital Twin consultancy department, which plays a pivotal role in supporting clients through the design and operational phases of projects by offering innovative DT solutions. Their core expertise lies in leveraging DTs to address issues such as inefficiencies, sustainability and data complexity, while also enhancing stakeholder engagement and articulating the value of DTs across asset lifecycle. The primary informant for this case was a Digital Twin consultant and

Business & IT architect, selected due to extensive experience in managing DT-related projects across multiple industries, their involvement in strategic initiatives related to digital transformation, and comprehensive understanding of organizational capabilities required for effective DT implementation and use.

CompB is a boutique firm based in Canada, specializing in Digital Twin as a Service (DTaaS) and recognized for its innovative approach to delivering DT solutions. The company employs approximately 70 professionals and integrates diverse technological services to transform organizational operating models through highly tailored DTs. Its strategic focus centers on fostering agility, innovation, and data-driven decision making. The firm collaborates closely with client organizations to articulate and realize their digital ambitions, developing roadmaps for both value strategy and technical implementation. The key informant interviewed was the co-founder and chief growth officer, whose strategic leadership role and direct involvement in client engagement across multiple sectors provided valuable insights. The informant was selected due to a deep understanding of the technical, strategic, and organizational capabilities required for DT development and their alignment with broader goals such as DSI.

Data were primarily collected through semi-structured interviews supplemented by secondary sources, including internal company documentation, presentations provided by the interviewees, and publicly available material from organizational websites. Interviewees' experience, their central roles and comprehensive knowledge of both technical and organizational dimensions enabled the collection of rich and detailed data directly relevant to the study's objectives. Interviews took place in March and April 2024 via video conferencing platforms, each lasting between 60 and 90 minutes. An interview guide (see Appendix A) was developed to maintain consistency across cases while allowing flexibility to explore emergent themes (Myers & Newman, 2007).The interviews addressed five areas: 1) capabilities required to develop and exploit DTs, 2) capabilities achieved through DTs, 3) the role of DTs in deploying DSI, 4) organizational culture, and 5) DT implementation goals. After covering the first two areas, the researchers presented the capability tables (Tables 1–6) and initial versions of capability interrelationship frameworks (Figures 1 and 2) which were developed by the authors through a combination of literature review and the authors' interpretive analysis of existing research. Participants were invited to validate these findings and contribute additional insights. After incorporating their inputs, the interrelationship figure was sent back to the interviewees via email for final feedback to ensure accuracy and completeness. All interviews were video-recorded with the consent of the participants and transcribed verbatim for analysis.

A systematic analytical strategy was employed, integrating both within-case and cross-case analysis techniques (Eisenhardt, 1989). In the first phase the transcribed interview data were analyzed on a case-by-case basis to construct a detailed understanding of DT and DSI capabilities within each organizational context. This was followed by a cross-case analysis aimed at identifying shared patterns, divergences, and overarching themes across the two cases.

The qualitative data analysis followed an iterative coding process. Initial coding drew upon the capability sets identified from the literature while remaining open to new insights through inductive open coding. These initial codes were then refined through axial coding, which facilitated the clustering of themes into broader categories relevant to the study's focus on capabilities (Corbin & Strauss, 2015). This approach enabled a structured yet flexible examination of both theoretically grounded and emergent capabilities. To strengthen the validity and reliability of the findings, two strategies were employed. Triangulation was achieved by incorporating the previously mentioned secondary data to corroborate and contextualize the interview data (Denzin, 1978). Additionally, reflexivity was maintained throughout the research process. The researchers engaged in continuous critical reflection on their assumptions, interpretations, and potential biases to ensure a more objective and nuanced analysis (Finlay, 2002).

4. Findings and analysis

This section presents the findings and analysis of the empirical data structured to address the two research questions guiding this study. The first subsection validates the DT capabilities identified from the literature and introduces any new capabilities emerging from the cases. The subsequent subsection explores the role of these DT capabilities in enabling DSI, specifically examining the alignment between DT capabilities and the requirements for successful DSI, as well as the way in which organizations leverage DT capabilities to facilitate DSI deployment.

4.1 Empirical validation and extension of Digital Twin capabilities

The analysis of CompA and CompB provided robust validation of the technical Digital Twin (DT) capabilities identified in the literature, as summarized in Table 7. Both organizations validated Data Management and Analytics as a foundational technical DT capability, particularly emphasizing robust IT infrastructure and metadata management to address complex and large-scale data requirements. Integration of Heterogeneous Systems and Technologies was similarly affirmed, with both organizations highlighting the necessity of comprehensive technical stacks capable of aggregating diverse data sources tailored to specific business objectives. Modeling received partial validation; CompA supplemented this capability through the identification of two additional capabilities, namely Knowledge Graphs and Ontology Management. CompB notably pointed out the necessity of tailored AI and Machine Learning models to effectively operationalize DTs in various use cases. Simulation Ability was jointly validated, reflecting the strategic utilization of DTs for scenario analysis. While CompB explicitly validated Cybersecurity & Data Privacy as critical, particularly regarding the secure integration of external data, CompA did not initially include this capability; however, its importance was subsequently acknowledged following the interviewee's review of Figure 1. Furthermore, Data Interoperability and Digital Platforms was recognized as crucial: CompA highlighted interoperability standards, whereas CompB emphasized data governance to facilitate external data integration.

Both organizations confirmed significant technical capabilities achieved through DT use, notably Operational Optimization, Predictive Analysis, Scenario Analysis for Decision Making, and Data Interoperability. Operational Optimization was explained differently, with CompA providing examples of DTs enabling optimized operations in complex environments (e.g., real-time adjustments in complex water systems), whereas CompB contextualized it as part of a broader evolution from initial cost reduction toward sustained efficiency improvements. Predictive and Scenario Analyses were similarly validated, with both organizations recognizing the integration of AI-driven foresight into DTs and the ability to test scenarios and decisions before implementation as central benefits. However, perspectives diverged regarding Real-time Monitoring and Control: CompA strongly supported this capability, reflecting its operational focus, while CompB provided only partial support, noting the potential of DTs primarily for decision support and simulation scenarios rather than for explicit real-time applications. This divergence suggests varying organizational priorities: CompA's emphasis on immediate operational outcomes aligns with the nature of its clients, whereas CompB focuses more on a strategic planning orientation.

------ Insert Table 7 here ------

In the sphere of technical DT capabilities, each case contributes distinctively to the identification of novel capabilities (Table 8), clearly reflecting their organizational context and strategic focus. CompA introduced the capabilities of Knowledge Graphs and Ontology Management. Knowledge Graphs was highlighted as an essential capability for effectively modeling complex relationships, while Ontology Management was identified as vital for ensuring data consistency and interoperability. These capabilities are particularly relevant given CompA's involvement in large-scale engineering projects, where managing multi-dimensional and domain-specific information is critical. In contrast, CompB highlighted Edge Computing and Advanced Visualization (e.g., AR/VR). Edge Computing emerged as significant for addressing challenges associated with large-scale data processing, enhancing real-time analytics, and reducing latency. Advanced Visualization emerged as a distinct capability, referring to the ability of organizations to adopt and effectively utilize technologies such as Augmented Reality (AR), Virtual Reality (VR), and tools like HoloLens. This capability was recognized for its potential to enhance user experience, support intuitive data exploration, and improve training as well as decision-related processes in DT applications. The identification of these new capabilities aligns with CompB's position as a boutique Digital Twin-as-a-Service provider, where scalability, real-time responsiveness, and user engagement are central to delivering adaptable and client-oriented solutions.

------ Insert Table 8 here ------

Non-technical DT capabilities were consistently validated across cases, as indicated in Table 9. Strategic Alignment and Complexity Management were crucial for both organizations, though articulated differently. CompA discussed the importance of enterprise architecture integration to connect DT initiatives with broader organizational objectives and value chains, whereas CompB associated these capabilities with the necessity of leadership vision and organizational maturity to drive digital transformations such as DT development. Effective Collaboration emerged as critical, with both cases emphasizing Stakeholder Management as essential for aligning technical initiatives with business ambitions, thereby requiring iterative change management to ensure successful adoption. Indeed, insufficient collaboration was identified as a common reason for the failure of many DT initiatives. Organizational Learning and Adaptation was highlighted through the importance of understanding internal barriers, organizational culture, and cross-departmental collaboration before implementing technical solutions. CompA introduced the concept of a DT maturity matrix as a means of guiding organizations through the technological and business transformation processes necessary for developing and utilizing a DT. The capability of Building and Maintaining Trust was partially validated by both organizations. The interviewee from CompA described efforts to address internal resistance by educating teams and demonstrating the advantages of DTs through tangible examples. In contrast, CompB linked this capability closely with Governance, emphasizing trust-building as crucial due to the potential of DTs to enable secure and relevant data sharing. These differences reflect variations in organizational scale and project complexity. CompA's emphasis on internal education and stakeholder engagement underscores the importance of managing resistance and aligning interests within large, complex engineering environments. Conversely, CompB's focus on governance and secure data sharing likely stems from its frequent collaborations with diverse clients who rely on external data sources across distributed ecosystems.

Both companies validated the critical role of Strategic Decision Making Support enabled by DT use. CompA recognized the potential of DTs to facilitate scenario-based analyses that explore various options and optimize decision-making processes, whereas CompB emphasized their ability to enhance transparency and visibility into operations. Likewise, improved Collaboration Across Departments and Ecosystem was consistently recognized, emphasizing the role of DTs in reducing organizational silos and enhancing cross-organizational communication. Optimization of Design and Development Processes was fully supported by CompA, highlighting the benefits of virtual scenario testing, while CompB's validation was partial, primarily addressing operational automation without explicit connections to design processes. Similarly, Educational and Training Applications were strongly confirmed by CompA, which emphasized DTs as tools for organizational knowledge transfer and workforce upskilling. This capability was not supported by CompB, possibly indicating this is not a primary area of focus in their projects, where formal training mechanisms may be less prominent. Regarding the Customer-Centric Approach, CompA provided partial validation, primarily within the context of servitization strategies, viewing DTs as aids in transitioning to servitization and enhancing customer value through tailored services. In contrast, CompB placed stronger emphasis on the role of DTs to better serve customers by providing operational transparency. This aligns with their observation that the market is increasingly leveraging DTs to innovate and enhance customer satisfaction. Finally, Sustainable Practices and Waste Reduction received partial and no validation, respectively. CompB touched on sustainable practices and waste reduction indirectly by discussing cost reduction and operational efficiencies but did not explicitly link these to sustainability goals. CompA, although not initially mentioning these capabilities in response to the first block of questions, later supported them during discussions of the non-technical capability interrelationship model (Figure 2).

------ Insert Table 9 here ------

In terms of additional non-technical DT capabilities, both organizations agreed on the importance of Bridging Technical and Business Domains. CompA described this capability as essential for aligning technical DT capabilities with strategic business goals, ensuring that projects involving DTs deliver meaningful value. CompB focused on the formation of multidisciplinary teams capable of effectively communicating and integrating expertise from both domains to ensure that DT solutions align with business objectives and deliver measurable outcomes. Change Management and Overcoming Organizational Resistance also emerged as critical capabilities in both cases, reflecting the importance of managing cultural and operational shifts through stakeholder involvement and gradual implementation strategies. Distinctively, CompA introduced the importance of integrating Domain Knowledge to ensure DT relevance, illustrating the critical role of specialized industry expertise in large-scale, sector-specific DT projects, where accurate contextualization of DT solutions is essential. CompB underlined Skill Development and Talent Management, advocating investment in training to build balanced technical and business expertise. Finally, Resource Liquification was uniquely identified by CompB as a non-technical capability, referring to the enhanced mobility and accessibility of information and services enabled by DT platforms. This capability supports greater agility and responsiveness in DSI, particularly in environments requiring dynamic resource allocation and real-time adaptability. The capabilities emerging from the cases are presented in Table 10.

------ Insert Table 10 here ------

4.2 Understanding the role of DTs in DSI deployment

4.2.1 The extent to which DT capabilities align with those required for DSI deployment

Case CompA: Consulting Engineering Firm (Digital Twin consultancy department)

The interviewee from CompA validated several technical DT capabilities identified from the literature as crucial for enabling DSI. Specifically, Data Management and Analytics, Integration of Heterogeneous Systems and Technologies, Interoperability, Advanced Visualization, and Cybersecurity were confirmed as technical DT capabilities required for developing and exploiting DTs, which are also essential for DSI, as presented in the initial conceptual framework (Figure 1). Additionally, the interviewee highlighted two supplementary technical DT capabilities enabled through DT use, Scenario Analysis and Predictive Analysis, as significantly overlapping with technical DSI capabilities.

