Review of Managerial Science
https://doi.org/10.1007/s11846-025-00955-1

ORIGINAL PAPER

Antecedents, enablers and outcomes of twin transformation in high reliability organizations: a systematic literature review

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Received: 29 March 2025 / Accepted: 29 October 2025

Abstract

A growing body of research currently explores twin transformation (TT), defined as the integrated and simultaneous pursuit of sustainability transformation (ST) and digital transformation (DT), in various types of companies. However, the current understanding of how high-reliability organizations (HROs), typically known for exceptional reliability in error-prone operations, address these challenges is limited. Although HROs, especially in high-impact sectors like energy and transportation, are under increasing pressure to reduce emissions and embrace digital innovation, only a few studies address the dual challenge of balancing and managing digital and sustainability transformations simultaneously in HROs. To bridge this gap, this study conducts a systematic literature review to synthesize existing work. We identify the antecedents, enablers, and outcomes of these transformations and derive an HRO-specific framework that integrates digital transformation, sustainability transformation, and their synergistic integration. To broaden the applicability, we compare this framework with established, non-context-specific frameworks. Our results highlight that many enablers are shared by both transformations, suggesting that a synchronized and coordinated sustainability and digitalization strategy can improve efficiency and coherence in achieving transformational goals in HROs. This study makes three contributions: (1) it integrates previously siloed research on DT and ST into a systematic understanding of TT within HROs, (b) developing a novel conceptual framework that balances transformation imperatives with reliability, and (c) providing evidence-based guidance for TT implementation in safety–critical sectors such as energy, aviation, and healthcare.

Keywords Twin transformation · Digital transformation · Sustainability transformation · High-reliability organizations · Systematic literature review

JEL Classification M10 · M15 · O32

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Published online: 25 November 2025

1 Introduction

The growing pressures of contemporary digitalization and sustainability are reshaping strategic and operational landscapes for organizations across all sectors (Bjerkan & Ryghaug 2021; Damman & Steen 2021; He et al. 2024). Organizations increasingly face the dual challenge of adapting to rapid technological advances while meeting heightened expectations for environmental responsibility (Lindberg & Kammermann 2021).

To respond to these pressures, organizations pursue two distinct but increasingly interlinked transformation types: Digital Transformation (DT) and Sustainability Transformation (ST). DT refers to the use of digital technologies to enhance operational efficiency, decision-making, and organizational agility (Delgosha et al. 2021; Kim et al. 2021; Ogrean & Herciu 2021; Vial 2019). In contrast, ST focuses on an 'outside-in' perspective, integrating environmental, social, and governance (ESG) concerns to address pressing challenges and reorient business models towards benefiting society as a whole (Bocken et al. 2014; Christmann et al. 2024; Dyllick & Muff 2016).

While each transformation has distinct antecedents, enablers and outcomes, their convergence as Twin Transformation (TT) has gained increasing attention (Christmann et al. 2024; Crome et al. 2023; Graf-Drasch et al. 2023). TT refers to the integrated process of aligning DT with sustainability to achieve operational efficiency, environmental responsibility, and organizational resilience (Schallmo & Jehle 2025).

The focus on TT is driven by rising attention towards how digital technologies support sustainability improvements (Chopra et al. 2024; Guandalini 2022; Kolb et al. 2023; Ortega-Gras et al. 2021). TT offers promising opportunities for building a sustainable economy and society (Cooke 2021; Lazzeretti et al. 2022; Sedita et al. 2022). However, adopting TT presents unique challenges and opportunities that remain underexplored, as recent reviews and empirical studies highlight persistent sectoral biases, inconsistent terminology, and a tendency to portray digital transformation as the primary driver of sustainability rather than a bidirectional process (Hammerschmidt et al. 2025; Leipziger et al. 2025). Particularly, sectors like energy and transportation are significant contributors to greenhouse gas emissions and face the need to converge DT and ST while maintaining high standards of reliability and operational efficiency (European Environment Agency 2024; U.S. Environmental Protection Agency 2023). These organizations must navigate the transformations within competitive markets and achieve sustainability targets set by policymakers (Crome et al. 2023; European Commission, 2022; Jabłoński & Jabłoński 2021; Manyika et al. 2021; Philp & Ulrich 2025; Poláková-Kersten et al. 2023). These sectors are not only central to digital and sustainability disruption but also exemplify High-Reliability Organizations (HROs).

HROs, defined as organizations in which errors are infrequent despite the inherently error-prone nature of their operations (Roberts 1990a), operate in complex, high-risk environments where even minor errors can result in severe consequences (Poláková-Kersten et al. 2023; Weick 1987). In sectors such as healthcare (Carroll & Rudolph 2006; Sepetis et al. 2024), transport (Farrington-Darby et al. 2005), aviation (Powell-Dunford et al. 2017), and energy (Poláková-Kersten et al. 2023), these orga-

nizations face exceptionally stringent safety requirements intensifying the challenge of aligning transformations with compliance while maintaining reliability. Their deeply ingrained cultures of safety and accountability often resist digital disruption or demand tailored approaches to embedding sustainability. Hence, HROs prioritize factors like reliability and risk in their strategies, making their approach fundamentally distinct. This highlights transformation challenges, as HROs must balance transformation initiatives with their need for exceptional safety and reliability (Navajas et al. 2013). For example, an airport consortium implemented a digital twin-based platform to manage sustainable aviation fuel, enabling real-time data integration across stakeholders to reduce emissions while maintaining operational safety (Barbano et al. 2024).

Understanding how DT and ST coexist in HROs is critical, as TT offers a pathway to achieving digital and sustainability goals without compromising reliability.

Despite the potential benefits of integrating TT and the existence of real-word examples demonstrating its advantages, these approaches are often isolated (Crome et al. 2023; Schallmo et al. 2022; Schallmo & Tidd 2021). While significant research has explored DT and ST individually (e.g. Jabłoński & Jabłoński 2021; Waring et al. 2023), existing work remains either siloed or cross-sectoral, without providing a systematic account of TT tailored to the distinctive conditions of HROs. Despite TT gaining increasing attention in academic research (Burinskienė & Nalivaikė, 2024; Christmann et al. 2024; Ogrean & Herciu 2021; Ortega-Gras et al. 2021), the field remains fragmented, with limited conceptual integration and sector-specific theorization (Hammerschmidt et al. 2025; Leipziger et al. 2025).

According to Guandalini (2022), management literature still lacks integrative studies that guide companies in implementing TT, primarily due to the lack of overarching strategic studies and limited understanding of how DT and ST interact within specific organizations or stakeholder types. Furthermore, a comprehensive and practically relevant framework for TT in HROs is absent (Del Río Castro et al. 2021; Feng et al. 2022).

This leaves a critical research gap: while DT and ST have been studied extensively in isolation, their integration as TT in the distinctive setting of HROs remains poorly theorized and insufficiently synthesized. This study addresses this gap by systematically reviewing and synthesizing literature on DT, ST, and TT in the context of HROs. We develop an HRO-specific framework that identifies shared and distinct antecedents, enablers, and outcomes of these transformations while accounting for the unique requirements of error-prone, high-stakes environments. To enhance generalizability, we further compare this HRO-specific framework with established, non-contextual frameworks, thereby distinguishing universal from context-dependent features of TT. As such, the study is guided by the research question: *What are distinct and shared antecedents, enablers, and outcomes for digital and sustainability transformations and their integration as twin transformations in HROs*?

In doing so, the study makes three contributions. First, it advances theoretical understanding by integrating previously siloed research on DT and ST into a systematic account of TT within HROs. Second, it develops a novel conceptual framework that highlights how HROs can balance transformation imperatives with their need for exceptional reliability. Third, it enriches managerial practice by providing evidence-

based guidance for implementing TT in highly regulated, safety–critical sectors such as energy, aviation, and healthcare.

2 Theory and background

HROs excel in complex, high-risk environments, achieving exceptional reliability and proactively minimizing errors (Roberts 1990b; Rochlin 1996). They consistently avoid disasters under challenging and risky conditions (Rochlin 1996; Weick 1987). HROs are often risk-averse and unconventional because of their extraordinary operational requirements and focus on error prevention (Navajas et al. 2013). Their foundational theoretical framework is rooted in principles of mindfulness and a persistent preoccupation with failure (Sutcliffe 2007), highlighting organizational learning processes utilized to mitigate risk and maintain reliability over time.

To achieve consistent performance in high-risk, complex environments, HROs prioritize operational efficiency, risk management, and resilience (Reason 1997). They constantly adapt and improve their systems and processes through rigorous planning and implementation strategies, ensuring that even minor changes do not have disproportionate consequences (Dekker 2011; Sutcliffe 2011). This rigor is critical in their tightly coupled operational systems, where minor errors can lead to significant cascading effects. HROs also operate under rigorous regulatory frameworks due to the potential societal impact of their activities (Chassin & Loeb 2013; Schulman et al. 2004). Adhering to legal requirements, industry standards, and regulatory guidelines is fundamental to their operations (Poláková-Kersten et al. 2023). Additionally, risk management is a vital component of HRO culture. Adopting new technologies or practices requires comprehensive risk assessments to address potential hazards and ensure safe implementation (Weick 1987).

DT aims to improve an organization by triggering significant changes to its properties through combinations of information, computing, and communication using digital technologies (Vial 2019). For HROs, DT involves adopting new technologies and fundamentally changing organizational structures (Poláková-Kersten et al. 2023). Digital technologies such as AI, internet of things (IoT), and big data offer opportunities to enhance resource efficiency and operational control. However, they also introduce challenges in integrating these advanced technologies into safety–critical operations (Jabłoński & Jabłoński 2021). DT necessitates modelling new risk-minded behaviors and leadership approaches (Singh et al. 2020). Furthermore, HROs must reconcile the need for rapid solution delivery, autonomy, trust, and the tolerance of failure to embrace digital innovation (Demirkan et al. 2016).

ST aligns organizational practices with ecological, social, and economic dimensions to enhance resource efficiency, social responsibility, and long-term value creation (Ortega-Gras et al. 2021). HROs, as significant contributors to the climate crisis through greenhouse gas emissions, face heightened scrutiny to adopt sustainability-focused strategies (Chen & Zhang 2025; Crome et al. 2023). These strategies often require significant organizational shifts, including redesigning operational processes, fostering stakeholder collaboration, and embedding sustainability into the corporate culture (Bosman et al. 2018). However, the inherent risk aversion of HROs and focus

on operational stability can function as barriers to meaningful progress in ST (Bjerkan & Ryghaug 2021).

TT refers to the integrated process of aligning DT with sustainability to achieve operational efficiency, environmental responsibility, and organizational resilience (Schallmo & Jehle 2025) and can be understood as the simultaneous and reciprocally reinforcing transformation of digital and sustainable processes within organizations, strategically implemented to drive innovation, efficiency, and competitive advantage (Hammerschmidt et al. 2025). Consequently, TT should be understood as more than the sum of DT and ST. TT represents more than the coexistence of DT and ST, as it constitutes a distinct construct with its own dynamics. Adequately managed digital technologies can enhance resource efficiency, circularity, and climate neutrality, thereby supporting sustainability goals (Delgosha et al. 2021; Kim et al. 2021; Ogrean & Herciu 2021). TT can unlock unforeseen connections and secure competitive advantages (Crome et al. 2023), as it integrates DT's focus on efficiency and agility (Vial 2019) with ST's emphasis on responsibility, resilience, and long-term value creation (Bocken et al. 2014; Dyllick & Muff 2016). Rather than running in parallel, TT requires orchestrating these divergent logics into a coherent strategy. Recent studies underline that TT involves unique dynamics, often marked by asymmetry, since DT is frequently perceived as enabling ST, while the reverse is less evident. The essence of TT lies in recognizing and cultivating this mutual interdependence (Hammerschmidt et al. 2025; Leipziger et al. 2025).

This framing positions TT as a distinct organizational phenomenon that can be better understood by synthesizing insights from DT and ST literature, while highlighting the need for integrative perspectives that go beyond each domain in isolation.

TT in HROs involves adopting strategies that simultaneously address DT and ST challenges. This comprehensive approach can guide HROs in navigating the complexities of both transformations, ensuring they remain resilient and efficient while contributing to broader sustainability goals.