Scenario Analysis, in particular, was recognized for its potential to facilitate service-oriented innovation, as it allows organizations to digitally explore multiple scenarios, thereby reducing costs and enhancing the efficiency of new service development:

"In the design phase, digital twins allow companies to explore all kinds of scenarios and options, helping to create smarter and more optimized services"

"…you can also use digital twins to explore all kinds of options digitally… that is not as expensive as if you start trying to engineer and build it"

Predictive Analysis was also identified as transformative for enabling innovative services, particularly those related to predictive maintenance:

"With AI and machine learning models in digital twins, you can develop better data-driven models and offer better services around predictive maintenance, especially in complex environments…"

From a non-technical perspective, CompA's interviewee affirmed that a set of the DT capabilities outlined in the literature overlapped significantly with capabilities necessary for DSI. Specifically, Strategic Alignment and Complexity Management, Effective Communication and Collaboration, Organizational Learning and Adaptation, and a Customer-Centric Approach were validated as essential capabilities for DSI. Furthermore, three of the newly identified capabilities. Bridging Technical and Business Domains and Domain Knowledge emerged as critical for aligning DT capabilities with DSI objectives. The interviewee emphasized the necessity of integrating business understanding and context-specific knowledge to enhance services through DT initiatives:

"…(to offer services)..you want to understand the value chain of the company, the business capabilities, not just the capabilities to build digital twins…understand the ecosystem done by enterprise architecture, to identify what exists and what needs to be connected."

Finally, case CompA explicitly linked Change Management to DSI; specifically, overcoming organizational resistance was discussed:

" (about how to promote service innovation through Digital twins)…Maybe that's also an idea to do it, to say, yeah, evangelize based on use cases and services internally and externally."

Case CompB: : Digital Twin as a Service (DTaaS) provider

The interviewee from CompB validated several technical DT capabilities identified in the literature as crucial for enabling DSI, including Data Management and Analytics, Cybersecurity, Interoperability, and Integration of Heterogeneous Systems and Technologies. These capabilities were considered fundamental in supporting service-oriented business transformations. Additionally, the interviewee introduced and identified four further technical DT capabilities as significant for enabling DSI. These include two newly identified capabilities, Edge Computing and Advanced Visualization, and two capabilities - Predictive Analytics and Scenario Analysis - that were previously classified within DT capabilities but were not integrated into the initial framework (Figure 1) as technical DSI capabilities. Among these newly recognized capabilities, some were particularly reinforced during the interview.

Edge Computing was particularly emphasized as essential in scenarios requiring immediate data handling and rapid decision-making:

"The more data you take on, the more complex the infrastructure management becomes… it takes quite a bit of time to understand the needs, the capacity… that's when we start talking about edge computing...to process massive amounts of data."

Advanced Visualization was also highlighted as transformative, with its potential to enhance user experience and enable interactive, customer-oriented services:

"What we call the visualization layer… visualization, it could be anything from 3D visualization, AR, VR (HoloLenses)… can enhance the user experience, creating opportunities for tailored and interactive services."

Similarly, Predictive Analytics and Scenario Analysis were identified as integral capabilities for driving innovation in digital services:

"…the what-if scenarios analysis are quite connected (with innovation)… some organizations use them for the design of new products and services."

From a non-technical perspective, the interviewee validated several capabilities from the initial framework (Figure 2) as essential enablers of DSI. These included Strategic Alignment and Complexity Management, Organizational Learning and Adaptation, Effective Communication and Collaboration, and Customer-Centricity. In addition, the interviewee contributed to the initial framework by identifying four additional non-technical capabilities - Bridging Technical and Business Domains, Skill Development, Resource Liquification, and Change Management - as critical for supporting DSI initiatives.

In relation to Strategic Alignment and Complexity Management, the interviewee underscored the importance of aligning DT initiatives with strategic objectives, ensuring a comprehensive understanding of organizational processes and their interdependencies:

"We start with conversations about business strategy, objectives, and challenges… This top-to-bottom approach helps create the foundation for digital twins to deliver the business outcomes needed."

The ability to bridge technical and business domains was also strongly emphasized as a key enabler of DSI. According to the interviewee, aligning these domains facilitates the development of services that meet both operational and strategic needs:

"You have to have a business understanding alongside technical knowledge. Digital twin projects focus on a multidisciplinary team… bringing these two worlds together to create innovative business outcomes."

Cross-case analysis

The cross-case analysis revealed a high degree of alignment between the two cases regarding the extent to which DT capabilities overlap with those required for DSI (Figures 3 and 4). Both CompA and CompB identified several key technical capabilities as essential for DSI, including Data Management and Analytics, Cybersecurity, Interoperability, and Integration of Heterogeneous Systems. These capabilities constitute the foundational technical infrastructure necessary for the effective deployment of innovative digital services, as initially outlined in the literature. Additionally, both organizations expanded upon the initial model by emphasizing the critical role of two DT-enabled capabilities - Scenario Analysis and Predictive Analytics - in supporting DSI. Furthermore, both cases introduced the newly identified capability of Advanced Visualization, which was viewed as instrumental in enhancing user experience, enabling interactive scenario exploration, and supporting innovative service offerings. CompB uniquely stressed the importance of Edge Computing in addressing real-time data processing challenges within dynamic environments.

The cross-case analysis revealed substantial alignment between both organizations around the extent to which DT capabilities overlap with those required for Digital Service Innovation (DSI). Key technical capabilities recognized by both CompA and CompB as essential for DSI include Data Management and Analytics, Cybersecurity, Interoperability, and Integration of Heterogeneous Systems.

The analysis also revealed convergence in relation to non-technical capabilities. Both CompA and CompB emphasized the importance of Strategic Alignment and Complexity Management, recognizing these as fundamental to the successful DSI. Similarly, capabilities such as Effective Communication and Collaboration, Organizational Learning and Adaptation, and Customer-Centricity were consistently recognized as overlapping capabilities between DT and DSI. In addition, newly identified non-technical DT capabilities such as Bridging Technical and Business Domains and Change Management were reinforced across both cases as playing a critical role in enabling DSI. This alignment underscores the need for organizations to strategically connect DT-related competencies with business and innovation objectives to support effective DSI deployment.

The analysis also demonstrated convergence in relation to non-technical capabilities. Both CompA and CompB emphasized the importance of Strategic Alignment and Complexity Management, recognizing these as fundamental to the successful integration of DT initiatives within broader organizational strategies, including DSI. Similarly, capabilities such as Effective Communication and Collaboration, Organizational Learning and Adaptation, and Customer-Centricity were consistently validated. In addition, newly identified non-technical DT capabilities such as Bridging Technical and Business Domains and Change Management were reinforced across both cases as having an important role for DSI as well. This alignment highlights the need for organizations to strategically connect DT-related competencies with business and innovation objectives in order to enable effective DSI deployment.

Nevertheless, the analysis revealed notable distinctions in the specific DT capabilities each organization associated most closely with DSI requirements. For example, CompA uniquely emphasized the integration of Domain Knowledge to tailor DT solutions to industry-specific contexts. This emphasis reflects CompA's role as a consulting engineering firm engaged in large-scale infrastructure projects, where deep sectoral expertise is essential for ensuring that DT applications are relevant, accurate, and aligned with complex technical and regulatory environments. In contrast, CompB identified Skill Development, enabled through DT use, and Resource Liquification as distinctive non-technical capabilities supporting DSI. The focus on these capabilities reflects CompB's need to navigate the dynamic ecosystems of their clients, often operating with partners across varied sectors and digital infrastructures.

------ Insert Figure 3 and Figure 4 here ------

4.2.2 Leveraging DT capabilities for DSI deployment

Case CompA: Consulting Engineering Firm (Digital Twin consultancy department)

CompA's interviewee provided valuable insights into how DT capabilities are actively leveraged in practice to support the deployment of DSI. The interviewee discussed the role of Change Management, particularly strategies for overcoming organizational resistance, as a DT capability that critically enable successful DSI. In Case A, a clear connection was made between DT capabilities related to knowledge management, domain expertise, and customer-centric approaches and their relevance in supporting servitization and knowledge-based service offerings. These capabilities were recognized for enabling a shift from product-based models to service-oriented ones, with DTs seen as key tools for capturing organizational expertise and facilitating this transition:

"I'm convinced that with the help of digital twins, the servitization of products and selling services instead of hardware will enormously grow."

"You can also use them (digital twins) to catch and capture the knowledge about all those assets, especially when you fill in or when you set up digital trends based on knowledge graphs…"

The interviewee further explained how DTs enable dynamic, real-time representations of physical systems, thereby enhancing the ability of firms to provide performance-based and innovation-driven services:

"[Talking about performance-based services] …You can do that much better if you have digital twins because then you have the physical dynamic representation of part of the company."

In this context, DTs were identified as drivers of continuous improvement and optimization across operational and engineering processes, highlighting their transformative potential for traditional service delivery:

"Most of the time, you improve operational or engineering processes and use digital twins to optimize, improve, and do smarter optimization of operational processes … Can we call that innovation? Maybe we can."

These findings highlight the active role of DT capabilities in facilitating not only the initial deployment but also the ongoing evolution of innovative digital services.

Case CompB: : Digital Twin as a Service (DTaaS) provider

CompB's interviewee and secondary data provided insights into how DT capabilities are actively leveraged to support the deployment of DSI. Effective Change Management was highlighted as a crucial capability, particularly in facilitating successful DT adoption and sustained innovation. The interviewee advocated for iterative implementation strategies to enhance organizational acceptance and alignment with evolving service goals:

"You don't overwhelm the organization with automation; you do it in small pieces to increase adoption… This approach helps align digital twin capabilities with evolving service goals."

Skill Development also emerged as a key enabler of DSI, emphasizing the critical role of DTs in supporting training and developing operational and business understanding of assets. This capability was seen as essential for equipping teams with the expertise needed to effectively apply DTs in innovative digital service offerings:

"This takes a lot of time from a business to train people and provide the right understanding… but these skills are essential for creating solutions that connect data, processes, and business insights."

Resource Liquification was uniquely emphasized, highlighting the potential of DTs to enable dynamic utilization of internal and external resources. This capability supports innovative forms of collaboration across organizational ecosystems:

"When you negotiate governance methods to acquire external data, it provides a huge business advantage… Digital twins help simulate scenarios and understand impacts, enabling better collaboration and innovative solutions."

In addition to the interview findings, secondary sources reinforced CompB's perspective of DTs as orchestrators that support enhanced decision making, resource optimization, and the development of innovative value propositions. The strategic vision of CompB positions DTs as integrative frameworks that bridge technical and business domains, enabling service innovation, operational excellence, and the creation of new service models, such as data monetization:

"We are helping [customers] leverage their own data to create new revenue streams… helping them package and sell their existing technology … now I see new needs come up with customers such as data monetization… this is a new service that never existed before."

In conclusion, CompB regards DT capabilities not merely as technical tools, but as strategic enablers that bring together diverse competencies to support DSI. In this view, DTs are instrumental in generating new value through service innovation, bridging internal silos, and fostering agile responsiveness within evolving digital ecosystems. As the interviewee summarized:

"Digital twins allow different types of services to play a part at the same time… they bring these two worlds [physical and digital] together and enable organizations to speak the same language."

This perspective also reflects the integration of knowledge across organizational boundaries, whereby companies use digital twins as shared models to integrate data and simulate common and interconnected activities.

Cross-case analysis

Both organizations demonstrated how DT capabilities are leveraged to facilitate and accelerate the deployment of DSI, though they emphasized distinct strategic orientations and responded to different market-driven considerations.

CompA primarily leveraged DT capabilities to support its clients' transition toward servitization, transforming traditional product-based offerings into innovative, service-oriented business models. DT-enabled capabilities such as Scenario Analysis and Predictive Analytics were specifically recognized as means to test, optimize, and improve new services in virtual environments, thereby reducing costs and associated risks. In addition, CompA highlighted the use of DTs for capturing and sharing critical organizational knowledge, as well as supporting educational and training applications aimed at workforce upskilling and continuous adaptation, which are key enablers of effective DSI.

In contrast, CompB emphasized leveraging DT capabilities around value creation and orchestration. The company identified the capability of Resource Liquification, which allows enhanced mobility and accessibility of data and services across platforms, as pivotal in enabling highly responsive and flexible service innovation. CompB also illustrated how capabilities such as Advanced Visualization and Edge Computing are applied to create tailored digital services that support real-time decision-making and strengthen customer engagement. Notably, CompB's strategic use of DTs to facilitate new services for their clients, such as data monetization and productization, exemplifies how DT capabilities can support the development of novel business models and revenue streams.

Overall, this cross-case analysis illustrates that, while both cases explain how DT capabilities support DSI, their distinct industry contexts shape the specific manner in which these capabilities are employed by their clients to facilitate DSI.

5.- Contributions and Implications

5.1 Theoretical contributions

This study advances the literature on service innovation and DT by illuminating how DT capabilities can serve as strategic enablers of DSI. Existing research in DT has predominantly focused on the technical aspects of DTs (e.g., Kritzinger et al., 2018; Fuller et al., 2020) but has rarely integrated the service innovation perspective to explore their broader impact on DSI. By contrast, this study systematically maps DT capabilities, both those required to develop and exploit DTs and those achieved through DT use, against essential capabilities for DSI (Figures 3 and 4), demonstrating concrete overlaps and synergies between these domains.

First, the study identifies a set of novel DT capabilities emerging from the empirical analysis that had not been previously recognized. These include the technical capabilities of Knowledge Graphs, Ontology Management, Edge Computing, and Advanced Visualization, as well as the non-technical capabilities of Change Management, Bridging Technical and Business Domains, Domain Knowledge, Skill Development, and Resource Liquification. These newly identified technical DT capabilities enable more sophisticated DT functionalities, such as real-time data processing and immersive user experiences, while non-technical capabilities extend beyond the traditional engineering focus of DT by enhancing organizational functions such as knowledge sharing, strategic alignment, and agile resource deployment. These functions influence service innovation by fostering greater agility, co-creation, and user-centric design (Lusch & Nambisan, 2015; Vargo et al., 2024). Furthermore, these results extend existing discussions on the transformative potential of DTs (Fukawa & Rindfleisch, 2024; Galera-Zarco, 2024), underscoring that their value is not limited to operational optimization alone but also encompasses broader innovation and service ecosystems. Additionally, these findings emphasize the importance of organizational and strategic capabilities in digital transformation and service innovation contexts, and expand upon previous studies in this area (Kohtamäki et al., 2020; Rabetino et al., 2024).

Second, the integration of DT capabilities with DSI frameworks constitutes an important theoretical contribution. Findings demonstrate that many DT capabilities, both technical (Data Management and Analytics, Cybersecurity, Interoperability, Integration of Heterogeneous Systems, Scenario Analysis, Predictive Analysis, Edge Computing, and Advanced Visualization) and non-technical (Strategic Alignment and Complexity Management, Domain Knowledge, Change Management, Organizational Learning and Adaptation, Bridging Technical and Business Domains, Effective Communication, Customer-Centricity, Skill Development, and Resource Liquification) overlap significantly with those required for DSI. This convergence supports a synergistic pathway through which DTs act as catalysts for DSI, aligning technical infrastructure with organizational and strategic imperatives. In this vein, these results underscore the importance of aligning technological initiatives with business objectives in a continuous process of learning and alignment (Coreynen et al., 2024), driving a culture receptive to innovation, resonating with previous studies (e.g., Barrett et al., 2015; Opazo-Basáez et al., 2022 - 3).

Third, comparative insights from CompA and CompB illuminate how organizations leverage DT capabilities to drive DSI in distinct ways. For CompA, DT capabilities (e.g., Scenario Analysis, Predictive Analytics, and Domain Knowledge) serve as conduits for servitization and deeper asset knowledge, aligning with literature emphasizing domain-specific expertise in advanced service offerings (Story et al., 2017). Conversely, CompB recognizes DT capabilities such as Edge Computing, Advanced Visualization, Skill Development, and Resource Liquification as critical for value co-creation (Vargo et al., 2024), enabling agile, data-driven collaboration with clients and partners across diverse ecosystems (Bustinza et al., 2024). Collectively, these findings enhance theoretical understanding of how DTs can function as strategic platforms for DSI, enabling servitization pathways, bridging organizational silos, and facilitating new service models.

Finally, by incorporating the Digital Servitization Pathway (DSP) perspective outlined by Vendrell-Herrero et al. (2024), this study further emphasizes that DT-enabled digital transformation acts as a precursor to advanced service innovation. Accordingly, the integrative framework presented in Figures 3 and 4 provides a structured foundation for understanding how DT capabilities facilitate DSI by supporting both the technological and organizational transformations necessary for successful digital servitization. Taken together, these contributions enrich theoretical discourse on digital transformation and service innovation, demonstrating that DT capabilities can evolve from isolated technical tools into strategic enablers of innovation.

5.2 Managerial contributions

This research offers several practical implications for organizations involved in developing DTs as well as those seeking to deploy DSI. Primarily, the identification and validation of both established and newly emerged DT capabilities across technical and non-technical dimensions offer a comprehensive framework that can guide strategic investments in DT initiatives.

Organizations should adopt a dual-focused approach when investing in DT capabilities. On the technical side, developing robust DT infrastructures able to support advanced digital services. Concurrently, building organizational readiness through effective change management, multidisciplinary collaboration, and continuous skill development is equally important. Aligning technical expertise with business strategy is essential to ensure that DT initiatives are embedded within broader organizational objectives and contribute effectively to service innovation. To this end, organizations should develop multidisciplinary teams that combine technological proficiency with business insight, enabling DT projects to generate concrete value and advance strategic priorities. Such integration supports the translation of technological potential into service innovations that respond to customer needs and reinforce competitive positioning.

Moreover, the integration and overlap of DT capabilities with DSI requirements underscore the existence of strategic pathways for achieving DSI through DTs. First, DTs can facilitate digital servitization by enhancing asset knowledge and enabling virtual scenario simulations and predictive maintenance, thereby reducing associated risks and costs, as evidenced in the findings from CompA. Second, DTs can promote value co-creation through capabilities such as resource liquification, adaptive collaboration, and real-time decision support, as demonstrated by CompB. This dual-pathway perspective provides organizations with a structured approach to transitioning from traditional product-centric models toward innovative, service-oriented solutions.

Lastly, prioritizing data governance and cybersecurity is imperative. Given the substantial volumes of sensitive data managed by DTs, establishing robust data governance frameworks and implementing stringent cybersecurity measures not only mitigate potential risks but also enhance stakeholder trust, thereby supporting sustainable DSI deployment. Proactively investing in these technical and organizational capabilities positions organizations to leverage digital assets effectively, respond adaptively to evolving market conditions, and secure sustained competitive advantage within the digital economy.

6. Limitations

While this study offers valuable insights into the role of DT capabilities in enabling DSI, several limitations must be acknowledged. First, the empirical analysis is confined to two specific organizational contexts: a consulting engineering firm and a Digital Twin as a Service (DTaaS) provider. This sectoral focus may limit the broader applicability of the findings, particularly to organizations operating in industries with distinct technological infrastructures, business models, or regulatory environments. However, it is worth noting that both companies work across a range of client sectors, and the insights presented reflect a cross-industry perspective derived from their cumulative experience.

Additionally, although the multiple-case design supports in-depth analysis and comparison, the limited number of cases restricts the extent to which conclusions can be generalized. This is particularly relevant in relation to the empirical validation of capabilities, the identification of emergent ones, and the proposed pathways linking DT use to DSI. Broader studies including a more diverse range of organizations may reveal additional dynamics not captured here.

Second, data collection relied on a single informant per case. While both individuals held senior roles with extensive visibility over DT-related initiatives and strategic developments, their views inevitably represent individual interpretations. This approach may constrain the depth and diversity of perspectives captured, particularly concerning internal processes and organizational culture.

Finally, the qualitative nature of the study, although well-suited to uncovering complex interrelationships and context-specific mechanisms, does not allow for the quantification of causal effects between DT capabilities and DSI outcomes. The research offers detailed conceptual insights but does not empirically assess the magnitude or statistical significance of the identified capability linkages.

7. Conclusions and future research lines

This study has examined the role of DT capabilities in driving DSI within organizations. The findings reveal a significant overlap between DT capabilities and those required for DSI, thus providing empirical support for the study's first hypothesis. In addressing the alignment between DT capabilities and the needs for effective DSI deployment, the analysis demonstrates robust convergence across both capability sets. Technical and non-technical dimensions essential for DT development and exploitation, as well as capabilities enabled through DT use, substantially correspond to those necessary for deploying innovative digital services (Figures 3 and 4). This alignment indicates that investments in DT capabilities do not merely enhance digital infrastructures but also initiate a transition from conventional digital transformation toward more innovative, service-oriented business models. Consequently, DTs provide a natural bedrock for achieving DSI.

With respect to the second hypothesis - that organizations utilizing DTs are better positioned for successful DSI - the evidence from both cases confirms that leveraging DT-enabled capabilities, such as scenario analysis, predictive analytics, and resource liquification, significantly enhances service design. Specifically, DTs reinforce strategic alignment by demanding coherence between DT initiatives and overarching business objectives, thus enabling effective complexity management. Additionally, through sophisticated data management, advanced analytical capabilities, and a customer-centric approach, DTs facilitate the delivery of personalized services. DT capabilities not only support the initial implementation of innovative digital services but also promote ongoing organizational learning and agile adaptation, thereby strengthening competitive positioning in dynamic digital ecosystems

Furthermore, in exploring how DT implementation and usage drive organizational readiness for DSI deployment, this study identifies critical enabling capabilities facilitated by DTs. On the technical side, DTs bolster digital agility by encouraging the adoption of advanced technological solutions and the integration of complex systems, which enhances data utilization, advanced visualization, and real-time decision making. From a non-technical perspective, DTs enable strategic alignment and effective complexity management, ensuring close integration between digital initiatives and business goals. Importantly, this research highlights two distinct pathways through which DT capabilities drive innovation in digital services: first, DTs facilitate digital servitization by enhancing knowledge of assets and client needs within their operational context.; second, DT capabilities enhance collaboration, interoperability, and resource liquification, resulting in superior and more effective value co-creation processes. This dual-pathway perspective underscores the multifaceted potential of Digital Twins as strategic enablers of DSI.

Future research could broaden the understanding of Digital Twin (DT) capabilities and their role in Digital Service Innovation (DSI) by examining a larger and more varied sample of organizations from different industries. Expanding the empirical scope would enhance the generalizability of the findings and offer deeper insights into industry-specific dynamics influencing the relationship between DT adoption and DSI outcomes. Additionally, incorporating multiple informants representing diverse organizational roles could mitigate potential biases associated with single-informant data and provide richer, more nuanced perspectives on internal processes and capabilities. Quantitative studies would also contribute significantly by empirically validating the extent to which specific DT capabilities directly influence DSI performance. Such studies could quantify relationships identified qualitatively in this research, thereby strengthening the robustness of conclusions drawn about capability impacts. Lastly, investigating manufacturing firms that are pursuing servitization strategies and also deploying DTs would be particularly valuable, as it could further illuminate the role of DTs as value orchestrators, enabling novel business models and fostering ecosystem-based collaboration.

8. References

Agrawal, A., Fischer, M. and Singh, V. (2022), "Digital twin: From concept to practice", *Journal of Management in Engineering*, Vol. 38 No. 3, p. 06022001.

Akter, S., Hossain, M.A., Sajib, S., Sultana, S., Rahman, M., Vrontis, D. and McCarthy, G. (2023), "A framework for AI-powered service innovation capability: Review and agenda for future research", *Technovation*, Vol. 125, p. 102768.

Awad, J.A.R. and Martín-Rojas, R. (2024), "Digital transformation influence on organisational resilience through organisational learning and innovation", *Journal of Innovation and Entrepreneurship*, Vol. 13, p. 69.

Baines, T. and Lightfoot, H.W. (2013), "Servitization of the manufacturing firm", *International Journal of Operations & Production Management*, Vol. 34 No. 1, pp. 2–35.

Baines, T., Ziaee Bigdeli, A. and Kapoor, K. (2024), "Servitization, advanced services and outcomes", in Servitization Strategy: Delivering Customer-Centric Outcomes Through Business Model Innovation, Springer Nature Switzerland, Cham, pp. 17-48.

Barrett, M., Davidson, E., Prabhu, J. and Vargo, S.L. (2015), "Service innovation in the digital age: key contributions and future directions", *MIS Quarterly*, Vol. 39 No. 1, pp. 135-154.

Barricelli, B.R., Casiraghi, E. and Fogli, D. (2019), "A survey on digital twin: definitions, characteristics, applications, and design implications", *IEEE Access*, Vol. 7, pp. 167653-167671.

Beloglazov, I.I., Petrov, P.A. and Bazhin, V.Y. (2020), "The concept of digital twins for tech operator training simulator design for mining and processing industry", *Chemical Industries*, Vol. 18, p. 19.

Bharadwaj, A., El Sawy, O.A., Pavlou, P.A. and Venkatraman, N.V. (2013), "Digital business strategy: toward a next generation of insights", *MIS Quarterly*, Vol. 37 No. 2, pp. 471-482.