HROs encounter specific challenges when implementing change, especially in the context of TT. The demand for near-zero operational defects requires a high level of care and thoroughness in implementing change (Riley 2009). Unlike organizations with greater operational flexibility, HROs must navigate transformation in a way that maintains their high-reliability standards while adopting innovative practices (Cantu et al. 2021). This necessitates the development of specialized frameworks that address their specific operational requirements, risk profiles, and cultural characteristics. These frameworks must balance the objectives of DT and ST while maintaining the stability required in high-reliability contexts.

3 Methodology

To address the research question, we conducted a systematic literature review (SLR), facilitating a comprehensive examination of the intersection between DT and ST. Our SLR enabled the identification of patterns and connections among various empirical findings, playing a crucial role in a post-hoc theorization of previous literature (Frank & Hatak 2014; Kraus et al. 2020, 2022). This methodological choice was

validated by the substantial yet fragmented body of research on TT, necessitating a conceptual integration as a foundation for further research and evidence-based management (Kraus et al. 2024). This approach ensured objectivity and reproducibility by following the structured methodology proposed by Tranfield et al., (2003), which has become a quasi-standard for SLRs in the past decade (Breslin et al. 2020). By following a specific methodology with literature as data, searching, selecting, and synthesizing relevant literature was conducted in a transparent and replicable manner, thereby minimizing bias and subjectivity (Kraus et al. 2022).

The methodology employed in this review followed a two-step approach, ensuring rigor and transparency throughout the process. The two consecutive steps are: (1) systematic data collection involving meticulous planning, defining the research question, setting criteria, and systematically searching databases; and (2) data analysis and synthesizing focus on identifying key themes, patterns, and connections to present findings coherently and comprehensively (Tranfield et al. 2003). The review identified distinct and shared organizational antecedents and enablers regarding TT by systematically sampling, analyzing, and structuring literature from domains of DT and ST from the perspective of HROs.

3.1 Data sampling

For this study, we systematically collected data using two primary databases: EBSCOhost Business Source Ultimate and the Web of Science Core Collection. We chose these databases because they are recommended sources for entrepreneurship research, as noted by Kraus et al. (2020) and had necessary access. These comprehensive databases ensured a robust foundation for the literature review. Recognizing that different terms are often used synonymously in entrepreneurship research, educational literature was utilized to uncover interdependencies between keywords (Kraus et al. 2020). To maintain methodological rigor, we restricted our analysis to business- and management-related articles from journals indexed in the Social Science Citation Index (SSCI) (Gernsheimer et al. 2021). Additionally, we utilized the journal ranking conversion table by Bouncken et al. (2015) and Kraus et al. (2020) that have been commonly used in earlier systematic reviews (Antonio & Kanbach 2023; Gernsheimer et al. 2021) and applied two quality thresholds by including only academic journals that contain an Impact Factor of ≥ 1.5, according to Thomson Reuters' *Journal Citation Reports* (JCR 2025), and those rated ≥ 2 in the *Academic Journal Guide* (ABS/AJG 2024). Figure 1 outlines the selection process.

This approach informed the creation of two specific search strings designed to target the relevant research areas. The search strings included titles, keywords, and abstracts, incorporating relevant synonyms and covers the period from the year 2000 to mid 2025 to capture the breadth of the field (Fig. 1). The keywords and search strings were discussed with experts from theoretical (academia) and practical (industry) backgrounds. The industry experts represented core HRO sectors such as energy, aviation, healthcare, and transport. Their role was limited to validating keyword coverage and ensuring all relevant domains were captured, rather than influencing inclusion or exclusion decisions. In addition, the search terms were cross-checked against educational and grey literature to ensure accuracy and consistency (Kraus et

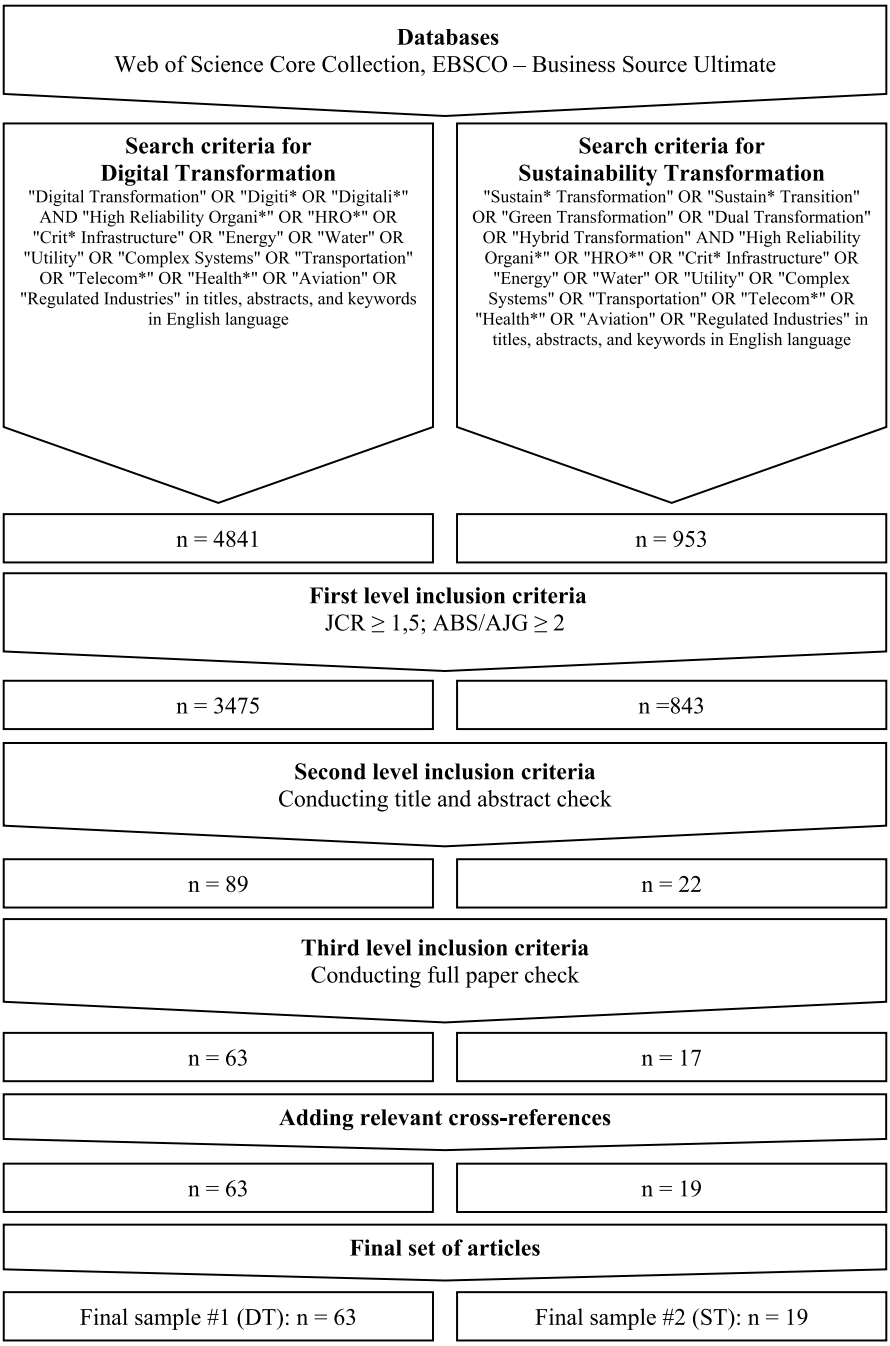

Fig. 1 Systematic literature review – research protocol, source: authors' own work

al. 2020). The last search occurred at the end of September 2025 and returned 4841 matching results for the DT sample and 953 for the ST sample. Following this process reduced the final sample to 63 DT articles and 19 ST articles. This significant difference from the initial results can be attributed to the broad and comprehensive search terms utilized, which ensured that no potentially relevant literature was overlooked. Consequently, extensive manual cleaning of the literature database was necessary afterwards.

To ensure comprehensiveness, a forward and backward search, recommended by Vom Brocke et al. (2009) and Webster and Watson (2002), was applied. Reference lists from the identified articles and relevant literature reviews related to DT and ST in HROs were manually scanned to include additional pertinent articles. This resulted in two additional articles. Multiple sampling steps were employed to ensure a relevant and current sample, including seminal papers on each concept and their interconnections.

The final sample was reviewed with fellow researchers, as suggested by Webster and Watson (2002), and during conference submissions to ensure its comprehensiveness and suitability for building a conceptual framework. This rigorous sampling process ensured that the SLR extended beyond summarizing relevant scientific evidence, aiming to extend existing theories and provide a solid foundation for understanding TT in HROs.

Although previous literature reviews have offered important insights into either DT or ST on their own, a combined look at TT, especially within HROs, has not been explored. Earlier reviews frequently analyze DT and ST in isolation or touch upon how they interact without providing a structured conceptual framework merging these ideas (George et al. 2021; Guandalini 2022; Vial 2019). Furthermore, no existing literature review provides a specific TT framework grounded in high-reliability settings. To clearly show where this study fits in, Table 1 compares with a selective but representative set of prior literature reviews. These reviews were chosen based on their citation impact, recency, and conceptual relevance, thereby illustrating what makes this work distinct.

3.2 Data analysis

To conduct a detailed content analysis of the data samples, an inductive concept development method outlined by Gioia et al., (2013) was employed using MAXQDA software. This involved clustering text segments from all articles into meaningful concepts, themes, and aggregate dimensions. In total, we identified 1441 text passages, with 82 articles contributing to the first-order concepts. This pattern-inducing technique identified relevant categories and their interrelationships, continuously refined through an iterative process of comparing theory and data, as Glaser and Strauss (1967) suggested. This approach facilitated a thorough view of patterns and connections among the various empirical findings within a broader scope.

Utilizing an open coding approach, we synthesized the articles' content, labelling notable concepts in the literature to uncover recurring themes, patterns, or ideas. This iterative process involved deriving first-order concepts by refining the emerging ele-

Table 1 Comparison with selected existing Literature Reviews on DT, ST, or TT

References	Type of Transformation	Findings	Limitations	Our Distinction
Morioka and de Carvalho (2016)	ST	Systematic review on sustainability performance integration; proposes operational-tactical-strategic framework	No DT or TT focus; no HROs; lacks DT-ST integration	Provides a useful structure for sustainability performance, but our research integrates both dimensions and targets industry-specific context
Vial (2019)	DT	Drivers, processes, moderators, outcomes of DT	No TT or ST focus, no HROs, no quality assessment	Provides foundational DT structure, but lacks TT integration and context specificity
Ortega-Gras et al. (2021)	DT/ST	Enablers and barriers for digitalization in circular economy	No TT terminology, no conceptual framework, no HROs	Touches DT-ST link but lacks TT theorization, HRO focus, and conceptual integration
Guandalini (2022)	DT + ST	Fragmentation of DT/ST literature; overlap of concepts; conceptual integration	No structured synthesis, no theoretical framework, no HROs	Highlights need for TT research but lacks systematic synthesis, theoretical depth, and empirical contextualization
Philp et al. (2025)	TT	Systematic review explicitly on TT; identifies five major future research areas (industry, politics, sustainability, business, environmental impact)	Search String limits sample to TT but lacks the intersection of DT and ST; no focus on HROs; does not explore sector-specific application	Broadens TT theorization and sectoral focus; our work adds TT integration in HRO; HRO framework
Ahrens and Heubeck (2025)	TT	Identifies leadership, human capital, and governance as key enablers of TT through review of 48 studies	Smaller sample; no theoretical model for HROs or analysis of safety–critical organizational contexts	Our framework enriches the understanding of enablers and differentiates between shared and distinct factors
Our research	TT	First systematic TT review with focus on HROs; integrates DT & ST into a comprehensive framework; extends it beyond HROs	Systematic review of academic literature without primary data collection	Fills a gap by providing the first integrated TT framework tailored to HROs with potential generalizability

ments, ensuring that the identified concepts were robust and accurately represented by the data.

Through continuous comparison and identification of inconsistencies or gaps, a total of 1,142 descriptive elements from Sample 1 (DT) and 299 from Sample 2 (ST) was derived. These descriptive elements, including duplicates, were consolidated into 122 first-order concepts. The first-order concepts were further aggregated into 26 s-order themes based on their links and interactions, allowing for a more organized and less granular categorization.

The second-order themes were then abstracted to derive 10 aggregate dimensions. This abstraction process aided in simplifying the data and highlighting the broader themes that emerged from the literature. The resulting aggregate dimensions provided a higher-level understanding of the distinct and shared enablers of both transformations (Fig. 2).

The subsequent analysis and synthesis of the examined literature focused on concepts instead of authors, adopting a nonchronological approach. This focus allowed for the derivation of a conceptual framework, presenting a novel contribution to the field. The analysis was accompanied by explanatory figures that complemented the supplementary material, ensuring a balanced representation of breadth and depth, as recommended by Webster and Watson (2002), Fisch and Block (2018) and Kraus et al. (2020).

The inductive concept development and pattern-inducing techniques employed in this study facilitated the identification and synthesis of major themes and dimensions within the literature on TT in HROs (Alavi & Leidner 2001). This methodological rigor ensured that the resulting conceptual framework was comprehensive and insightful, providing a solid foundation for future research and practical applications.

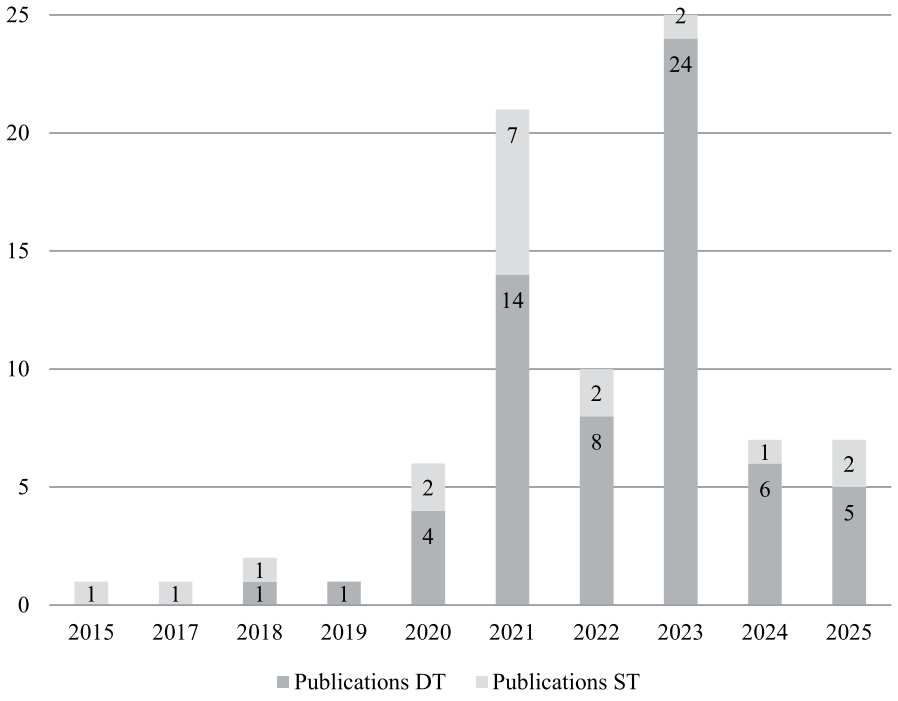

Fig. 2 Distribution of selected publications per year for DT and ST in HROs, source: authors' own work

3.3 Descriptive sample overview

The final samples comprised of 63 publications on DT and 19 on ST, revealing distinct patterns and similarities. These articles were published in 27 journals for DT and 11 journals for ST, reflecting a broad yet concentrated scholarly interest in these fields.

3.3.1 DT sample

In the DT sample of 63 publications, we observed a peak in scholarly interest in DT within HROs in 2023, when 24 publications, representing 38% of the total DT sample, were published (Fig. 2). Additionally, we found that 17% (11 publications) of the DT sample were published in the journal *Technovation*, followed by 11% (7 publications) in *Technological Forecasting and Social Change*.

The methodological approaches in the DT sample were qualitative, with 49% of the empirical studies (31 publications) employing methods such as surveys, interviews, company-provided documents, and field observations. Quantitative approaches, including regression analysis and t-tests, were utilized in 33% of the studies (21 publications). Additionally, 14% of the studies adopted mixed methods (9 publications), combining mathematical models with interview-based validation, while one study followed a theoretical legal analysis approach. This diverse methodological landscape underscores the complexity of researching DT in system-relevant sectors.

The industry focus of the DT publications was notably leaning towards healthcare, accounting for 59% of the articles (37 publications), followed by the energy and utilities sector, which comprised 32% (20 publications). This focus reflects the critical importance of DT in enhancing operational reliability and efficiency in these industries. Furthermore, almost half of the DT sample (44%) consisted of case studies (28 publications), highlighting the practical and applied nature of the research.

3.3.2 ST sample

In the ST sample, the highest number of publications on ST in HROs occurred in 2021, with seven articles (37%) indicating a significant focus on sustainability issues. Additionally, 21% (4 publications) of the articles were published in *Sustainability*, followed by 16% (3 publications) in the journal *Energy Policy*. Like the DT studies, the ST research adopted qualitative approaches, with 90% (17 publications) of the empirical studies utilizing surveys, interviews, company documents, and field observations. Only a small fraction (11%, 2 publication) employed quantitative or mixed methods, combining quantitative models with qualitative validation. The industry distribution for ST publications showed a strong focus on the energy and utilities sector, which accounted for 68% of the articles (13 publications), followed by the transportation sector at 16% (3 publications). This emphasis reflects the pressing need for sustainable practices in energy-intensive and transport-related industries. As with the DT sample, most ST studies (58%, 11 publications) were case studies, indicating a strong orientation towards practical implementation and analysis of sustainable practices in high-reliability settings.

4 Findings

4.1 Digital transformation

4.1.1 Distinct antecedents of DT driven by regulatory and market forces

Providing certainty and managing complexity through regulation is the first antecedent for HROs engaging in DT. Regulation offers certainty and manages the complexity of adopting new technologies. Regulatory frameworks and government policies force HROs to engage in DT, ensuring compliance, enhancing operational standards, and addressing issues like data security and environmental aspects. Government regulations can enforce digital innovation by mandating specific technological implementations and compliance standards. For instance, regulatory measures often require HROs to integrate digital solutions to meet environmental and operational standards, driving DT (Ghosh et al. 2023; Y. Liu & Song 2023). This regulatory push provides a structured framework, reducing the uncertainty that often accompanies technological change. The influence of regulation is evident in multiple HROs. For example, the Affordable Care Act (ACA) mandated electronic health records (EHRs) in healthcare, forcing HROs to standardize processes and adopt new technologies (Ghosh et al. 2023). This regulatory compulsion ensures HROs align their operations with broader policy goals, accelerating DT. Government measures also target carbon emissions, compelling HROs to adopt digital solutions as part of compliance strategies. These measures, enacted by central and local governments, force HROs to transition towards sustainable practices through DT (F. Yu et al. 2023). The government provides institutional strength and policy assistance (F. Yu et al. 2023).

The regulatory landscape addresses complexity by providing clear guidelines and standards. For example, data security and privacy regulations significantly impact digital technology adoption, ensuring HROs prioritize protecting sensitive information (Steinhauser et al. 2020). These regulations offer a framework to mitigate risks. HROs' willingness to adopt digital strategies is influenced by the broader regulatory environment, including government incentives and support. Compliance with national policies and guidelines and regulatory funding catalyzes DT efforts in the public and private sectors (Biancone et al. 2023). This regulatory certainty helps HROs navigate technological adoption complexities, providing a clear path forward.

Building trust through transparent digital solutions is the second antecedent of DT. Addressing technology anxiety, usability barriers, and the overall customer experience to ensure that users embrace digital innovations is another vital enabler for DT. Technology anxiety can significantly hinder the adoption of new digital tools and systems, as users may feel intimidated or unsure about using them effectively (Biancone et al. 2023). It is essential to develop user-friendly technologies that minimize complexity and are intuitive. Usability barriers further complicate the adoption process. Users often encounter difficulties with the usability and interactivity of digital applications, which can deter them from fully engaging with new technologies. Key issues include difficulty accessing information, complex interfaces, and confusing navigation, all contributing to a negative user experience (Iyanna et al. 2022). Enhancing the usability of digital tools by simplifying interfaces and ensuring

that information is easily accessible can significantly improve customer acceptance. HROs must prioritize user-centered design principles to foster customer acceptance. Conducting thorough usability testing and involving users in the development process helps identify and address potential pain points (Iyanna et al. 2022). By creating digital solutions tailored to user's needs and preferences, HROs can reduce resistance and increase the likelihood of adoption.

Effective communication and education are vital to building trust through transparent digital solutions. Clear instructions, tutorials, and support can help users feel more confident using new technologies (Iyanna et al. 2022). This confidence, in turn, can reduce technology anxiety and encourage users to engage with digital tools. Furthermore, highlighting DT's benefits and potential positive impacts can help shift perceptions and build a more favorable attitude towards adoption. For instance, hospitals implementing EHR systems use transparent digital solutions to build patient trust (Ghosh et al. 2023; Gnugesser et al. 2025). These systems provide patients with secure, real-time access to their medical records, ensuring data accuracy and enabling them to track their treatment progress. Transparency in data managing also assures patients that their sensitive information is protected, fostering confidence in the healthcare provider.

4.1.2 Organizational resilience as distinct enabler of DT

Developing digital business models adapted to high-stakes environments represents a distinctive enabling factor. Exploring and exploiting digital business models by enabling HROs to innovate, access new market opportunities, and enhance service offerings is key in DT. This involves leveraging digital technologies to explore new possibilities and exploit existing capabilities, ensuring a balanced approach to innovation and operational efficiency. DT equips HROs with tools to access new markets, better understand target customers, and significantly improve new goods and services development (YahiaMarzouk & Jin 2023). HROs can create innovative business models that drive growth and competitiveness by utilizing DT. This utilization includes identifying and capitalizing on opportunities presented by digital technologies, transforming traditional business practices, and opening new revenue streams.

In the healthcare sector, for example, DT supports the creation of innovative business models that can revolutionize clinical practice and enhance patient care. Integrating digital technologies allows new ways of delivering medical services, promoting health, and improving healthcare systems' overall efficiency (Mejía-Miranda et al. 2023). This transformation benefits patients and creates new revenue streams and business models for healthcare providers. HROs can solve the exploration–exploitation paradox through diverse DT initiatives. This involves adopting a strategic approach that fosters exploring new digital opportunities and exploiting established capabilities (Gastaldi et al. 2018). As a result, HROs can ensure sustainable growth and competitiveness in an increasingly digital landscape. Exploring new digital business models requires a focus on innovation, adaptability, and continuous improvement. HROs should invest in digital skills development, foster a culture of innovation, and encourage cross-functional collaboration to identify and capitalize on new opportunities. Exploiting existing digital capabilities involves optimizing

current operations, leveraging data analytics for better decision-making, and enhancing customer experiences through personalized and efficient digital services.

4.1.3 People and culture as distinct enabler of DT

Enabling the workforce to adopt digital literacy and adapt to emerging digital roles represents another distinct enabler for DT (Kallmuenzer et al. 2024). Developing digital literacy fosters the necessary skills among employees and creates a continuous learning environment within HROs. To support DT, HROs must prioritize developing digital competencies and internal capabilities (Chwiłkowska-Kubala et al. 2023). This prioritization involves implementing comprehensive training programs that enhance digital skills across the workforce, ensuring employees can effectively use new digital tools and technologies. For instance, addressing data quality and ensuring employees understand how to manage and utilize it properly is crucial for DT (Chwiłkowska-Kubala et al. 2023; Gizelis et al. 2023).

Moreover, hiring new employees with specialized digital skills helps bridge the gap between traditional practices and the demands of a digitally driven environment. Bringing in new talent with expertise in digital technologies ensures the organization has the technical expertise to develop and implement digital solutions (Latilla et al. 2020). Ensuring all employees, regardless of age or prior experience, have access to training programs that enhance their digital literacy is essential. This effort helps overcome resistance to using new systems and tools (Alzghaibi 2023). Creating user-friendly and accessible systems is also crucial in mitigating challenges related to digital literacy, ensuring broader acceptance and adoption of digital technologies (Mejía-Miranda et al. 2023).

Additionally, leveraging networks and intermediaries supports digital literacy initiatives by providing valuable resources and expertise. Collaborating with educational institutions, technology providers, and other stakeholders facilitates the development of accessible systems and tools that cater to diverse user groups, including those with limited prior experience with digital technologies (Mejía-Miranda et al. 2023). These partnerships enable HROs to build a supportive environment DT, enhancing overall operational efficiency.