Bolton, A., Butler, L., Dabson, I., Enzer, M., Evans, M., Feeney, T., Housley, E., Kilpatrick, A., Luck, H., Pawsey, N., Schooling, J., Sharp, M., Smith, H., Tennison, J. and Whyte, J. (2018), *The Gemini Principles*, Centre for Digital Built Britain, available at: https://www.cdbb.cam.ac.uk [Accessed 18 Nov. 2024].

Broo, D.G., Bravo-Haro, M. and Schooling, J. (2022), "Design and implementation of a smart infrastructure digital twin", *Automation in Construction*, Vol. 136, p. 104171.

Burton, J., Story, V.M., Zolkiewski, J. and Nisha, N. (2024),** "Digital service innovation challenges faced during servitization: a multi-level perspective", *Journal of Service Management*, Vol. 35 No. 2, pp. 202-226.

Bustinza, O.F., Opazo-Basaez, M. and Tarba, S. (2022), "Exploring the interplay between Smart Manufacturing and KIBS firms in configuring product-service innovation performance", *Technovation*, Vol. 118, p. 102258.

Bustinza, O.F., Molina, L.M., Vendrell-Herrero, F. and Opazo-Basaez, M. (2024), “AI-enabled smart manufacturing boosts ecosystem value capture: The importance of servitization pathways within digital-intensive industries”, *International Journal of Production Economics*, Vol. 277, p. 109411.

Chin, H., Marasini, D.P. and Lee, D. (2023), “Digital transformation trends in service industries”, *Service Business*, Vol. 17 No. 1, pp. 11-36.

Coreynen, W., Matthyssens, P., Struyf, B. and Vanhaverbeke, W. (2024), “Spiraling between learning and alignment toward digital service innovation”, *Journal of Service Management*, Vol. 35 No. 2.

Corbin, J. and Strauss, A. (2015), *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory* (4th ed.), SAGE Publications, Newbury Park, CA.

Crespi, N., Drobot, A.T. and Minerva, R. (2023), “The digital twin in action and directions for the future”, in The Digital Twin, Springer, Cham.

Denzin, N.K. (1978), *The Research Act: A Theoretical Introduction to Sociological Methods* (2nd ed.), McGraw-Hill.

Edvardsson, B., Kleinaltenkamp, M., Tronvoll, B., McHugh, P. and Windahl, C. (2014), “Institutional logics matter when coordinating resource integration”, *Marketing Theory*, Vol. 14 No. 3, pp. 291-309.

Eisenhardt, K.M. (1989), “Building theories from case study research”, *Academy of Management Review*, Vol. 14 No. 4, pp. 532–550.

Ferko, E., Bucaioni, A. and Behnam, M. (2022), “Architecting digital twins”, *IEEE Access*, Vol. 10, pp. 50335-50350.

Finlay, L. (2002), “Negotiating the swamp: the opportunity and challenge of reflexivity in research practice”, *Qualitative Research*, Vol. 2 No. 2, pp. 209–230.

Fukawa, N. and Rindfleisch, A. (2023), “Enhancing innovation via the digital twin”, *Journal of Product Innovation Management*, Vol. 40 No. 4, pp. 391-406.

Fuller, A., Fan, Z., Day, C. and Barlow, C. (2020), “Digital twin: enabling technologies, challenges and open research”, *IEEE Access*, Vol. 8, pp. 108952-108971.

Galera-Zarco, C. (2022), “Unleashing the potential of digital twin in offering green services”, in *Competitive Advantage in the Digital Economy (CADE 2022)*, Venice, Italy, pp. 158-161.

Galera-Zarco, C. (2024), “Digital twin and services: a theoretical development framework”, *2024 IEEE Technology and Engineering Management Society (TEMSCON LATAM)*, Panama, pp. 1-6.

Galera-Zarco, C. and Papadonikolaki, E. (2023), “Digital twin-based services: a taxonomy”, in *International Conference on AI and the Digital Economy (CADE 2023)*, pp. 98-102.

Greenhalgh, T., Robert, G., Macfarlane, F., Bate, P. and Kyriakidou, O. (2004), “Diffusion of innovations in service organizations: systematic review and recommendations”, *The Milbank Quarterly*, Vol. 82 No. 4, pp. 581-629.

Grieves, M. (2014), “Digital twin: manufacturing excellence through virtual factory replication”, White Paper, pp. 1-7.

Grieves, M. and Vickers, J. (2016), "Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems", in Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches, Springer, Cham, pp. 85–113.

Gummesson, E. (2006), "Qualitative research in management: addressing the complexity of the business reality", *Management Decision*, Vol. 44 No. 2, pp. 167-179.

Heller, J., Chylinski, M., de Ruyter, K., Keeling, D.I., Hilken, T. and Mahr, D. (2021), "Tangible service automation: decomposing the technology-enabled engagement process (TEEP) for augmented reality", *Journal of Service Research*, Vol. 24 No. 1, pp. 84–103.

Jamwal, A., Agrawal, R. and Sharma, M. (2022), "Deep learning for manufacturing sustainability: models, applications in Industry 4.0 and implications", *International Journal of Information Management Data Insights*, Vol. 2 No. 2, p. 100107.

Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. (2020), "Characterising the digital twin: a systematic literature review", *CIRP Journal of Manufacturing Science and Technology*, Vol. 29, pp. 36-52.

Kamalaldin, A., Linde, L., Sjödin, D. and Parida, V. (2020), "Transforming provider–customer relationships in digital servitization: a relational view on digitalization", *Industrial Marketing Management*, Vol. 89, pp. 306-325.

Kang, H.S., Lee, J.Y., Choi, S., Kim, H., Park, J.H., Son, J.Y., Kim, H.J. and Noh, S.D. (2016), "Smart manufacturing: past research, present findings, and future directions", *International Journal of Precision Engineering and Manufacturing-Green Technology*, Vol. 3 No. 1, pp. 111-128.

Kohtamäki, M., Parida, V., Oghazi, P., Gebauer, H. and Baines, T. (2020), "Digital servitization business models in ecosystems: a theory of the firm", *Journal of Business Research*, Vol. 104, pp. 380-392.

Kohtamäki, M., Parida, V., Rabetino, R., Sjödin, D. and Henneberg, S. (2022), "Framing the digital servitization path towards autonomous solutions", in *Achieving Net-Zero through Servitization: Proceedings of the Spring Servitization Conference*, Aston Business School, pp. 1-6.

Kraus, S., Palmer, C., Kailer, N., Kallinger, F.L. and Spitzer, J. (2021), "Digital transformation: an overview of the current state of the art of research", *SAGE Open*, Vol. 11 No. 3, p. 21582440211047576.

Kreye, M.E. (2022), "When servitized manufacturers globalise: becoming a provider of global services", *International Journal of Operations and Production Management*, Vol. 42 No. 10, pp. 1521-1543.

Kritzinger, W., Karner, M., Traar, G., Henjes, J. and Sihn, W. (2018), "Digital twin in manufacturing: a categorical literature review and classification", *IFAC-PapersOnLine*, Vol. 51 No. 11, pp. 1016-1022.

Kumar, R., Abrougui, K., Verma, R., Luna, J., Khattab, A. and Dahir, H. (2023), "Digital twins for decision support system for clinicians and hospital to reduce error rate", in Digital Twin for Healthcare, Elsevier, Amsterdam, pp. 241–261.

Lehner, D., Pfeiffer, J., Tinsel, E.F., Strljic, M.M., Sint, S., Vierhauser, M., Wortmann, A. and Wimmer, M. (2021), "Digital twin platforms: requirements, capabilities, and future prospects", *IEEE Software*, Vol. 39 No. 2, pp. 53-61.

Lehrer, C., Wieneke, A., Vom Brocke, J., Jung, R. and Seidel, S. (2018), "How big data analytics enables service innovation: materiality, affordance, and the individualization of service", *Journal of Management Information Systems*, Vol. 35 No. 2, pp. 424-460.

Lu, Q., Parlikad, A.K., Woodall, P., Don Ranasinghe, G., Xie, X., Liang, Z., Konstantinou, E., Heaton, J. and Schooling, J. (2020), "Developing a digital twin at building and city levels: case study of West Cambridge campus", *Journal of Management in Engineering*, Vol. 36 No. 3, pp. 1–19.

Lusch, R.F. and Nambisan, S. (2015), "Service innovation", *MIS Quarterly*, Vol. 39 No. 1, pp. 155-176.

Lusch, R.F. and Vargo, S.L. (2014), *Service-Dominant Logic: Premises, Perspectives, Possibilities*, Cambridge University Press, New York, NY.

Martinez, V. and Huss, N.F. (2022), "Digital twins: thought leadership in the satellite industry", *University of Cambridge*.

Meierhofer, J. and West, S. (2019), "Service value creation using a digital twin", in *Naples Forum on Service, Service Dominant Logic, Network & Systems Theory and Service Science: Integrating Three Perspectives for a New Service Agenda*, Ischia, Italy, pp. 4-7.

Meierhofer, J., West, S., Rapaccini, M. and Barbieri, C. (2020), "The digital twin as a service enabler: from the service ecosystem to the simulation model", in Exploring Service Science: 10th International Conference, IESS 2020, Springer International Publishing, pp. 347-359.

Minerva, R., Lee, G.M. and Crespi, N. (2020), "Digital twin in the IoT context: a survey on technical features, scenarios, and architectural models", *Proceedings of the IEEE*, Vol. 108 No. 10, pp. 1785-1824.

Moyne, J., Qamsane, Y., Balta, E.C., Kovalenko, I., Faris, J., Barton, K. and Tilbury, D.M. (2020), "A requirements driven digital twin framework: specification and opportunities", *IEEE Access*, Vol. 8, pp. 107781-107801.

Myers, M.D. and Newman, M. (2007), "The qualitative interview in IS research: Examining the craft", *Information and Organization*, Vol. 17 No. 1, pp. 2-26.

Negri, E., Fumagalli, L. and Macchi, M. (2017), "A review of the roles of digital twin in CPS-based production systems", *Procedia Manufacturing*, Vol. 11, pp. 939-948.

Nicoletti, L. and Padovano, A. (2019), "Ubiquitous knowledge empowers the smart factory: the impacts of a service-oriented digital twin on enterprises' performance", *Annual Reviews in Control*, Vol. 47, pp. 221-236.

Nylén, D. and Holmström, J. (2015), "Digital innovation strategy: a framework for diagnosing and improving digital product and service innovation", *Business Horizons*, Vol. 58 No. 1, pp. 57-67.

Opazo-Basáez, M., Bustinza, O.F. and Molina, L.M. (2024a), "The effect of industrial solution services (ISS) on innovation performance: The moderating role of sustainable development goals (SDGs)", *Journal of Cleaner Production*, Vol. 455, p. 142265.

Opazo-Basáez, M., Vendrell-Herrero, F., Bustinza, O.F. and Raddats, C. (2024b), "Guest editorial: digital service innovation: ontology, context and theory", *Journal of Service Management*, Vol. 35 No. 2, pp. 129-140.

Opazo-Basáez, M., Monroy-Osorio, J.C. and Marić, J. (2024c), “Evaluating the effect of green technological innovations on organizational and environmental performance: A treble innovation approach”, *Technovation*, Vol. 129, p. 102885.

Opazo-Basáez, M., Vendrell-Herrero, F. and Bustinza, O.F. (2022), “Digital service innovation: a paradigm shift in technological innovation”, *Journal of Service Management*, Vol. 33 No. 1, pp. 97-120.

Opazo-Basáez, M., Vendrell-Herrero, F., Bustinza, O.F., Vaillant, Y. and Marić, J. (2023), “Is digital transformation equally attractive to all manufacturers? Contextualizing the operational and customer benefits of smart manufacturing”, *International Journal of Physical Distribution & Logistics Management*, Vol. 53 No. 4, pp. 489-511.

Patton, M.Q. (2015), *Qualitative Research & Evaluation Methods* (4th ed.), SAGE Publications, Thousand Oaks, CA.

Plummer, D., Kearney, S., Monagle, A., Collins, H., Perry, V., Moulds, A., Mroczka, M., Robertson, J., Smith, T., Trewavas, S. and Lewis, C. (2021), “Skills and competency framework—supporting the development and adoption of the information management framework (IMF) and the national digital twin”, *Centre for Digital Built Britain*.

Porter, M.E. and Heppelmann, J.E. (2014), “How smart, connected products are transforming competition”, *Harvard Business Review*, Vol. 92 No. 11, pp. 64–88.

Rabah, S., Zacharewicz, G. and Chapurlat, V. (2022), “Digital twin for services (DT4S): conceptual strategy”, *IFAC-PapersOnLine*, Vol. 55 No. 10, pp. 3256-3261.