4.2 Sustainability transformation

4.2.1 Distinct antecedents of sustainability transformation driven by regulatory and market forces

Meeting the demand for sustainable solutions without compromising reliability represents our framework's first distinct antecedent for ST. Demand for sustainable products from customers compels HROs to adopt more sustainable practices and innovations to meet the evolving expectations of their customer base, thereby driving comprehensive sustainability initiatives (Bjerkan & Ryghaug 2021). Customers are increasingly aware of the environmental impact of their products and services. This heightened awareness influences their purchasing decisions, favoring companies that are committed to sustainability. For example, operators have observed that users

are now more conscious of their energy systems' carbon and other environmental impacts, highlighting a growing preference for sustainable energy solutions (Tong et al. 2020). Steps towards sustainable development enhance operational efficiencies and contribute to increasing customer trust and loyalty. HROs prioritizing sustainability is seen as more reliable and trustworthy, particularly those fulfilling their disclosure requirements as listed companies. This transparency in sustainability efforts builds stronger customer relationships, reinforcing their commitment to sustainable practices (Lorenc & Kustra 2021).

Moreover, co-creating long-term visions with stakeholders, including customers, is essential in shaping the future of sustainable technologies. By involving customers and other stakeholders in envisioning sustainable solutions such as energy production and storage, autonomous systems, and alternative fuels, HROs can align their innovations with customer expectations and market trends (Bjerkan & Ryghaug 2021). This collaborative approach meets the current demand for sustainable products and anticipates future needs. Building strong networks with interested HROs, experts, and users is crucial for mobilizing collective action towards sustainability goals. These networks help foster a culture of sustainability, encouraging HROs to innovate and adopt sustainable practices in response to customer demand (Bjerkan & Ryghaug 2021).

The second distinct antecedent is to enforce radical change through regulation and guarantee operational stability. Regulatory frameworks and policies play a crucial role in enforcing radical changes necessary for ST. These regulations push enterprises to adapt strategically and operationally to meet environmental standards and policy requirements, driving significant advancements in sustainable practices.

Enterprises must adapt to changes in the external environment and make strategic modifications that comply with environmental policy requirements (F. Yu et al. 2023). Conflicts between national-level regulations and local development priorities often present significant barriers, indicating the complex landscape that enterprises must navigate (Kirch Kirkegaard et al. 2021; Tong et al. 2020). Despite these challenges, the regulatory and policy frameworks, rather than technological innovations alone, often drive the implementation of critical sustainability initiatives, investments in renewable energy, and the adoption of energy efficiency technologies (Bortoleto et al. 2021).

Regulatory constraints can hinder the ability of enterprises to freely develop their business models, particularly concerning expansion, mergers, and the pursuit of alternative technologies (Lieberherr & Truffer 2015). Operators face difficulties implementing significant changes because of the time-consuming and often protracted process of project approval within the political regulatory system (Lieberherr & Truffer 2015). However, these regulations also allow enterprises to gain competitive advantages through stricter environmental policies. For instance, various organizations view sustainability transitions as viable business opportunities that enhance their competitive edge, leading to the mobilization for stricter regulations and greener policies (Bjerkan & Ryghaug 2021). Proactive environmental disclosure in response to governmental regulations can help HROs strive for government approval and align with environmental standards (Mosconi et al. 2022). Environmental regulations force enterprises to undertake green reforms and drive them to innovate to compensate for

environmental protection costs (Mosconi et al. 2022). Regulatory incentives have been instrumental in prompting companies to transition from traditional to more sustainable business models (Ngar-yin Mah et al. 2017).

4.2.2 Strategy as distinct enabler for sustainability transformation

Fostering long-term thinking and systematic change in sustainability is the distinct enabler in strategy for our framework. This enabler focuses on fostering radical innovations, restructuring organizational frameworks, and aligning leadership and talent with sustainability goals. ST necessitates significant structural changes within HROs. Technological advancements alone are insufficient; radical innovations often require broader structural changes (Damman & Steen 2021). For example, transitioning to renewable energy involves adopting new technologies and rebranding and redefining the organization's mission and strategy, as seen in companies transforming their entire business model towards 100% renewable energy (Lindberg & Kammermann 2021). Organizational restructuring plays a pivotal role in accelerating ST (Kirch Kirkegaard et al. 2021). This includes diversifying organizational functions, setting up dedicated transition teams, and creating specialized departments to support the transition process (Bosman et al. 2018). A change in leadership can also drive these transformations, bringing new perspectives and a renewed commitment to sustainability (Lippolis et al. 2023). Radical transformation of the organizational structure can significantly enhance business orientation and prepare the organization for sustainability-focused initiatives (Lippolis et al. 2023). This structural reorganization ensures that sustainability becomes a core aspect of the business strategy, rather than a peripheral concern. HROs that prioritize the development of strong R&D capabilities can better grasp the developments in sustainability. These resource-based enterprises can effectively allocate green innovation resources, leading the way in sustainable innovation (Mosconi et al. 2022).

4.2.3 Organizational resilience as distinct enabler for sustainability transformation

Exploring for sustainability solutions without disrupting critical operations focuses on building networks, exchanging knowledge, and collaborating with external experts to foster environmental protection, sustainable development while running stable operations. For instance, a hospital implements an energy-efficient heating, ventilation, and air conditioning (HVAC) system in non-critical areas, such as administrative offices, to reduce energy consumption and carbon emissions. This phased approach allows the hospital to evaluate the feasibility of the solution while ensuring that critical operations, such as patient care in surgical and intensive care units, remain unaffected by potential system downtime or performance issues (Del Regno et al. 2023).

HROs must actively seek knowledge and expertise from various sectors to drive sustainability initiatives. Engaging with experts from different fields allows HROs to gain diverse perspectives and innovative solutions for sustainable practices. For instance, forming strategic research alliances with universities and research centers facilitates the exchange of knowledge and strengthens the organization's capacity

for sustainable (open) innovation (Lieberherr & Truffer 2015; Wang et al. 2023). ST requires engaging with political parties, companies, and institutions that share a similar agenda. Building new partnerships and reassessing ongoing collaborations ensure that HROs align their sustainability goals with broader societal and environmental objectives. By forming technology-specific advocacy coalitions, HROs can build a broader constituency behind specific sustainable technologies and drive collective action towards sustainability (Lindberg & Kammermann 2021). Developing sensing capabilities through networks is essential for identifying new sustainability opportunities and challenges. HROs must optimize stakeholder engagement, including startups, universities, research centers, communities, customers, suppliers, NGOs, and international organizations (Lippolis et al. 2023). These networks provide valuable insights and resources that enable HROs to adapt to changing environmental conditions and advance their sustainability goals. For example, orchestrating a wide range of users and actors to develop joint zero-emission concepts, demonstrating the importance of external collaboration in achieving sustainability targets (Bjerkan & Ryghaug 2021). Technology coalitions allow HROs to pool resources and expertise to advance specific sustainable technologies. These coalitions create a supportive environment for innovation and facilitate the development and deployment of sustainable solutions. Strategic partnerships with academic institutions and research organizations further enhance the organization's technological capabilities and contribute to sustainability (Bosman et al. 2018).

4.2.4 People & culture as distinct enabler of sustainability transformation

Aligning the workforce towards sustainability means fostering a proactive mindset towards sustainable practices and ensuring that all stakeholders agree with the HROs sustainability goals. By creating a unified vision and encouraging collaborative efforts, HROs can effectively drive ST (Bosman et al. 2018). The alignment of actors towards sustainable production, operations, and value chains with shared expectations of a green future is another fundamental aspect (Bjerkan & Ryghaug 2021). Actors must prepare for a green future by reducing emissions and improving energy efficiency.

This alignment drives HROs to explore and implement sustainable solutions, ensuring that all stakeholders are working towards common sustainability goals (Bjerkan & Ryghaug 2021). The adjustment of risk-averse behavior is particularly important in HROs. Operators may become risk-averse which can be negative for innovation (Lieberherr & Truffer 2015). Encouraging a culture that embraces calculated risks, and innovation is essential for ST. This involves reducing resistance to transition by creating an environment that supports and rewards sustainable initiatives.

4.3 Twin transformation

Following our systematic review of existing literature on DT and ST, we identified several shared antecedents and enablers essential for both transformation processes. As such, these have been incorporated into the TT domain.

4.3.1 Shared antecedents of twin transformation driven by regulatory and market forces

Utilizing economic incentives is essential in enabling DT and ST, consequently serving in both transformations as a key antecedent for TT. By addressing cost-related barriers, leveraging financial resources and regulatory support, economic incentives facilitate the adoption of transformative practices across various organizational contexts. High costs associated with integrating new technologies present significant challenges, including infrastructure issues, technical support requirements, data regulations, interoperability issues, and security concerns (Abi Saad et al. 2024). HROs with greater financial resources can more effectively overcome these challenges, benefiting from economies of scale that positively influence DT (Raimo et al. 2023). A shift in business models and mindsets is also fundamental to enhance financial performance and transform internal capabilities (Carroll & Maher 2023). However, some HROs overestimate the costs of digital technology adoption, perceiving them as prohibitively high and deterring them from replacing established practices (Santarsiero et al. 2022, 2023). The high cost of errors in HROs further deters experimentation with new strategies lacking sufficient expertise (Ahmad et al. 2021). DT initiatives often require specific resources and expertise (F. Yu et al. 2023). It shows that financial constraints and lack of supportive legislation hinder the implementation of innovative practices (Q. Liu et al. 2021). However, access to central funds and governmental pressure can drive HROs to prioritize DT (Zhao & Canales 2021).

Economic incentives are equally critical in ST, even though as mentioned by Ardito et al., (2021), there is no evidence that combining digitalization and sustainability benefits a firm's performance. Increasing societal and governmental pressures, coupled with changes in leadership, create opportunities for a transition in management processes (Bjerkan & Ryghaug 2021; Bosman et al. 2018). Actors in various HRO industries often weigh the risks and benefits of sustainability, with a common assumption that initiatives will not be pursued if they entail economic losses (Abi Saad et al. 2024). Tong et al., (2020) argues that the demand for sustainable services, while driven by environmental considerations, must also align with cost-effectiveness to be viable. However, some organizations perceive sustainability as a competitive advantage, advocating for stricter regulations and greener policies to enhance their market positions (Bjerkan & Ryghaug 2021). Reforms aimed at sustainability frequently focus on cost-efficiency rather than radical innovation (Lieberherr & Truffer 2015) and in some instances, economic and industrial development ambitions drive sustainability initiatives rather than purely environmental motivations (Tan et al. 2021).

Overall, we observe that economic incentives are a pivotal antecedent for TT. Financial incentives and support structures can mitigate the high costs and perceived risks associated with DT and ST. By aligning economic benefits with transformative goals, HROs can overcome these challenges, leverage economies of scale, and integrate new technologies and sustainable practices more effectively. This intersection of economic and strategic incentives underscores the critical role of economic factors in driving comprehensive transformations within HROs.

Accelerating technological advancements improves operational efficiency and drives innovation, enabling HROs to achieve their transformative goals more rapidly and effectively. In DT, on the one hand advanced technologies like AI play a decisive role. They boost innovation potential, particularly in improving operational processes or forecasting demands contributing to a more efficient and innovative operational framework (Y. Liu & Song 2023; Lyu & Liu 2021). On the other hand, energy consumption, especially for the development of AI, are becoming concerns (Kolb et al. 2023). The training phase of AI models often considered the most energy-intensive, has been the focus of sustainability research recently (de Vries 2023). Resource-based enterprises highlight the importance of green innovation through digital technology, improving environmental efficiency (Mosconi et al. 2022). Efficient and connected information networks support information disclosure and provide resources for innovation. Digital technology enables HROs to realize green technology innovation swiftly, with lower input costs, offsetting the costs of environmental regulations (Mosconi et al. 2022).

For ST, implementing innovative technologies is equally crucial. The OECD recommends combining technological, operational, and alternative energy measures to achieve sustainability goals (OECD 2019). HROs ambitiously adopt new technologies to enhance sustainability performance, such as electric charging systems, alternative fuels, and other green technologies (Bjerkan & Ryghaug 2021).

Combining these insights to form a cohesive antecedent, technology innovation emerges as a pivotal antecedent for TT. Advanced technologies facilitate DT and ST by fostering innovation capabilities, reducing costs, and improving operational efficiency. This integration underscores the critical role of technological innovation in driving comprehensive and synergistic transformations within HROs.

Catalyzing green transformation through digital technologies provides a significant entry point for HROs to enhance their green innovation abilities. These technologies promote the integration and efficient flow of green innovation resources (He et al. 2024; Y. Liu & Song 2023; Mosconi et al. 2022). The application of advanced digital solutions, such as Artificial Intelligence (AI), cloud computing, and other emerging technologies, significantly enhances organizational productivity and innovation efficiency, thereby facilitating green transformation (Ahmad et al. 2021; Roppelt et al. 2024; Schwaeke et al. 2025). The role of AI is noteworthy, as it supports various green initiatives such as optimizing energy storage, forecasting energy demands, and integrating renewable energy sources in utilities. These AI applications contribute to the growth of low-carbon electricity generation and have substantial long-term impacts on achieving sustainability goals (Ahmad et al. 2021). Digital solutions also empower HROs to optimize green production processes, reduce pollution control costs, and improve overall environmental efficiency (Mosconi et al. 2022).

The growth of digital technology is critical in driving the green and low-carbon transformation necessary to meet these targets. By leveraging technological power and innovative innovations, HROs can significantly enhance their sustainability efforts (Y. Liu & Song 2023; F. Yu et al. 2023). Digital advancements foster a conducive environment for green technology innovation, which is fundamental to generating new technologies and improving existing processes. This, in turn, leads to more efficient and cost-effective solutions for environmental challenges. As HROs adopt

digital technologies, they are better positioned to innovate and implement sustainable practices that contribute to long-term environmental goals (Mosconi et al. 2022).

4.3.2 Strategy as shared enabler of twin transformation

Developing integrated risk-responsive strategies aligns organizational goals with transformative initiatives, ensuring safety, coherence and effectiveness in achieving digital and sustainability objectives. In DT, HROs need a coherent strategy that aligns business problems with appropriate digital technological initiatives. This requires setting concrete strategies, onboarding personnel with relevant skillsets, and orchestrating efforts through a central team to ensure alignment with business needs and culture (Kokshagina 2021). Fostering interactions among top management, professionals, and technical teams is crucial for developing an effective knowledge strategy supporting digital initiatives (Manny et al. 2021; Zhao & Canales 2021). Digitalization connects bottom-up technological innovation with top-down organizational, cultural, and systematic changes (Denicolai & Previtali 2023). This bridging function is essential for integrating technological advancements into the broader strategic framework, ensuring systematic alignment with organizational objectives.

For ST, strategic development involves embedding sustainability into the core business strategy. When strategy changes impact the entire business model, top management should assign a central role to sustainability, integrating it into all aspects of operations (Lippolis et al. 2023). Emphasizing the financial effects of operations and building positive stakeholder relations encourages enterprises to incorporate sustainable development policies into their strategies (Lorenc & Kustra 2021). Strategic alignment between sustainability goals and business objectives is essential for driving comprehensive transformation. Parallelizing these measures by developing a robust strategy is a pivotal enabler for TT. Strategy development for TT integrates top-down and bottom-up approaches, intersecting to influence transformation outcomes (Poláková-Kersten et al. 2023). This dynamic strategy leverages innovation while aligning digital and sustainability initiatives with organizational goals and fostering collaboration across all levels. A coherent strategy ensures DT and ST are effectively implemented, facilitating comprehensive and synergistic organizational change.

Successful strategy execution with phased implementation requires strategic alignment, dedicated management, stakeholder engagement, and a balance of top-down and bottom-up approaches. Effective strategy execution necessitates that all organizational units fully commit to transformation initiatives. Without this commitment, critical aspects of strategy implementation may falter, rendering senior management efforts ineffective (Poláková-Kersten et al. 2023). For DT leaders must possess a comprehensive understanding of the organization's digital and sustainable needs to ensure overall alignment (Johansson et al. 2022). This alignment requires managers to foster exploration and exploitation within their teams, empowering them to innovate while ensuring efficient execution of strategic plans (Latilla et al. 2020). The creation of dedicated departments or roles, such as strategy, Innovation, and Development, reporting directly to top leadership, can facilitate this process and ensure focused execution (Denicolai & Previtali 2023). However, the success

of digital strategies heavily depends on their adoption by end-users (Garcia-Perez et al. 2023). Balancing technological excellence with economic sustainability requires a mix of incremental and radical improvements, integrating top-down and bottom-up initiatives (Denicolai & Previtali 2023). In the context of ST, dedicated managers for environmental and energy issues are essential. Engaging stakeholders in the transition process is also crucial for successful execution (Damman & Steen 2021). Transition management processes need to be prepared in close cooperation with strategic departments, ensuring that strategic experimentation and reflexivity are integrated into the overall execution plan (Bosman et al. 2018). Sustainability transitions often require a dual strategy incorporating existing economic activities and new, innovative approaches. This involves system optimization, such as carbon capture and storage, alongside system innovation for sustainable, low-carbon production (Bosman et al. 2018). Strategic execution in this context is about managing the unpredictable nature of transitions through continuous experimentation and adaptation. Overall, executing strategy is a pivotal enabler for both transformations. It involves ensuring strategic alignment, fostering dedicated management roles, engaging stakeholders, and balancing top-down and bottom-up initiatives. This comprehensive approach ensures that DT and ST are effectively implemented, aligning with organizational goals and driving systemic change.

4.3.3 Data & IT as shared enabler of twin transformation

Leveraging data analytics to align safety, efficiency, and sustainability is another pivotal TT enabler. Developing and integrating IT and technology capabilities ensures that HROs are well-equipped to manage and implement transformative initiatives effectively. For DT, HROs must develop enabling capabilities before executing a digital strategy. This preparation ensures maturity for sustaining the transformation (Oliveira et al. 2024). The process involves overcoming DT gaps by developing new processes, assets, and competencies (Pundziene et al. 2022). HROs must be aware of changes in external and internal environments and build digital capabilities in areas such as AI, Blockchain, and the IoT (Bhatti et al. 2021; Fernandez-Vidal et al. 2022; Spanò et al. 2023). Sustainable DT depends on developing digital skills and capabilities and following their dynamic evolution (Akadiri et al. 2025; Hou et al. 2024). This includes hiring new employees, training the existing workforce, and ensuring management is equipped to manage new digital tools (Latilla et al. 2020; Ulrich et al. 2024; Zhao & Canales 2021). Structural IT capabilities, combined with dynamic capabilities (DCs), support the structural change in DT, encompassing technical IT integration and organizational and individual competencies (Ghosh et al. 2023). DCs are in this case critical for HROs to adapt to changing environments, innovate, and to maintain their competitive advantage (Eisenhardt & Martin 2000; Teece et al. 1997; Winter 2003). Emerging digital technologies like big data and cloud computing play a significant role in transforming sectors (Basile et al. 2024; Bhatti et al. 2021; Lyu & Liu 2021; Meske et al. 2021). HROs must view technology as a strategic investment rather than just a cost (Ghosh et al. 2023). Training programs for managing DT and operating new platforms are essential for improving employee efficiency and skill output (Giraldo et al. 2021; Y. Yu et al. 2024). Technology capabilities drive innova-

tion, enhance efficiency, and integrate sustainable practices into business strategies, thus contributing to the overall sustainability goals and ensure that HROs remain competitive and effective in achieving long-term sustainability. Leveraging technology capabilities in ST involves incremental learning and experimentation with specific technologies. This "learning by doing" approach allows HROs to integrate new technologies gradually (Bjerkan & Ryghaug 2021). Establishing dedicated data departments and transition teams supports this integration (Bosman et al. 2018). Building technology-specific advocacy coalitions and networks is crucial for ST, supporting the diffusion of knowledge and resources (Lindberg & Kammermann 2021). Collaboration with external research networks enhances technical IT-expertise and innovation capacity, facilitating the development of technical standards and sustainable solutions (Ngar-yin Mah et al. 2017). Essentially, leveraging IT and technology capabilities is a fundamental enabler for TT. HROs must develop and integrate a wide range of digital and technological competencies to manage and implement transformative initiatives effectively. For example, an airline uses data analytics to optimize flight paths, reducing fuel consumption and carbon emissions while ensuring strict compliance with air traffic safety regulations (Bailey et al. 2023). By integrating real-time weather data, air traffic conditions, and fuel efficiency metrics, the airline aligns operational goals with sustainability targets without compromising passenger safety. This comprehensive approach ensures that DT and ST are supported by robust technological foundations, driving innovation and operational efficiency.

Harmonizing and using data for proactive decision-making focuses on addressing data privacy, quality, and integration challenges to ensure that data-driven decision-making processes can be effectively implemented across organizational contexts. Within DT, data protection is a significant concern. Trust in data sharing must be considered from technological and ethical perspectives, especially in highly regulated industries that must comply with stringent ethics, safety, and data privacy standards (Gizelis et al. 2023; Pundziene et al. 2022). Resistance to sharing sensitive data further slows the adoption and diffusion of digital technologies (Santarsiero et al. 2023). Privacy and security are among the most pressing concerns, with issues such as data uncertainty and unreliable analysis posing significant challenges (Ahmad et al. 2021; Q. Liu et al. 2021). Data quality is another major factor impacting DT (Manny et al. 2021). Many HROs struggle with the quality of their data, affecting the effectiveness of data-driven operations (Tortorella et al. 2022). Integration challenges, such as the lack of standardized methods to collect data within and across departments or interoperability, can lead to efficiency losses and critical operational issues (Kokshagina 2021). Addressing these data quality and integration issues is essential for leveraging digital technologies effectively (Ghosh et al. 2023; Giraldo et al. 2021). Concurring in ST, data plays a pivotal role in designing efficient systems and driving green energy initiatives. For instance, building a global data governance system can reduce production costs and support the development of sustainable energy solutions through big data analysis (Mosconi et al. 2022). Data-driven approaches enable HROs to optimize their business practices and achieve sustainability goals more efficiently (Tong et al. 2020).

Combining insights from both contexts, harmonizing and using data becomes a foundational enabler for TT. HROs must harmonize data and establish robust data

governance frameworks that address privacy, security, quality, and integration challenges. By developing standardized methods for data collection and ensuring data integrity, HROs can enhance their decision-making processes and support DT and ST initiatives. For instance, a shipping company harmonizes data from vessels, weather forecasts, and port traffic systems into a centralized analytics platform. This integration enables proactive decision-making, such as optimizing routes to reduce fuel consumption, avoiding adverse weather to ensure crew and cargo safety, and minimizing emissions to meet sustainability targets (Kaklis et al. 2022). Furthermore, fostering a culture of trust and ethical data management is inevitable. HROs need to ensure that data sharing and usage comply with regulatory standards and build trust among stakeholders. This ethical approach to data management supports the broader goals of TT by aligning technological advancements with societal and environmental responsibilities.

4.3.4 Organizational resilience as shared enabler of twin transformation

Building innovation capabilities for risk-tolerant advances involves developing the necessary skills, structures, and processes to foster innovation, allowing HROs to respond effectively to evolving market demands and technological advancements while guaranteeing operational stability. For DT, developing innovation capabilities begins with assessing the maturity of digital tools and analyzing innovation capacities within different business areas (Giraldo et al. 2021). Implementing an innovative co-creation approach by involving stakeholders in the design and development process to ensure the success of digital initiatives can be advantageous (Meske et al. 2021). HROs must also focus on developing new business models that align with the digital strategy and customer needs, enhancing their ability to seize new opportunities (Giraldo et al. 2021). Fostering a culture of continuous learning and adaptation is vital. This includes training employees in new skills, integrating innovation capabilities across the organization, and promoting an environment that supports experimentation and risk-taking (Zhao & Canales 2021). HROs need to balance exploring new digital opportunities with exploiting existing capabilities, ensuring sustainable growth and competitiveness in the digital landscape (Gastaldi et al. 2018).