Rabetino, R., Kohtamäki, M. and Huikkola, T. (2024), “Digital service innovation (DSI): a multidisciplinary (re) view of its origins and progress using bibliometric and text mining methods”, *Journal of Service Management*, Vol. 35 No. 2, pp. 176-201.

Raddats, C., Naik, P. and Bigdeli, A.Z. (2022), “Creating value in servitization through digital service innovations”, *Industrial Marketing Management*, Vol. 104, pp. 1-13.

Raj, A., Dwivedi, G., Sharma, A., de Sousa Jabbour, A.B.L. and Rajak, S. (2020), “Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: an inter-country comparative perspective”, *International Journal of Production Economics*, Vol. 224, p. 107546.

Rosen, R., von Wichert, G., Lo, G. and Bettenhausen, K.D. (2015), “About the importance of autonomy and digital twins for the future of manufacturing”, *IFAC-PapersOnLine*, Vol. 48 No. 3, pp. 567-572.

Rothenberger, M. and Srite, M. (2009), “An investigation of customization in ERP system implementations”, *IEEE Transactions on Engineering Management*, Vol. 56 No. 4, pp. 663–676.

Schleich, B., Anwer, N., Mathieu, L. and Wartzack, S. (2017), “Shaping the digital twin for design and production engineering”, *CIRP Annals*, Vol. 66 No. 1, pp. 141-144.

Serrano-Ruiz, J.C., Ferreira, J., Jardim-Goncalves, R., et al. (2024), “Relational network of innovation ecosystems generated by digital innovation hubs: a conceptual framework for the interaction processes of DIHs from the perspective of collaboration within and between their relationship levels”, *Journal of Intelligent Manufacturing*.

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A. and Calinescu, A. (2022), "Digital twins: state of the art theory and practice, challenges, and open research questions", *Journal of Industrial Information Integration*, Vol. 30, p. 100383.

Sjödin, D., Parida, V., Kohtamäki, M. and Wincent, J. (2020), "An agile co-creation process for digital servitization: a micro-service innovation approach", *Journal of Business Research*, Vol. 112, pp. 478-491.

Soto Setzke, D., Riasanow, T., Böhm, M. et al. (2023), "Pathways to digital service innovation: the role of digital transformation strategies in established organizations", *Information Systems Frontiers*, Vol. 25, pp. 1017–1037.

Story, V.M., Raddats, C., Burton, J., Zolkiewski, J. and Baines, T. (2017), "Capabilities for advanced services: a multi-actor perspective", *Industrial Marketing Management*, Vol. 60, pp. 54-68.

Tao, F., Zhang, H., Liu, A. and Nee, A.Y.C. (2018a), "Digital twin in industry: state-of-the-art", *IEEE Transactions on Industrial Informatics*, Vol. 15 No. 4, pp. 2405-2415.

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H. and Sui, F. (2018b), "Digital twin-driven product design, manufacturing and service with big data", *The International Journal of Advanced Manufacturing Technology*, Vol. 94, pp. 3563-3576.

Trauer, R., Bravo-Haro, M. and Schooling, J. (2022), "A digital twin trust framework for industrial application", *Journal of Industrial Information Integration*, Vol. 26, p. 100257.

Tripathi, N., Hietala, H., Xu, Y. and Liyanage, R. (2024), "Stakeholders collaborations, challenges and emerging concepts in digital twin ecosystems", *Information and Software Technology*, p. 107424.

Uhlemann, T.H.J., Lehmann, C. and Steinhilper, R. (2017), "The digital twin: realizing the cyber-physical production system for Industry 4.0", *Procedia CIRP*, Vol. 61, pp. 335-340.

Vargo, S.L. and Lusch, R.F. (2004), "Evolving to a new dominant logic for marketing", *Journal of Marketing*, Vol. 68 No. 1, pp. 1-17.

Vargo, S.L., Fehrer, J.A., Wieland, H. and Nariswari, A. (2024), "The nature and fundamental elements of digital service innovation", *Journal of Service Management*, Vol. 35 No. 2.

Vargo, S.L., Maglio, P.P. and Akaka, M.A. (2008), "On value and value co-creation: a service systems and service logic perspective", *European Management Journal*, Vol. 26 No. 3, pp. 145-152.

Vendrell-Herrero, F., Bustinza, O.F. and Parry, G. (2021), "Digital business model innovation in SMEs: leveraging dynamic capabilities and tangible assets through digital technologies", *Journal of Business Research*, Vol. 123, pp. 289-301.

Vendrell-Herrero, F., Bustinza, O.F., Parry, G. and Georgantzis, N. (2017), "Servitization, digitization and supply chain interdependency", *Industrial Marketing Management*, Vol. 60, pp. 69-81.

Vendrell-Herrero, F., Para-González, L., Mascaraque-Ramírez, C. and Freixanet, J. (2024), "The order of the factors matters: how digital transformation and servitization integrate more efficiently", *International Journal of Production Economics*, Vol. 271, p. 109228.

Vial, G. and Grange, C. (2024), “Conceptualizing digital service: coconstitutive essence and value cocreation dynamics”, *Journal of Service Management*, Vol. 35 No. 3, pp. 408-437.

Wang, Y., Tian, Q., Li, X. and Xiao, X. (2022), “Different roles, different strokes: how to leverage two types of digital platform capabilities to fuel service innovation”, *Journal of Business Research*, Vol. 144, pp. 1121-1128.

West, S., Stoll, O., Meierhofer, J. and Züst, S. (2021), “Digital twin providing new opportunities for value co-creation through supporting decision-making,” *Applied Sciences*, Vol. 11 No. 9, p. 3750.

Xiao, X., Tian, Q. and Mao, H. (2020), “How the interaction of big data analytics capabilities and digital platform capabilities affects service innovation: A dynamic capabilities view”, *IEEE Access*, Vol. 8, pp. 18778-18796.

Items	Reviewer 1's comments	Responses
1	The article needs to be adjusted in length as it goes far beyond the length recommended by the journal's guidelines for authors. Particularly section 4, in my opinion, is excessively long, repeating (albeit in an orderly fashion) all the analyses in both cases, making it unattractive and repetitive. Furthermore, the enormous wealth and insights gained by the analysis of the cases are not used to indicate the causes of the results.	The authors thank the feedback regarding the length of the submitted version. We have worked in reducing the total numbers of words from the previous 15,322 words to 11,193 words in the reviewed version. In particular, following the indications, we have refurbished completely section 4 "Findings and Analysis" to avoid repetitive content and structure and focus on the insights gained from the individual case and cross-case analysis. We also reduced the number of tables in this section. Please, check section 4 in the new version of the manuscript.
2	In the methodology, hardly any information is given about the interviewee. It is not clear that he/she has the right profile, especially in the case of company A where it is not justified how it is ensured that he/she has the required vision and experience. It would be good if some aspects of his profile could be indicated to show that he justifies his selection.	Many thanks for your insightful comments. Methodology section has been improved. In relation to interviewees selection, we added the following in section 3, p.11. Regarding case CompA: *"The primary informant for this case was a Digital Twin consultant and Business & IT architect, selected due to extensive experience in managing DT-related projects across multiple industries, their involvement in strategic initiatives related to digital transformation, and comprehensive understanding of organizational capabilities required for effective DT implementation and use."* Regarding case CompB: *"The key informant interviewed was the co-founder and chief growth officer, whose strategic leadership role and direct involvement in client engagement across multiple sectors provided valuable insights. The informant was selected due to a deep understanding of the technical, strategic, and organizational capabilities required for DT development and their alignment with broader goals such as DSI."*

3	Finally, some formal issues: Typo in Appendix 4 in one of the interviewees' quotes: "...n ow I see new needs come up with customers such as data monetization…" ; in section 7, p. 27-28 "addressing or first research" and in section 2.2.1 "The presence of strong leadership from executive teams is vital for the successful integration and utilization of DTs within an organization In line with (Negri et al., 2017; Martinez & Huss, 2022). There are some words in bold.	Thank you for your detailed comments about formal issues. The new version has been carefully reviewed and professionally proofread to avoid typos and format issues.
4	The other reviewer's suggestion to incorporate the place of insertion of tables and figures has been misinterpreted by the authors.	Many thanks for your very valid point. The issue with the suggestion on the place of insertion of tables and figures have been now correctly interpreted and amended.

Items	Reviewer 2's comments	Responses
1	Section 1: Introduction In the introduction section of the paper the writing style tends to be informal and lacks the depth and rigor expected in academic writing. The text sometimes uses conversational phrases and redundant statements that detract from the academic tone. To enhance the clarity and academic rigor, the introduction could benefit from a more structured and concise presentation of key concepts and research objectives. For instance, sentences could be more straightforward, avoiding overly complex structures that can obscure the main points. The use of passive voice could be minimized to create a more active and engaging narrative. Additionally, the integration of citations should be more precise and seamlessly woven into the text, providing clear support for each claim without interrupting the flow of the argument. Recommendations: Refine the Writing Style: Adopt a more formal and academic tone by eliminating conversational phrases and redundant statements. Ensure that each sentence contributes directly to advancing the argument or providing essential background information. Enhance Clarity and Structure: Break down complex sentences into simpler, more digestible parts. Use clear and direct language to articulate the significance of DSI and DTs. Ensure that each paragraph transitions smoothly to the next, maintaining a logical flow of ideas. Improve Citations and Integration: Integrate	The authors thank the valuable comments given by the reviewer about the introduction section. This section has been completely refurbished following all your recommendations to provide a better logical flow of ideas and creating a more engaging narrative. Also, authors improve integration of citations throughout the whole document. Please, check the improved section 1 in the resubmitted version of the manuscript.

	citations more naturally into the text. Ensure that each claim is directly supported by relevant literature, enhancing the credibility and scholarly tone of the introduction.	
2	Section 2: Theoretical Framework The theoretical framework attempts to establish a solid base, nontheless this section suffers from issues of coherence and organization, often presenting disordered ideas that can confuse the reader. The writing style remains inconsistent, oscillating between formal and informal tones, which further impacts the clarity and perceived rigor of the analysis. To address these issues, the theoretical framework should be reorganized to present a clear and logical progression of ideas. Start with a concise definition of key terms, followed by a structured exploration of their interrelationships and implications. Ensure that each subsection clearly addresses specific aspects of the theoretical foundation, using headings and subheadings effectively to guide the reader through the arguments.	Many thanks for your insightful comments about the section 2: Theoretical Background. Following the recommendations, authors have re-structure the section improving the writing style and enhancing clarity and rigor of our statements. We particularly focus on providing clear definitions and explanations of key concepts. For instance, section 2.3 "Conceptualizing Digital Service Innovation and its enabling capabilities" includes now a contextualization and definition of Digital Service Innovation. Also, section 2.4 Research gap identification and conceptual framework development was thoroughly improved to highlighting gaps, and explaining how the current research addresses these gaps. We have also included new references to provide clear theoretical foundations. Please, check the new version of section 2 in the resubmitted manuscript.

	Recommendations for Improvement: Improve Coherence and Organization: Structure the section with clear headings and subheadings that delineate different aspects of the theoretical framework. Ensure each subsection logically follows from the previous one, building a coherent narrative that supports the research objectives. Maintain a Formal Academic Tone: Consistently use formal academic language throughout the section. Avoid informal expressions and ensure that the writing style is appropriate for a scholarly audience. Clarify and Deepen Analysis: Provide clear definitions and explanations of key concepts. Deepen the analysis by critically engaging with relevant literature, highlighting gaps, and explaining how the current research addresses these gaps. Ensure that all arguments are clearly supported by evidence from the literature.	
3	Review of Section 3: Methodology The methodology section covers the essential components required for a robust research methodology. Still, there are areas where the description could be expanded to enhance clarity and provide more detailed insights. This section should ensure that the reader understands the research design, procedures, and justifications for the chosen methods. Recommendations for Improvement Expand Data Collection Description: The methodology section should include a detailed account of the data collection procedures. This involves elaborating on the development and use of the semi-structured interview guide, specifying the number of	Thank you for your considerable comments around the methodology section. This section has been re-written to clarify the research design and procedures, data collection and analytical techniques. In particular, regarding data collection, new section 3 state: *"Data were primarily collected through semi-structured interviews supplemented by secondary sources, including internal company documentation, presentations provided by the interviewees, and publicly available material from organizational websites. Interviewees' experience, their central roles and comprehensive knowledge of both technical and organizational dimensions enabled the collection of rich and detailed data directly relevant to the study's objectives. Interviews took place in March and April 2024 via video conferencing platforms, each lasting between 60 and 90 minutes. An interview guide (see Appendix A) was developed to*

	interviews conducted, their duration, and the process for selecting and recruiting participants. Provide Justification for Case Selection: Include a detailed explanation of the criteria for case selection and how the selected organizations represent the broader population of firms using DT technologies. This can involve discussing the industry relevance, size, and technological engagement of the organizations. Detail Analytical Techniques: Provide a thorough description of the analytical techniques used in both within-case and cross-case analyses. This should include how data were coded and categorized, the use of any qualitative data analysis software, and the specific steps taken to ensure the reliability and validity of the analysis. Incorporate Methodological References: Strengthen the methodology section by referencing relevant methodological literature. This includes citing key texts on case study research, qualitative data analysis, and triangulation.	*maintain consistency across cases while allowing flexibility to explore emergent themes (Myers & Newman, 2007).The interviews addressed five areas: 1) capabilities required to develop and exploit DTs, 2) capabilities achieved through DTs, 3) the role of DTs in deploying DSI, 4) organizational culture, and 5) DT implementation goals. After covering the first two areas, the researchers presented the capability tables (Tables 1–6) and initial versions of capability interrelationship frameworks (Figures 1 and 2) which were developed by the authors through a combination of literature review and the authors' interpretive analysis of existing research. Participants were invited to validate these findings and contribute additional insights. After incorporating their inputs, the interrelationship figure was sent back to the interviewees via email for final feedback to ensure accuracy and completeness. All interviews were video-recorded with the consent of the participants and transcribed verbatim for analysis"* With respect to analytical techniques: *"A systematic analytical strategy was employed, integrating both within-case and cross-case analysis techniques (Eisenhardt, 1989). In the first phase the transcribed interview data were analyzed on a case-by-case basis to construct a detailed understanding of DT and DSI capabilities within each organizational context. This was followed by a cross-case analysis aimed at identifying shared patterns, divergences, and overarching themes across the two cases.* *The qualitative data analysis followed an iterative coding process. Initial coding drew upon the capability sets identified from the literature while remaining open to new insights through inductive open coding. These initial codes were then refined through axial coding, which facilitated the clustering of themes into broader categories relevant to the study's focus on capabilities (Corbin & Strauss, 2015). This approach enabled a structured yet flexible examination of both theoretically grounded and emergent capabilities. To strengthen the validity and reliability of the findings, two strategies were employed. Triangulation was achieved by incorporating the previously mentioned secondary data to corroborate and contextualize the interview data (Denzin, 1978). Additionally, reflexivity was maintained throughout the research process. The researchers engaged in*

		continuous critical reflection on their assumptions, interpretations, and potential biases to ensure a more objective and nuanced analysis (Finlay, 2002).” Finally, authors sstrengthen the methodology section by adding two new references relevant to our methodology : Myers, M.D. and Newman, M., 2007. The qualitative interview in IS research: Examining the craft. Information and organization, 17(1), pp.2-26. Corbin, J., & Strauss, A. 2015. Basics of qualitative research: Techniques and procedures for developing grounded theory (4th ed.). Newbury Park: Sage.
4	Review of Section 4: Analysis and Results The Analysis and Results section presents significant opportunities to be improved. While the section provides detailed descriptions of the findings, it could benefit from deeper analytical insights. For instance, the discussion on how specific DT capabilities impact DSI could be expanded to include more critical analysis and interpretation of the data. Also, the section should more explicitly link the findings back to the research questions posed in the introduction. This would help in demonstrating how the results address the study's objectives and contribute to the existing literature. Final thing: Incorporating direct quotations from the interviewees could enrich the analysis by providing concrete examples and insights from the participants.	Thank you so much for your general recommendations to improve this section. We consider that these suggestions improve our results significatively. Authors have followed thoughtfully your advice to improve the structure, coherence and focus of the Findings and Analysis section. - The section is now more critical, linking results to the context of the cases Authors explicitly linked findings back to the research questions by following a new structure that include subsection 4.2.1 *The extent to which DT capabilities align with those required for DSI deployment*, aligned with the first research question of the study and the subsection *4.2.2 Leveraging DT capabilities for DSI deployment*, with a clear connection with the second research question of this study. Authors Incorporated direct quotations from the interviewees to enrich the analysis by providing concrete examples and insights from the participants. In the resubmitted version, section *4.2 Understanding the role of DTs in DSI deployment* is filled with relevant quotations. .

5	One last thing: I believe my comment on how to present the tables was misunderstood.	Thank you for your comment around how to present tables and figures in text. Now, this has been correctly understood and simply include – insert table/figure – between paragraphs.
6	A strong recommendation is the use of an academic proof-reader .	Thank you so much for your general recommendations to improve the readability of the manuscript. This version has been professionally proofread to eliminate grammar issues and typos.

Capability	Description in the context of DT development and exploitation	References
Data Management and Analytics	Efficient management of large volumes of data, including its collection, storage, processing, and analysis, to extract actionable insights. This includes implementing robust data governance practices to ensure data quality, accessibility, and compliance.	Agrawal et al. (2022); Tao et al. (2018b)
Integration of Heterogeneous Systems and Technologies	Integrating diverse technologies, such as AI, IoT devices, legacy systems, and external data sources, to ensure the DT accurately replicates its physical counterpart and maintains dynamic consistency with real-world processes.	Barricelli et al. (2019); Rosen et al. (2015)
Modeling	Technological ability to model physical assets or processes using software tools that replicate the physical counterpart. This ensures accurate digital representations to serve as a foundation for simulations and analyses.	Schleich et al. (2017)
Simulation Abilities	Use of advanced simulation technologies to run "what-if" scenarios and test changes or optimizations in the digital twin. This supports decision-making, risk management, and operational optimization without disrupting the physical counterpart.	Schleich et al. (2017); Barricelli et al. (2019)
Cybersecurity & Data Privacy	Implementing strong measures to safeguard sensitive data and critical operations associated with DTs. This ensures protection against cyber threats, preserves system integrity, and maintains the trust and reliability of DT operations.	Jones et al. (2020); Plummer et al. (2021); Agrawal et al. (2022)
Data Interoperability and Development/Use of Digital Platforms	Establishing seamless integration and communication within digital ecosystems, including compatibility with various data formats, protocols, and interfaces. This capability ensures robust data exchange and facilitates the creation and operation of interconnected digital platforms.	Agrawal et al. (2022); Barricelli et al. (2019); Plummer et al. (2021)

Table 1: Key technical capabilities for the development and exploitation of Digital Twins

Capability	Description in the context of DT development and exploitation	References
Strategic Alignment and Complexity Management	Strong leadership ensures that DT initiatives align with broader business objectives, providing a strategic vision that guides technological investments toward tangible business outcomes. Leaders must manage the inherent complexity of DT projects, minimizing disruption during implementation while maximizing their contribution to organizational goals.	Negri et al. (2017); Martinez & Huss (2022); Plummer et al. (2021); Kritzinger et al. (2018)
Effective Communication and Collaboration / Stakeholder Management	Facilitating communication and collaboration across diverse departments, such as IT, operations, and engineering, is crucial for successful DT projects. Engaging diverse stakeholders to effectively ensure alignment of interests, knowledge sharing, and cooperation.	Uhlemann et al. (2017); Plummer et al. (2021); Tripathi et al. (2024)
Building and Maintaining Trust	Trust is fundamental for DT acceptance and effective use. This includes confidence in data integrity, system reliability, and overall DT performance. Stakeholder trust, particularly when sensitive data must be shared across domains, relies on transparency and reliability.	Broo et al. (2022); Tripathi et al. (2024); Plummer et al. (2021); Trauer et al. (2022)
Organizational Learning and Adaptation	Establishing a culture of continuous learning and adaptability enables organizations to effectively integrate emerging technologies and insights provided by DTs. This ensures businesses remain competitive and responsive to challenges and opportunities that arise during the lifecycle of DT development and exploitation.	Tao & Qi (2019)

Table 2: Key technical non-capabilities for the development and exploitation of Digital Twins

Capability	Description in the context of DT usage	References
Real-Time Monitoring and Control	DTs provide immediate responses to system changes and anomalies through real-time, accurate representations of physical processes, enhancing decision-making speed and reliability.	Galera-Zarco (2022); Tao & Qi (2019); Uhlemann et al. (2017)
Operational Optimization	DTs enhance operational efficiency by utilizing data-driven insights to reduce resource wastage and improve workflows, contributing to streamlined processes and environmental sustainability.	Galera-Zarco (2022); Uhlemann et al. (2017);
Predictive Analysis	DTs leverage predictive analytics to analyze data trends and foresee potential outcomes, enabling organizations to anticipate issues, optimize processes, and reduce risks proactively.	Agrawal et al., 2022; Grieves, 2014
Scenario Analysis for Decision-Making	DTs enable organizations to simulate "what-if" scenarios, allowing them to predict outcomes, assess risks, and support strategic decision-making with a virtual representation of physical assets.	Schleich et al. (2017); Tao & Qi (2019)
Data Interoperability and Development/Use of Digital Platforms	DTs enable seamless data exchange and integration across diverse systems and platforms, supporting interconnected digital ecosystems for comprehensive and cohesive operational insights.	Agrawal et al. (2022); Uhlemann et al. (2017)

Table 3: Key technical capabilities achieved through Digital Twin usage

Capability	Description in the context of DT usage	References
Strategic Decision-Making Support	DTs enable organizations to test and predict outcomes without risking physical assets, fostering strategic decision-making by simulating scenarios and exploring various operational strategies.	Broo et al. (2022); Rosen et al. (2015);
Optimization of Design and Development Processes	DTs facilitate rapid prototyping and virtual testing, significantly reducing time-to-market and enhancing product quality, thereby optimizing the design and development of new products and systems.	Schleich et al. (2017)
Sustainable Practices and Waste Reduction	DTs support sustainability by optimizing resource use, reducing waste, and promoting environmentally friendly processes through data-driven insights and simulations.	Galera-Zarco, (2022)
Educational and Training Applications	DTs provide realistic, risk-free environments for skills development and operational training, preparing a skilled workforce and enhancing readiness for industrial applications.	Beloglazov et al. (2020); Kang et al. (2016)
Collaboration Across Departments and Ecosystems	DTs drive collaboration by creating a unified platform for real-time information sharing across departments, such as R&D, operations, and supply chain, as well as across organizational ecosystems, enhancing cross-functional and external collaboration.	Tao et al. (2019); Uhlemann et al. (2017)
Customer-Centric Approach	DTs enable organizations to simulate customer experiences and create tailored solutions, fostering unique and effective interactions. By providing personalized services and engaging customer experiences, DTs enhance satisfaction and loyalty.	Barricelli et al. (2019); Broo et al. (2022); Galera-Zarco, (2024)

Table 4: Key non-technical capabilities achieved through Digital Twins usage

Capability	**Description in the context of DSI**	**References**
Digital Agility	The ability to adopt emerging technologies, adapt them to specific operational contexts, and leverage them to enhance service offerings and maintain competitiveness.	Barrett et al. (2015); Lehrer et al. (2018); Kohtamäki et al. (2020); Rabetino et al. (2024)
Technology Integration into Service Frameworks	Ensuring seamless integration of digital technologies into existing service frameworks to create efficient, comprehensive, and user-focused digital service systems.	Rabetino et al. (2024); Kohtamäki et al. (2019)
Data Management and Analytics	Managing and analyzing large data volumes to extract actionable insights, improve decision-making, and enhance service delivery, enabling service personalization and optimization.	Opazo-Basáez et al. (2022); Lehrer et al. (2018); Barrett et al. (2015); Raddats et al., (2022)
Integration of Heterogeneous Systems and Technologies	Incorporating diverse technological advancements such as IoT, AI, and big data analytics to enable and enhance service offerings across industries and operational contexts.	Rabetino et al. (2024); Kohtamäki et al. (2020) ; Vendrell-Herrero et al. (2017)
Data Interoperability and Development/Use of Digital Platforms	Leveraging digital platforms to integrate various digital services and technologies, offering scalable and flexible solutions tailored to diverse customer needs.	Kohtamäki et al. (2022)
Cybersecurity & Data Privacy	The ability to safeguard digital services and customer data from cyber threats and unauthorized access, ensuring trust, compliance, and reliability in digital service offerings.	Lusch and Nambisan (2015); Kraus et al. (2021)