In the context of ST, innovation capabilities are equally central. HROs need to expand their business models to address new areas within the environmental field, such as ecosystem services and sustainable resource management (Lieberherr & Truffer 2015). Establishing dedicated innovation departments and integrating sustainability into core business strategies are key steps in this process. These departments can focus on developing solutions to address climate change, enhance energy efficiency, and promote sustainable practices (Lieberherr & Truffer 2015). Collaboration with external research institutes, universities, and industry partners is essential for strengthening technological expertise and innovation capacity (Ngar-yin Mah et al. 2017). By participating in long-term research and development networks, public–private partnerships, and funded projects, HROs can stay at the forefront of technological advancements and sustainability practices (Damman & Steen 2021). An example of integrating innovation and sustainability is the creation of roles specifically focused on combining these elements within the organizational structure. For

instance, the introduction of an "innovability" function, which combines innovation and sustainability under direct leadership, ensures that both elements are strategically aligned and effectively managed (Lippolis et al. 2023). This approach fosters a holistic view of innovation, embedding it within the organizational culture and aligning it with sustainability goals. Ultimately, building innovation capabilities is a central enabler for TT.

Establishing strategic agility to manage interdependencies between transformations involves enhancing the HROs capabilities to reconfiguring its structure and fostering an environment that can rapidly adapt to changing circumstances. For DT, this involves developing structural IT capabilities that support the basic conditions for transformation and ensuring connectivity and interoperability across the organization (Kokshagina 2021). Reconfiguring processes to increase flexibility and agility in IT delivery and ensuring technical readiness and support (Garcia-Perez et al. 2023). In ST, DCs are vital for enabling HROs to implement radical innovations and structural changes for sustainable development (Damman & Steen 2021; Weiss & Kanbach 2021). Developing sensing capabilities within DCs is a key for strategic agility, allowing HROs to actively respond to environmental opportunities and threats. This includes leveraging collaborations with external partners, such as universities and research centers, to stay ahead of technological and market trends (Lieberherr & Truffer 2015). By continuously monitoring the external environment, HROs can identify new opportunities for digital and sustainable innovations to adjust their strategies, accordingly, maintaining competitiveness in rapidly changing markets. HROs may need to transition from traditional to more flexible, business-oriented structures. For example, shifting from a divisional to a matrix model can better support sustainability objectives (Lippolis et al. 2023). Additionally, fostering interdisciplinary knowledge within cross-functional teams builds resilience and supports integrating new technologies and sustainable practices. This adaptability is crucial for overcoming traditional business model inertia and effectively responding to transformation pressures (P. Liu & Wu 2023).

Overall HROs must be able to quickly adjust their strategies to incorporate new digital technologies and sustainable practices. This includes developing new business models focused on efficiency and sustainability, ensuring that all parts of the organization are aligned with these strategic goals (Ghosh et al. 2023; Lippolis et al. 2023). By aligning strategic initiatives with operational capabilities, HROs can effectively implement transformative changes and achieve long-term sustainability and digital objectives. By ensuring strategic agility, HROs can effectively navigate the complexities of DT and ST, aligning resources and processes to meet evolving demands. These capabilities allow HROs to reconfigure their resource allocation in response to unexpected circumstances, ensuring they can swiftly adapt to new challenges and opportunities (Ghosh et al. 2023; Y. Liu & Song 2023; YahiaMarzouk & Jin 2023).

Performing error-free while implementing digital and green solutions is a crucial requirement for HROs, ensuring they maintain high-reliability and safety standards while implementing digital and sustainable initiatives. This critical enabler involves managing inherent risks, fostering resilience, adaptability, and a culture of continuous improvement. The challenge of DT compels HROs to simultaneously meet economic objectives and fulfil their social responsibilities while maintaining error-free opera-

tions. Building institutional resilience is essential for HROs, enabling them to manage unexpected events and maintain high performance levels effectively. As highlighted by Jabłoński & Jabłoński, (2021), resilience is a cornerstone of high-reliability, supported by fostering interdisciplinary knowledge within cross-functional teams and ensuring technical readiness and support. This interdisciplinary approach enhances the organization's technical capabilities and promotes a holistic understanding of the challenges at hand, thus enabling more effective solutions (Garcia-Perez et al. 2023).

Moreover, HROs must be adept at sensing opportunities and threats in the external environment. This involves closing the gap between core business activities and emerging digital opportunities, ensuring they can diversify and adapt to changing market conditions. By doing so, they can remain competitive and resilient in the face of external pressures (Fernandez-Vidal et al. 2022; Liu & Wu 2023). ST presents additional challenges for HROs, requiring them to build sustainable alternatives while phasing out unsustainable practices. This process demands radical innovations and comprehensive reconfiguration of existing systems and processes. For example, utilities must balance safety, security, and reliability with the need for innovation and cost reduction. This balance is essential to ensure that while they innovate and adopt new technologies, they do not compromise on safety and reliability (Bosman et al. 2018; Imperiale et al. 2023). In conclusion, the path to achieving error-free performance during transformation for HROs is multifaceted, involving the integration of resilience, adaptability, and continuous improvement into their core operational frameworks. By fostering interdisciplinary knowledge, sensing external opportunities and threats, and embracing sustainable transformation, HROs can maintain high-performance standards and achieve long-term success (Fig. 3).

4.3.5 People & culture as shared enabler of twin transformation

Promoting a mindset of systemic thinking where digital and sustainability goals are pursued cohesively includes developing new competencies, fostering an open mindset, and aligning organizational values within the HRO staff. DT requires developing new competencies and internal capabilities. This involves hiring new employees, enhancing skillsets, and providing continuous training to improve digital literacy among the workforce (Ghosh et al. 2023; Giraldo et al. 2021). Empowering employees as change agents is crucial, as they drive innovation and support the transformation process internally (Aerts et al. 2023). A shift in organizational mindset is necessary to overcome internal resistance that can derail transformation efforts. Fostering a culture responsive to innovation and utilizing networks and intermediary organizations to facilitate change is essential (Denicolai & Previtali 2023).

Effective communication is critical to explaining the need for DT, creating a risk-agreeable space, and building employee trust. This accelerates the adoption of new technologies and practices (Carroll & Maher 2023). Enhancing digital literacy, providing the necessary technical support, and training can significantly boost an organization's capacity to implement DT initiatives (Ahmad et al. 2021). Creating a dedicated transition unit within the organization can support the cultural shift towards ST. This unit can align actors towards sustainable production, operations, and value

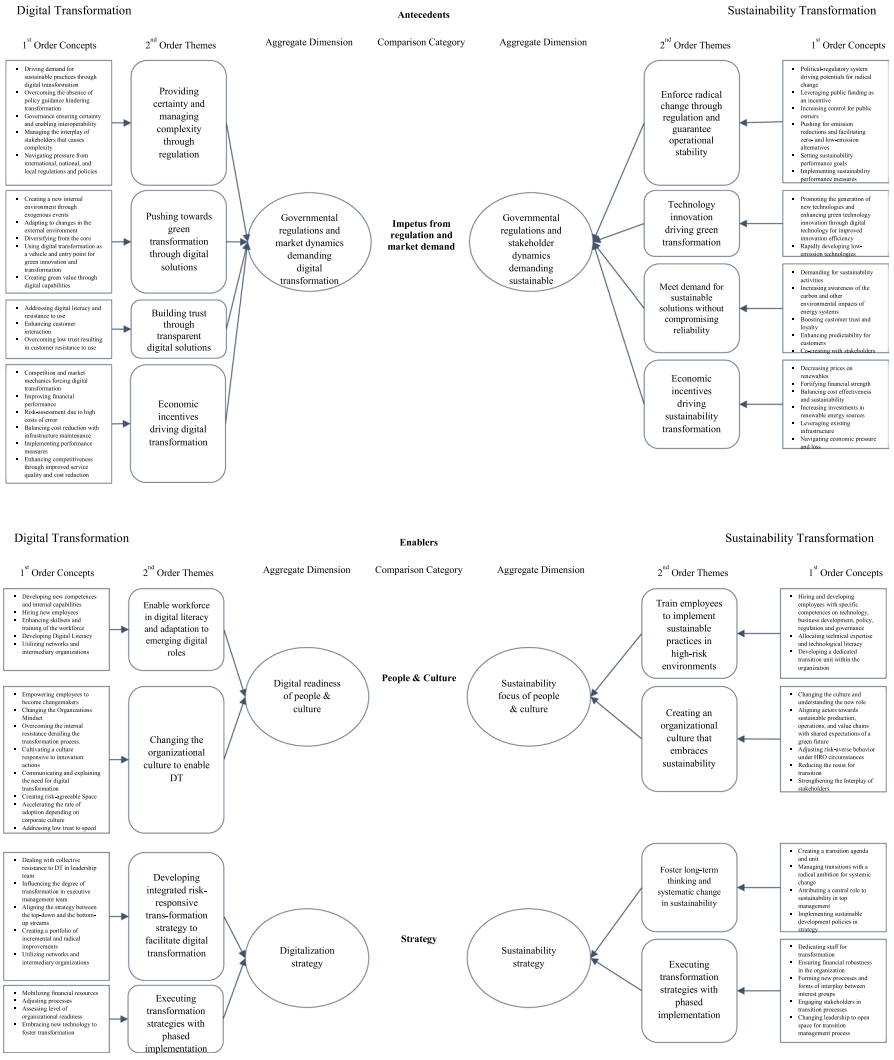

Fig. 3 Data structure – Twin Transformation, source: authors' own work

chains, ensuring everyone within the organization shares the expectation of a green future (Bjerkan & Ryghaug 2021).

Changing the culture to embrace the organization's new role in sustainability is vital for reducing resistance to transition and adjusting risk-averse behavior (Bosman et al. 2018). Hiring and developing employees with competencies in sustainability-related fields, such as technology, business development, policy, regulation, and governance, ensures readiness to drive sustainable practices (Bosman et al. 2018; Correia & Frank 2025). These aspects are important for DT and ST and contribute to TT. Strengthening stakeholder interplay by engaging with political parties, companies, and institutions with similar agendas helps build a supportive network driving

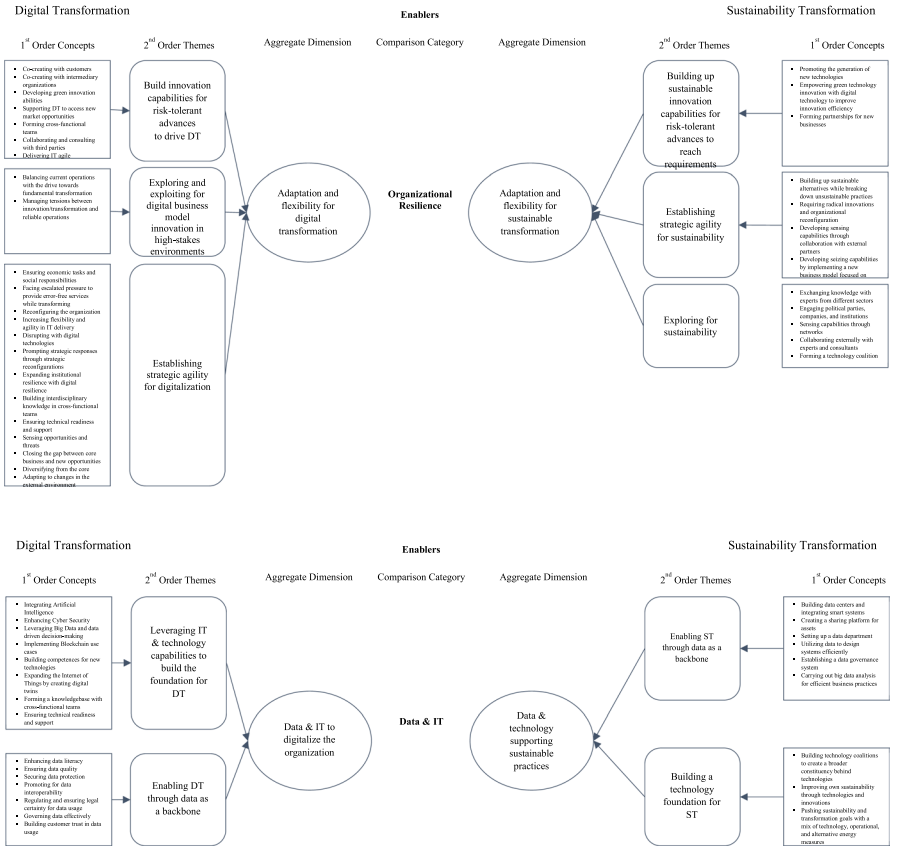

Fig. 3 (continued)

collective action towards TT. This includes fostering interdisciplinary knowledge, sensing external opportunities and threats, and embracing DT and ST to maintain high-performance standards (Garcia-Perez et al. 2023). Comprehensive training covering digital literacy and sustainability can enhance the organization's overall capacity to implement TT initiatives (Ahmad et al. 2021).

4.3.6 Outcomes of digital, sustainability and twin transformation

The outcomes of this framework for transformation are exemplary. DT individually can lead to several positive outcomes, including improved efficiency through streamlined processes, automation of tasks, and optimized workflows, which in turn enhance productivity and reduce operational costs (Ali Mohamad et al. 2023). Moreover, DT enables organizations to collect, analyze, and leverage vast amounts of data to gain insights into customer behavior, market trends, and internal operations, thereby supporting informed decision-making. It encourages HROs to rethink their business models, often resulting in new revenue streams, value propositions, and enhanced market positioning (Lyu & Liu 2021). ST can return multifaceted outcomes, includ-

ing regulatory compliance and effective risk management through adherence to sustainability standards and regulations (Lieberherr & Truffer 2015).

Furthermore, proactive sustainability measures facilitate anticipating and proactively addressing of emerging regulatory requirements. HROs prioritizing sustainability cultivate trust with customers, investors, employees, and communities, highlighting their unwavering commitment to social and environmental responsibility (Tong et al. 2020). This endorsed trust enhances reputation and fosters beneficial relationships. Moreover, ST holds the potential to generate substantial long-term value by aligning business strategies with the imperatives of sustainable development. HROs that seamlessly integrate environmental and social considerations into their core business strategies are strategically positioned for enduring success and resilience in the face of evolving challenges. This can include competitive advantages within the scope of TT by embracing both transformations simultaneously. HROs that proactively address sustainability concerns and leverage digital technologies to drive efficiency and innovation are better positioned to adapt to evolving market demands and differentiate themselves. Both transformations, when approached combined, foster innovation. HROs that proactively address sustainability concerns and leverage digital technologies to drive efficiency and innovation are better positioned to adapt to evolving regulatory and market demands (Bjerkan & Ryghaug 2021). Streamlining processes and workflows through automation, data-driven decision-making, and real-time monitoring can improve operational efficiency. When coupled with sustainability goals, this can lead to more efficient resource allocation, reduced energy consumption, and lower carbon emissions (Mosconi et al. 2022).

4.4 Conceptual framework on DT, ST, and TT for HROs

Using the data structure of the DT and ST samples, we developed a conceptual framework (Fig. 4) that categorizes the distinct (DT/ST) and the shared (TT) antecedents and enablers for each transformation type based on key comparison categories. This framework also outlines potential outcomes specific to each transformation. Shared antecedents and enablers, identified across data samples, are essential for TT, whereas distinct antecedents and enablers are required solely for DT or ST.

Various categories, such as strategy, data and IT, organizational resilience, or people and culture have been identified (e.g. Chwiłkowska-Kubala et al. 2023; Giraldo et al. 2021; Santarsiero et al. 2023). Within these broader categories, distinct and shared enablers were mapped to their corresponding transformation types. Through this SLR, which aims to integrate and contextualize the antecedents and enablers for DT, ST and TT, 7 antecedents and 13 enablers were identified.

The proposed conceptual framework demonstrates that 3 antecedents are directly connected to the TT process, while 2 are specifically related to DT or ST. Of the 13 enablers identified, 8 are shared between DT and ST and merging into the TT stream (see Table 1). These findings underscore the importance of shared enablers across both transformations.

The following empirical examples from the DT and ST samples illustrates how the shared TT enablers can materialize in practice. For instance, a European hospital's stroke unit exemplified an integrated, risk-responsive strategy by combining digi-

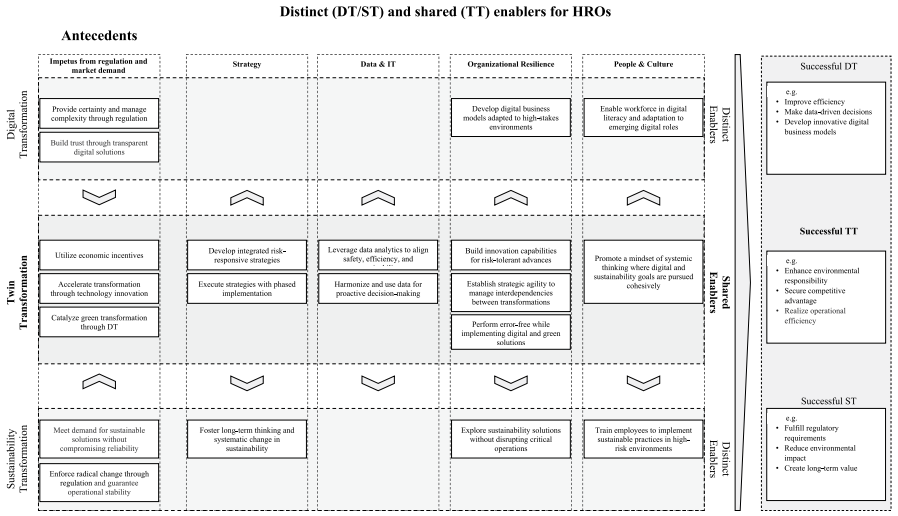

Fig. 4 Conceptual framework – Twin Transformation in High-Reliability Organizations, source: authors' own work

tal patient-management systems with process redesign, leading to both faster treatment and better clinical outcomes (Kokshagina 2021). In the same institution, phased implementation of digital tools in the cardiology department supported Value-Based Healthcare (VBHC), allowing iterative refinement across system levels. Moreover, healthcare organizations have used predictive analytics to optimize bed usage, aligning safety, efficiency, and sustainability goals (Denicolai & Previtali 2023). Beyond healthcare, AI-driven tools like predictive maintenance and intelligent chatbots have enabled proactive decision-making and improved resource use, demonstrating how data harmonization can drive both digital and sustainable outcomes (Gizelis et al. 2023). These examples ground the theoretical model in real-world settings, highlighting the tangible interplay of digital and sustainability goals within complex, risk-sensitive environments (Table 2).

5 Discussion

5.1 The development of an extended conceptual framework on DT, ST and TT

To enhance missing pieces from the focus on HRO, we analyzed, compared, and integrated key findings from existing non-HRO literature reviews and their resulting frameworks. Given the scarcity of comprehensive perspectives on TT, we compared our HRO framework with insights from two significant studies, identifying overlapping and new components and expanding its foundational scope.

As part of this framework expansion, we identified overlapping elements from prior literature, indicated with a single asterisk (*) in Fig. 5 while integrating additional core elements related to TT antecedents and enablers, clearly marked with a double asterisk (**). This distinction allows for a clear understanding of the origins

Table 2 Overview of Shared and Distinct Enablers for TT in HROs

Shared TT Enablers (DT + ST)	Distinct Enablers (DT or ST)
(1) Develop integrated risk-responsive strategies	DT: (1) Develop digital business models adapted to high-stakes environments
(2) Execute strategies with phased implementation	DT: (2) Enable workforce in digital literacy and adaptation to emerging digital roles
(3) Leverage data analytics to align safety, efficiency, and sustainability	ST: (1) Foster long-term thinking and systematic change in sustainability
(4) Harmonize and use data for proactive decision-making	ST: (2) Explore sustainability solutions without disrupting critical operations
(5) Build innovation capabilities for risk-tolerant advances	ST: (3) Train employees to implement sustainable practices in high-risk environments
(6) Establish strategic agility to manage interdependencies between transformations	
(7) Perform error-free while implementing digital and green solutions	
(8) Promote a mindset of systemic thinking where digital and sustainability goals are pursued cohesively	

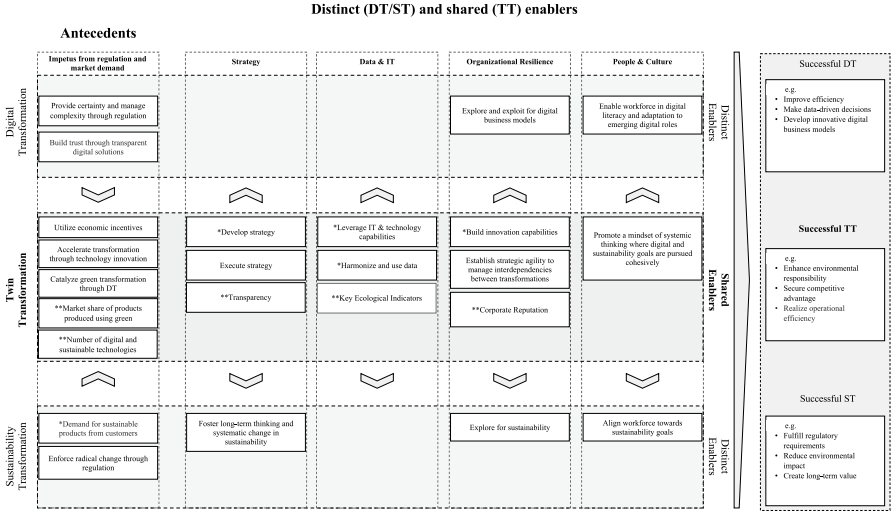

Fig. 5 Extended conceptual framework – Twin Transformation, source: authors' own work

of each component, ensuring that the framework comprehensively captures the foundational aspects of TT and the broader dynamics emerging from the literature.

The first study, conducted by Burinskienė & Nalivaikė, (2024), explored TT in small and medium enterprises (SMEs), introducing 4 enablers for TT: (1) resource productivity levels achieved during the transformation process, (2) market share of products produced using green technologies, (3) the number of digital technologies adopted, and (4) the number of sustainable technologies applied by SMEs. Integrating these insights allowed us to incorporate resource productivity and technological integration as core components of the extended framework.

The second study, by Vandevenne et al., (2023), focused on green enterprise architecture as a foundation for sustainable DT. This work introduced one additional antecedent (1) economic performance, and three enablers: (1) transparency, (2) key ecological indicators, and (3) corporate reputation. These elements were incorporated to add dimensions related to transparency and reputational factors, broadening the framework to emphasize ecological and economic forces.

By integrating these additional components, we ensured that our TT framework transcended the specifics of HRO literature, addressing TT in a more diverse set of organizational contexts. This more comprehensive approach aims to provide broader applicability for organizations beyond HROs, capturing the complexity and the opportunities inherent in simultaneous digital and sustainability transformations.

5.2 Theoretical contributions

This study makes two theoretical contributions. First, the HRO-specific TT framework developed in Chapter 4 advances theory by contextualizing TT in safety–critical environments, adapting siloed DT and ST perspectives to high-reliability settings. Second, the extended TT framework developed in Chapter 5.1 broadens the scope of theorization by integrating insights from non-HRO studies, ensuring that the conceptualization of TT is both context-specific and generalizable.

The extended TT framework addresses a novel research gap by integrating DT and ST. It uniquely adapts existing siloed theories to the challenges of TT in and out of highly regulated, risk-averse environments where safety and reliability are critical (Poláková-Kersten et al. 2023; Weick 1987). By synthesizing antecedents, enablers, and outcomes, the framework bridges previously isolated streams of research (e.g. Schallmo et al. 2022; Waring et al. 2023).

The comparison between our HRO-specific and extended TT frameworks highlights three contributions regarding similarity, distinctiveness, and absence of antecedents, enablers, and outcomes. First, several enablers such as strategy execution, data governance, and organizational resilience consistently appear across DT, ST, and TT studies, which underscores their shared relevance. Second, our analysis identifies distinct antecedents and enablers that earlier frameworks have not considered in depth, for example digital literacy in HROs or stakeholder alignment around sustainability, which reflect the unique demands of safety–critical contexts. Third, some anticipated elements in prior frameworks, including broad ecological indicators or corporate reputation in sustainability-focused studies, were largely absent in the HRO literature, which suggests contextual blind spots. By systematically integrating shared, distinct, and missing elements, our TT frameworks clarify both the overlap with existing theorization and the novel contributions required for high-reliability settings.

The framework identifies several shared enablers (e.g. Lippolis et al. 2023; Lyu & Liu 2021) while highlighting distinct factors such as digital literacy and emerging digital roles (e.g. Ahmad et al. 2021). Novel synergies, such as establishing strategic agility, reveal how enablers can manage interdependencies between the transformations (e.g. Alzghaibi 2023; Lippolis et al. 2023). These findings align with recent SME research showing that TT enablers are shaped by contextual conditions

(Burtscher et al. 2025). In contrast to SMEs, where external ecosystems help to overcome constraints, our analysis highlights that HROs must reconcile transformation with stringent reliability demands, underscoring the need for a tailored framework.