Table 5: Key technical capabilities for deploying Digital Service Innovation

Capability	Description in the context of DSI	References
Organizational Learning and Adaptation	Continuous improvement and adaptation to technological advancements and changing market conditions for successful implementation of DSI, ensuring iterative learning and strategy adjustments for effective deployment of digital technologies.	Awad & Martin-Rojas (2024); Coreynen et al. (2024); Sjödin, et al., 2020 ; Nylén & Holmström (2015); Sjödin, et al. (2020)
Effective Communication and Collaboration / Participation in Collaborative Ecosystems	Involvement in partnerships with firms, clients, and stakeholders to foster innovation and enable effective service offerings through collaboration within service ecosystems.	Serrano-Ruiz et al. (2024); Vargo et al. (2024)
Co-Creation Value Management	Accurate management of co-creation processes to drive innovation, enhance value, and leverage external resources within service ecosystems to create impactful service offerings.	Serrano-Ruiz et al. (2024); Vargo et al. (2024)
Strategic Alignment and Complexity Management	Ensuring alignment of digital initiatives with overall business strategies to support broader objectives, while managing the complexities inherent in DSI transformations, fostering strategic coherence across organizational levels.	Awad & Martin-Rojas (2024); Rabetino et al. (2024)
Resource Liquification	Removing barriers and enhancing resource mobility across digital platforms, enabling flexible and responsive DSI through the efficient flow of information and services.	Vargo et al. (2024)
Customer-Centric Approach	Focusing on understanding and meeting customer needs by designing personalized services that enhance experiences and satisfaction, leveraging customer data to inform service design and delivery.	Lehrer et al. (2018); Soto Setzke et al. (2023);

Table 6: Key non-technical capabilities for deploying Digital Service Innovation

Technical DT Capability	**Stage**	**CompA** **Level of support from data analysis**	**CompB** **Level of support from data analysis**
Data Management and Analytics	Develop and Exploit DTs	Completely supported	Completely supported
Integration of Heterogeneous Systems and Technologies	Develop and Exploit DTs	Completely supported	Completely supported
Modeling	Develop and Exploit DTs	Partly supported *The interviewee related modeling capability with two new capabilities: Knowledge Graph and Ontology Management	Partly supported *The interviewee related modeling with the ability to run AI within the models
Simulation Abilities	Develop and Exploit DTs	Completely supported	Completely supported
Cybersecurity & Data Privacy	Develop and Exploit DTs	Not supported *The interviewee validated this capability after showing results from literature review	Completely supported
Data Interoperability and Development/Use of Digital Platforms	Both Develop and Exploit DTs and Achieved through DTs	Completely supported	Completely supported
Operational Optimization	Achieved through DTs	Completely supported	Completely supported
Predictive Analysis	Achieved through DTs	Completely supported	Completely supported
Scenario Analysis for Decision Making	Achieved through DTs	Completely supported	Completely supported
Real-Time Monitoring and Control	Achieved through DTs	Completely supported	Partly supported *While the interviewee focuses on decision support and what-if scenarios, did not explicitly mention real-time monitoring and control

Table 7: Empirical validation of technical Digital Twin capabilities

NEW Technical DT Capability emerged from empirical data	Stage	Description in the context of Digital Twins	Case	Quotations
Knowledge Graphs	Develop and Exploit DTs	The ability to design, implement, and utilize knowledge graphs to enhance data representation by modeling complex relationships and semantics. This enables more intelligent and flexible DTs.	CompA	*"If you want to set up digital twins you can do that based on knowledge graphs... the techniques to work with knowledge graphs have improved immensely, and you can do a lot based on graphs…"*
Ontology Management	Develop and Exploit DTs	Developing and managing ontologies to ensure consistent data representation and interoperability within DTs. This includes defining common vocabularies, data models, and semantic frameworks for integration.	CompA	" (About capabilities to develop a DT)… an important one is really coping with ontologies... it's a very important one, and I think we have developed how to cope with ontologies..."
Edge Computing	Develop and Exploit DTs	Processes data near its source (e.g., IoT devices), reducing latency and bandwidth usage.	CompB	*"So this is one of the most expensive and challenging parts in building a digital twin, because the more data you take on, the more complex the infrastructure management becomes... that's when we start talking about edge computing..."*
Advanced Visualization	Develop and Exploit DTs	Utilization of 3D visualization, augmented reality (AR), virtual reality (VR), and devices like HoloLens to enhance data representation and user interaction in digital twins.	CompB	*"Then all the way to the top, what we call the visualization layer... visualization, it could be anything from 3D visualization, AR, VR... You can put, you know, HoloLenses; you can go as far as that…"*

Table 8: New technical Digital Twin capabilities emerged from the cases

Non-Technical DT Capability	**Stage**	**CompA** **Level of support from data analysis**	**CompB** **Level of support from data analysis**
Strategic Alignment and Complexity Management	Develop and Exploit DTs	Completely Supported	Completely Supported
Effective Communication and Collaboration / Stakeholder Management	Develop and Exploit DTs	Completely Supported	Completely Supported
Building and Maintaining Trust	Develop and Exploit DTs	Partially Supported *The interviewee related Building and Maintaining Trust capability with a new capability: Change Management and Overcoming Organizational Resistance	Partly Supported *The interviewee mostly linked Building Trust to Governance
Organizational Learning and Adaptation	Develop and Exploit DTs	Completely Supported	Completely Supported
Sustainable Practices and Waste Reduction	Achieved through DTs	Not supported *The interviewee validated this capability after showing results from literature review	Partly Supported *The interviewee mentions cost reduction and creating efficiencies but does not specifically discuss sustainability or waste reduction
Strategic Decision-Making Support	Achieved through DTs	Completely supported	Completely Supported
Optimization of Design and Development Processes	Achieved through DTs	Completely supported	Partly Supported *The interviewee discusses process automation and creating efficiencies, but does not specifically address optimization of design and development processes for new products or systems.
Educational and Operational Training	Achieved through DTs	Completely supported	Not Supported *The interviewee validated this capability after showing results from literature review
Collaboration Across Departments and Ecosystems	Achieved through DTs/ Develop and Exploit DTs	Completely supported	Completely Supported
Customer-Centric Approach	Achieved through DTs	Partially Supported *The interviewee linked customer-centric approach with servitization strategy	Completely supported

Table 9: Empirical validation of Non-technical Digital Twin capabilities

NEW Non-Technical DT Capability emerged from empirical data	Stage	Description in the context of Digital Twins	Case	Quotations
Bridging Technical and Business Domains	Develop and Exploit DTs	The ability to connect technical expertise with business objectives, ensuring that DT initiatives align with organizational goals and deliver tangible value. This involves translating technical possibilities into business strategies and integrating DT projects within the broader business context. It also involves multidisciplinary teams that can communicate effectively across technical and non-technical domains	CompA and CompB	*CompA: "* (in using successfully digital twins)…*You need to understand the business capabilities, not the capabilities to build digital twins, but the business capabilities..."* *"It's understanding that ecosystem done by enterprise architecture... then you can build on with your use cases..."* *CompB: "Now, I've seen from my observations... when we close this gap between technical and non-technical... So what's beautiful about digital twins is that you won't be able to implement a successful digital twin if you don't close that gap. So you have to have, like we talked earlier, technical and non-technical... you have to have a business understanding alongside a technical knowledge..."*
Change Management and Overcoming Organizational Resistance	Develop and Exploit DTs	Implementing effective change management strategies to address organizational resistance to new technologies like DTs. This involves engaging stakeholders, creating a culture open to innovation, and proactively addressing concerns and barriers to adoption.	CompA and CompB	*CompA: "We have an internal challenge... our engineers are all very stubborn, and they want to do it the old-fashioned way... we have to evangelize... making glossaries about it and say why it's good and also to show projects where we've done it..."* *CompB: "* But also change management where you have to introduce changes according to the automation that you've achieved in iterations, so you don't overwhelm the organization with the amount of automation that you're producing..."
Domain Knowledge Integration	Develop and Exploit DTs	The capability to integrate deep domain knowledge into DT projects to ensure relevance, effectiveness, and accuracy. This involves collaborating with domain experts and understanding industry-specific processes, regulations, and challenges.	CompA	*"A very important part of capabilities is that you have the domain knowledge of the use cases you are working on... you must understand how the processes of that industry are working... that is really domain knowledge."*

Table 10 (continued)

NEW Non-Technical DT Capability emerged from empirical data	Stage	Description in the context of Digital Twins	Case	Quotations
Skill development and Talent Management	Develop and Exploit DTs	Recognizing the need for developing skill sets that combine both technical and business expertise. Investing in training and talent development to build multidisciplinary teams capable of handling digital twin projects.	CompB	*"This takes a lot of time from my business to train people, even the most senior consultants, the most senior project managers, solution architects. It's a heavy, heavy investment in time and training to be able to help people understand both worlds... We need people who understand business and technical capabilities in organizations involved in digital twin projects..."*
Resource Liquification	Achieved through DTs	It refers to the improved mobility and accessibility of resources, such as data, knowledge, and services, across platforms and organizational boundaries. This capability enables seamless information flow and dynamic resource allocation, driving collaboration, operational flexibility, and responsive digital service innovation	CompB	*"One of the very fascinating parts... is the capability of orchestrating external and internal resources for organizations... So when you were able to negotiate kind of governance method that enables the organization to acquire external data, that provides a huge advantage."*

Table 10: New Non-technical Digital Twin capabilities emerged from the cases

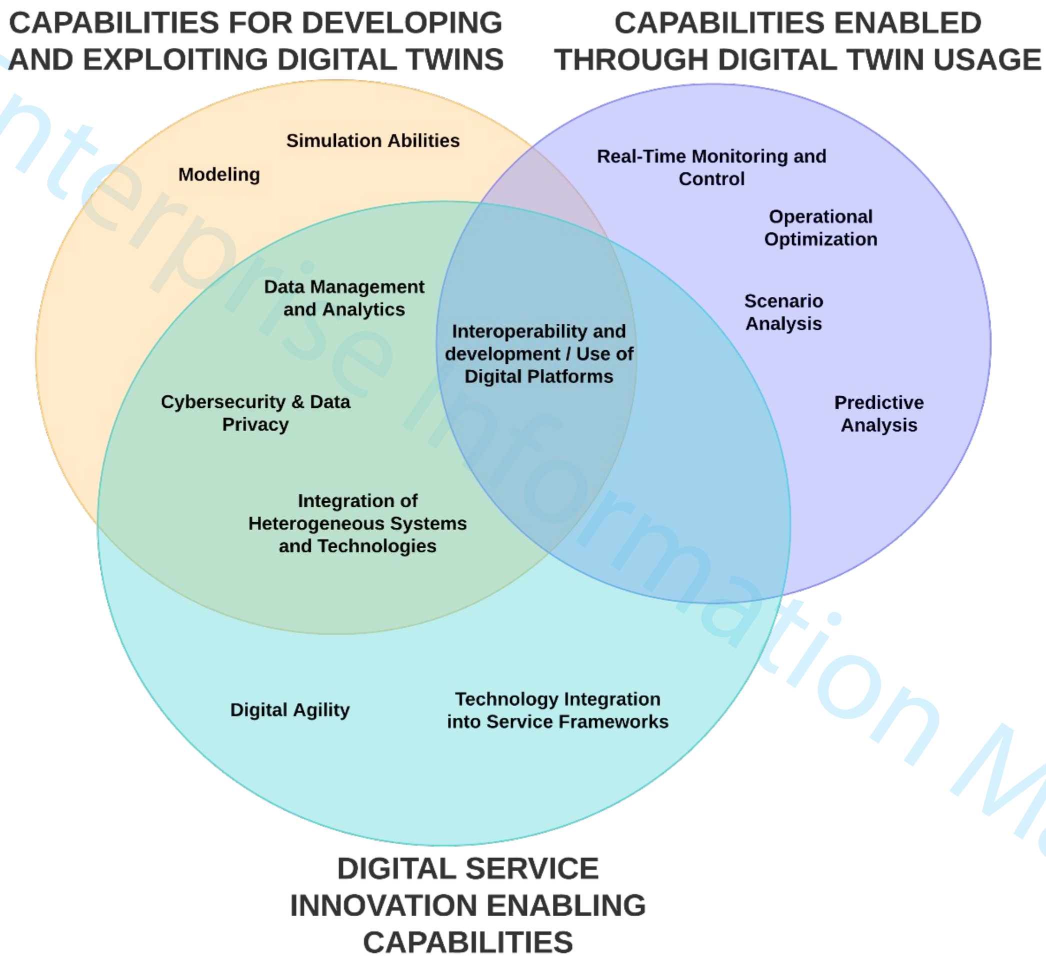

Figure 1: Overlap of technical Digital Twin (DT) capabilities and technical Digital Service Innovation (DSI) enabling capabilities

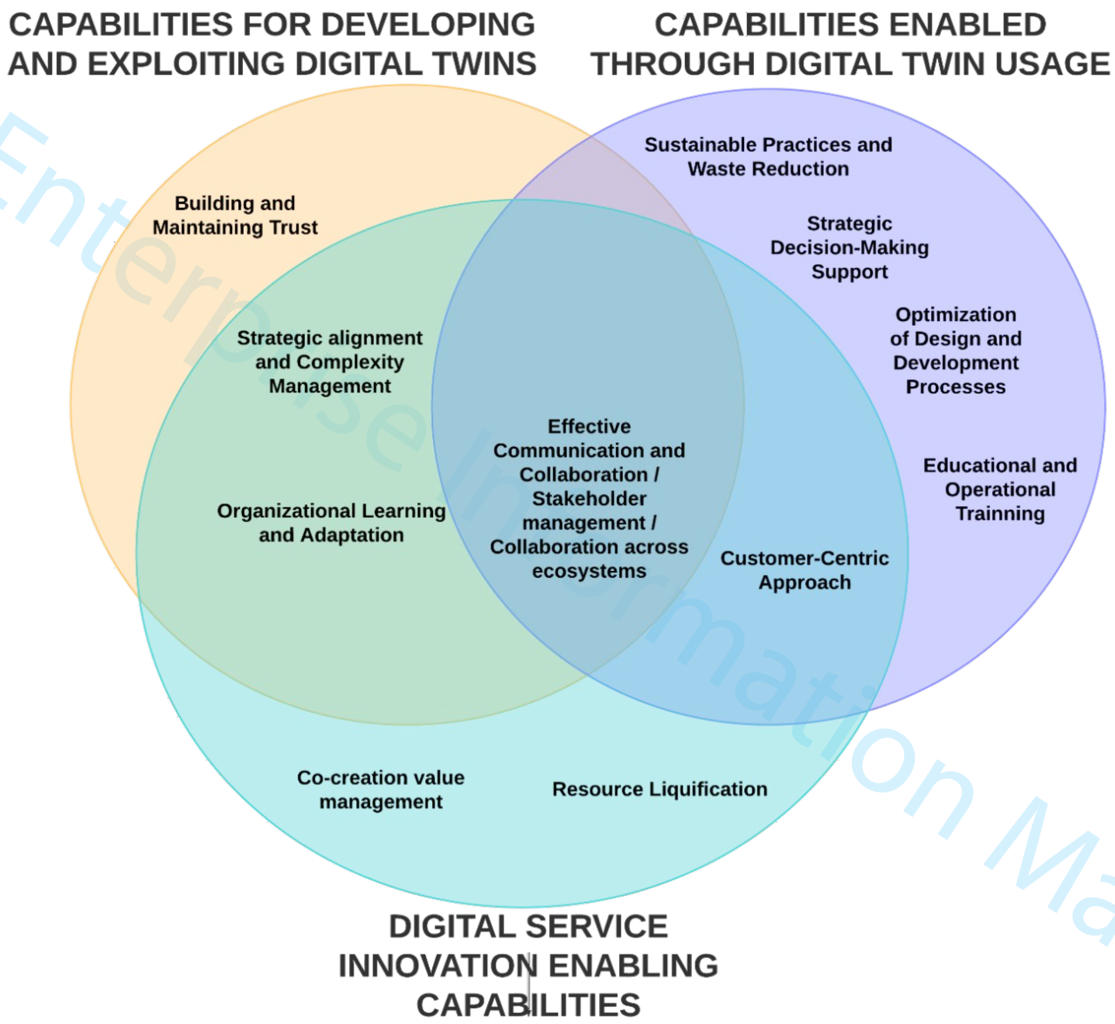

Figure 2: Overlap of non-technical Digital Twin (DT) capabilities and non-technical Digital Service Innovation (DSI) enabling capabilities

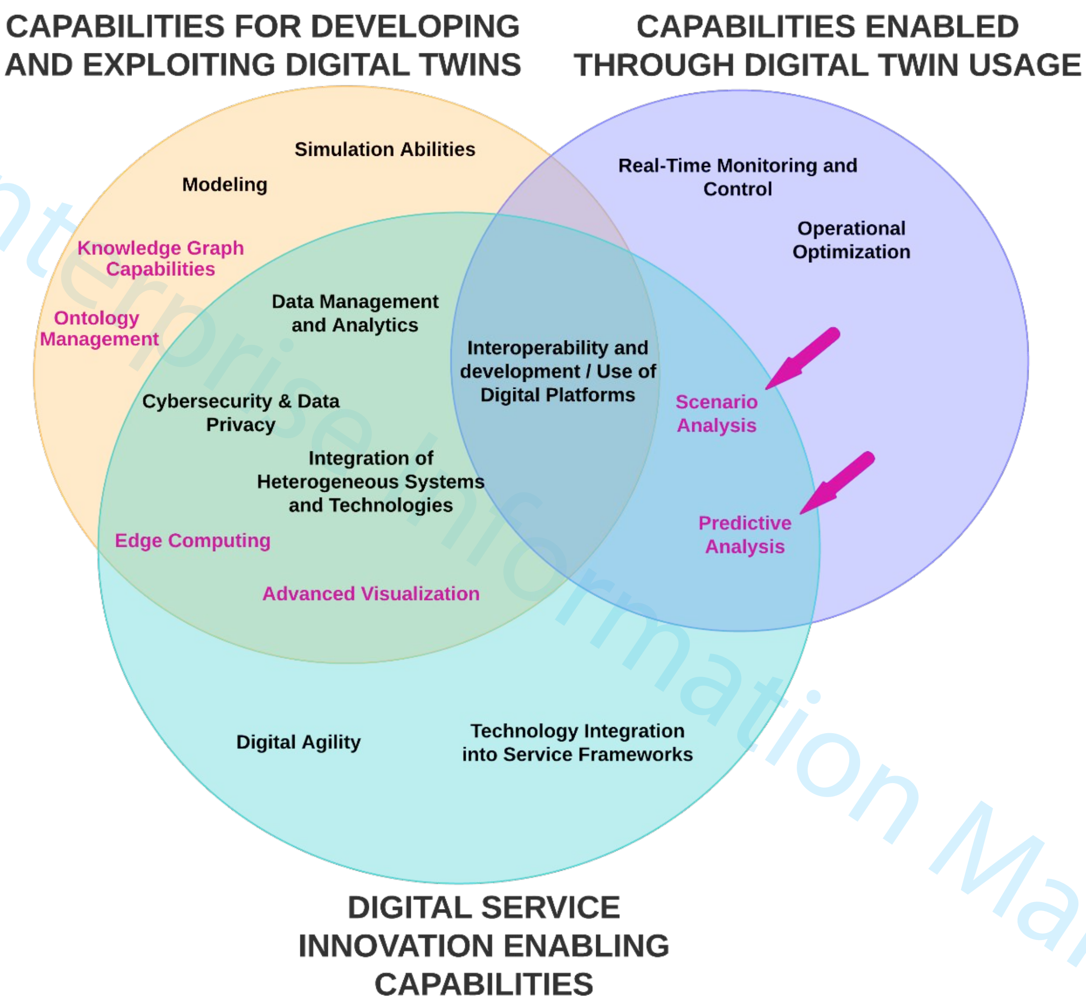

Figure 3: Framework illustrating how Technical DT Capabilities enable Digital Service Innovation (DSI) Deployment

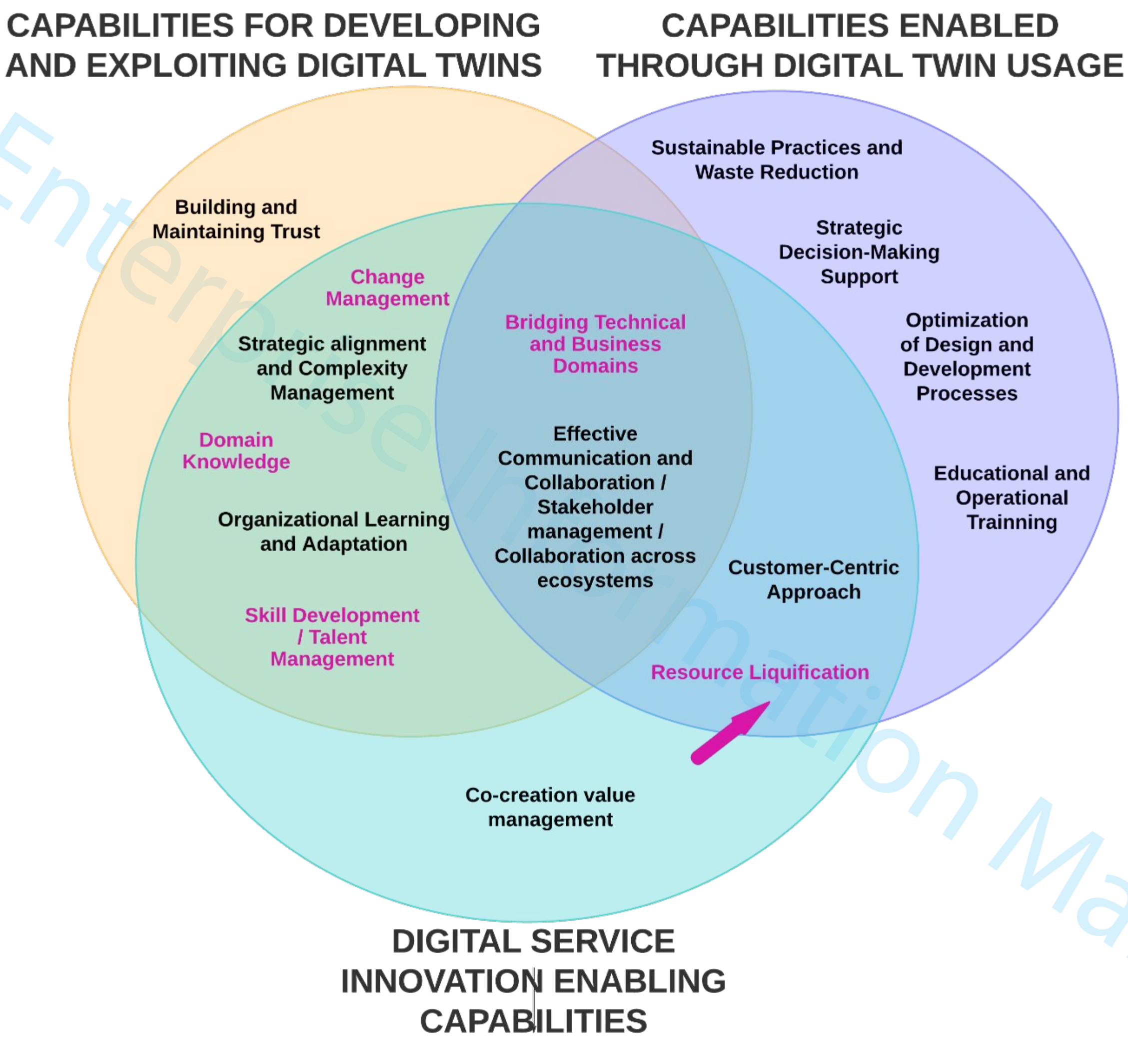

Figure 4: Framework illustrating how Non-Technical DT Capabilities enable Digital Service Innovation (DSI) Deployment

Appendix A: Interview Questions and Structure

A. Introduction to the Participant's Role and Organisational Involvement

- Can you describe your role and involvement in Digital Twin projects?
- What is the role of your company in Digital Twin projects?

B. Objectives and Aims of Digital Twin Implementation

- What are the most common objectives and capabilities companies aim to achieve with Digital Twins, based on your experience?
- Could you share examples of innovative uses of Digital Twins across different industries?

C. Capabilities Required for Developing and Exploiting Digital Twins

- What specific technical and non-technical capabilities are necessary to develop Digital Twin projects?
- How do organisations typically acquire these capabilities, and what role does your company play in this process?

D. Capabilities Achieved Through Digital Twin Usage

- What are the key capabilities organisations gain through the use of Digital Twins?
- Can you provide examples of how these capabilities have been utilised by companies?

E. Role of Digital Twins in Driving Digital Service Innovation

- In what ways do the capabilities developed through Digital Twin projects enhance an organisation's ability to innovate in digital services?
- Could you explain how these capabilities are applied to conceptualise, develop, and deploy digital services?
- Do you have examples of such applications in practice?

F. Organisational Culture and Digital Twin Projects

- How do organisations foster the development of capabilities through Digital Twin projects and their application to service innovation?

G. Framework Development and Validation

- After these initial blocks of the interview, we shared two figures outlining Digital Twin capabilities (technical and non-technical) and their interrelationships based on our sense-making of the literature review. Could you validate these capabilities and their relationships?
- Do you feel there are any additional capabilities or interrelationships that should be considered?
- How would you suggest refining this framework to better capture the dynamics of Digital Twin capabilities and service innovation in your experience?

Future Perspectives on Digital Twin Evolution

- Where do you see the future of Digital Twins heading in the next 5-10 years, particularly regarding service innovation?

Closing Comments

- Are there any additional thoughts or insights you believe are important to this topic that we haven't yet covered?