Together, the HRO-specific and extended frameworks contribute to theory by clarifying what distinct and shared antecedents, enablers, and outcomes must be considered across different organizational contexts. To the best of the authors' knowledge, this is the first study synthesizing a conceptual framework for TT in and outside of HROs from combining literature on digital and sustainability transformations, answering calls for research (e.g. Burinskienė & Nalivaikė, 2024; Guandalini 2022). The existing literature in this field is focusing on either DT or ST and has proceeded in separate research streams. By integrating these streams into one framework, the study adds conceptual clarity and extends existing theoretical discussions. The results from this framework for TT show consistency with previous research focusing on the individual transformations of DT or ST with their outlined capabilities and enablers (Konopik et al. 2022; Linnér & Wibeck 2021; Schallmo et al. 2017). In this manner, the systematic literature review achieves its objective of contributing to the academic discourse and enhancing decision-making processes for policymakers and managers (Kraus et al. 2020).

5.3 Practical and managerial implications

Beyond its theoretical value, this study provides actionable guidance for practitioners. The insights derived from our extended conceptual framework provide several actionable recommendations for managers. These recommendations focus on the collective assessment and development of DT and ST, acknowledging the overlapping enablers and fostering a holistic approach to organizational change.

One of the key managerial implications is the necessity to approach both DT and ST collectively rather than in isolation. The extended conceptual framework indicates that most enablers are shared to both transformations, suggesting that a synchronized strategy can enhance efficiency and coherence in achieving transformational goals. Managers should conduct comprehensive assessments that consider the interdependencies between DT and ST, leveraging shared resources and capabilities to address both transformation needs simultaneously. This integrated approach of applying both DT and ST can prevent resource duplication and ensure that the organization's strategic objectives are aligned across all transformation efforts.

Given that the extended conceptual framework identifies a substantial overlap in the enablers required for both DT and ST, it is practical for managers to develop these enablers collectively. The ten shared enablers should be the focal points of development initiatives. By concentrating efforts on these shared enablers, managers can create a unified transformation strategy that supports both digital and sustainability goals. This not only maximizes resource utilization but also fosters a more cohesive organizational culture geared towards comprehensive transformation.

The reciprocal nature of DT and ST highlighted in the extended conceptual framework suggests that advancements in one area can support and reinforce progress in the other. Managers should recognize and exploit these synergies, ensuring that initiatives in DT are designed to complement and enhance sustainability efforts, and vice versa. For instance, digital tools and data analytics can be leveraged to optimize sustainability initiatives, while sustainability principles can guide the ethical and responsible implementation of digital technologies. Emphasizing this reciprocity can amplify the impact of transformation efforts, leading to more robust and sustainable organizational change.

5.4 Limitations

The interpretation of qualitative data and thematic analysis in the literature review process introduces an element of subjectivity. The theoretical and practical contributions of this research are subject to the limitations inherent in the chosen methodology and the constraints of the research project (Tranfield et al. 2003).

Different researchers might interpret the same data differently, leading to variations in the identified themes and enablers. Personal bias cannot be eliminated entirely, even with a transparent sampling and analysis process. Despite discussing the methodology and preliminary results with fellow researchers at relevant conferences, resource limitations prevented conclusive evidence (Kraus et al. 2020).

SLRs are generally regarded as providing strong evidence, however, their findings are fundamentally shaped by the nature and scope of the available literature. One significant limitation, stemming from the inherent constraint of the literature review methodology, is the fragmented nature of the existing body of knowledge on DT and ST.

Consequently, the proposed TT framework, derived from this synthesis, might reflect these imbalances, perhaps by not fully articulating certain synergistic relationships or by being skewed towards more established theoretical viewpoints present in the literature. For instance, our analysis of the included studies revealed a notable industry-specific focus. In the DT sample, healthcare (57%) and the energy/utilities sector (32%) were predominant. Similarly, the ST sample showed a strong concentration in the energy/utilities sector (63%) and transportation (15%). While this reflects the critical importance of DT and ST in these areas, this concentration means that the insights derived, and the enablers identified in our SLR may be influenced by the specific contexts, challenges, and operational realities of these sectors.

Furthermore, the methodological leaning towards case studies across both samples could also introduce a bias. This emphasis might lead to a framework that prioritizes operational and implementation aspects, potentially underemphasizing broader strategic considerations or theoretical nuances that other research methodologies might reveal.

Such systemic biases and concentrations within the literature could mean that our SLR and the derived framework may not fully capture the spectrum of challenges, failures, or contextual variations crucial for a comprehensive understanding of DT and ST transformations across a wider array of industries or organizational types. This, in turn, may limit both the theoretical generalizability of our framework and its immediate managerial applicability beyond the contexts most represented in the sample.

The selection criteria for reviewed articles also introduce limitations that affect the SLR's outcomes and the subsequent framework. The first-level inclusion criteria, which were based on journal rankings, led to the inclusion of articles from high-quality academic journals (Fig. 1). However, this also resulted in the exclusion of contributions such as conference proceedings and articles from lower-ranked or unranked journals. This decision, while aimed at ensuring a certain level of academic rigor, might have inadvertently omitted valuable nascent insights, practical case studies, or critical perspectives more frequently discussed in conference proceedings or newer journals. As a result, the evidence base for our SLR, and thus the comprehensiveness of the TT framework, may be constrained, potentially missing out on cutting-edge developments or alternative viewpoints not yet consolidated in highly ranked publications.

Both DT and ST are dynamic and continuously evolving fields. The rapid pace of technological advancements and the changing landscape of sustainability challenges mean that the findings of this study and the TT framework may become less comprehensive or quickly outdated. Continuous updates and validations of the TT framework are necessary to ensure its relevance and applicability over time. Measuring the outcomes and impact of transformations, especially in a combined framework, is inherently complex. The study relies on the identified enablers and antecedents to infer the success of transformations, but quantifying these elements and their interactions can be challenging. The lack of standardized metrics for assessing the success of TT further complicates the evaluation process.

By acknowledging these limitations, the study provides a balanced view of its contributions and sets the stage for future research to address these gaps and build upon the initial findings.

5.5 Future research directions

The framework opens numerous avenues for future research. The novel approach of combining these two streams of transformation presents a comprehensive view that can significantly contribute to academic discourse.

Future transformation research should examine the development and refinement of integrated transformation models. The TT framework provides a foundational structure, but further empirical validation and theoretical elaboration are necessary.

Researchers can explore how different organizations implement integrated transformation strategies, identifying best practices, challenges, and outcomes. Comparative studies across industries and regions could shed light on the contextual factors influencing the success of these models (Burinskienė & Nalivaikė, 2024). The identification of distinct and shared enablers for DT and ST within the TT framework suggests that further investigation into the interdependencies of these enablers is warranted. Scholars should examine how these enablers interact and influence each other, both positively and negatively. Longitudinal studies could track the evolution of these interdependencies over time, providing insights into how HROs can strategically manage and leverage them for sustained transformation.

The TT framework highlights the importance of cultural change as a critical enabler for both DT and ST. Future research should explore the specific cultural attributes that facilitate successful transformations in HROs. Studies could investigate how different cultural dimensions such as risk aversion, innovation propensity, and resilience affect the implementation and outcomes of transformation initiatives. This line of inquiry can help in developing targeted interventions to foster a supportive organizational culture. The framework suggests a reciprocal relationship between DT and ST, where advancements in one area can support and enhance the other. Researchers should empirically test this reciprocity, examining case studies where digital innovations have driven sustainability outcomes and vice versa. Quantitative studies could measure the impact of integrated transformation efforts on organizational performance, sustainability metrics, and digital maturity.

There is a need for robust metrics and evaluation frameworks to assess the success of integrated transformation initiatives. Future research can contribute by developing and validating tools that measure the effectiveness of transformation strategies, capturing both digital and sustainability dimensions. These metrics can help organizations benchmark their progress and identify areas for improvement. Given the importance of regulatory guidance in HROs, future research should explore the policy and regulatory implications of integrated transformations. Studies could investigate how existing regulations facilitate or hinder the integration of DT and ST, and what changes are necessary to support holistic transformation efforts. Engaging with policymakers to translate research findings into actionable policy recommendations could enhance the practical impact of academic work.

Finally, future research should consider the broader impact of integrated transformations on various stakeholders, including employees, customers, suppliers, and the community. Qualitative studies could capture stakeholder perceptions and experiences, providing a nuanced understanding of the benefits and challenges associated with TT in HROs. This can inform strategies to enhance stakeholder engagement and support throughout the transformation process.

In summary, the conceptual TT framework and its extension offers a rich foundation for future research. By exploring these implications, scholars can contribute to a deeper understanding of how HROs and other types of organizations can successfully navigate the complexities of DT and ST, ultimately advancing both theory and practice in this evolving field.

6 Conclusion

Following the research question "*What are distinct and shared antecedents, enablers, and outcomes for digital and sustainability transformations and their integration as twin transformations in HROs*?", this study conducted a SLR to identify and develop a conceptual framework. We found that the simultaneous adoption of DT and ST is crucial for balancing operational efficiency, sustainability goals, and maintaining reliability standards. Our integrative framework consolidates distinct and shared antecedents, enablers, and outcomes for DT, ST, and TT, offering a structured understanding to guide HROs through the complexities of concurrent transformations.

To broaden the applicability of the conceptual framework beyond HROs, we adopted a comparative approach by synthesizing findings from previous non-HRO studies together with our initial framework to develop an extended conceptual framework. This resulted in an extended TT framework, contributing to a more holistic understanding.

This research offers valuable insights. For practitioners, it underscores the importance of integrated TT strategies focusing on shared enablers and synergies to optimize resources and enhance resilience. Academically, it provides a novel TT synthesis, bridging distinct research streams and proposing future inquiry into empirical validation of the frameworks, longitudinal studies, and the interplay of enablers and context. Key recommendations are also offered for policymakers. As regulatory frameworks are primary drivers in HROs, clear, consistent mandates are needed to manage complexity (e.g., harmonizing environmental regulations, streamlining approvals). Targeted financial incentives and supportive legislation are crucial for HROs to overcome TT adoption costs and risks. The implementation of robust data governance, skills programs for digital and sustainability literacy, and collaborative research and development will also be pivotal for advancing the TT agenda.

Providing a foundational conceptualization for navigating TT, this research, through its comprehensive analysis of critical factors in HROs and beyond, offers a robust foundation for practitioners, scholars, and policymakers working collaboratively towards a resilient, sustainable, and digitally transformed future.

Appendix

See Tables 3, 4, 5.

Table 3 Journal overview

Journal Name	Paper Count		ABS/AJG-Ranking (2024)	JCR-Ranking (2025)
Technovation	11	13.41	3	10.9
Sustainability	9	10.98	#NV	3.3
Technological forecasting and social change	8	9.76	3	13.3
Energy policy	7	8.54	2	9.2
Environmental innovation and societal transitions	3	3.66	#NV	6.1
Business process management journal	2	2.44	2	5.8
Energies	2	2.44	#NV	3.2
Energy economics	2	2.44	3	14.2
International journal of innovation management	2	2.44	2	1.2
Journal of cleaner production	2	2.44	1	10.0
Journal of decision systems	2	2.44	1	4.3
Journal of health services research & policy	2	2.44	#NV	2.7
Journal of management information systems	2	2.44	4	6.2
MIS quarterly executive	2	2.44	2	2.9
Technology in society	2	2.44	2	12.5
Applied energy	1	1.22	#NV	11.0
Business strategy and the environment	1	1.22	3	13.3
California management review	1	1.22	3	7.3
Decision support systems	1	1.22	3	6.8
Digital health	1	1.22	#NV	3.3
European journal of information systems	1	1.22	4	8.6
Frontiers in public health	1	1.22	#NV	3.4
Healthcare	1	1.22	#NV	2.7
Information systems frontiers	1	1.22	3	8.3
Information systems journal	1	1.22	4	6.3
International journal of production research	1	1.22	3	7.3
Jmir public health and surveillance	1	1.22	#NV	3.9
Journal of business research	1	1.22	3	9.8
Journal of computer information systems	1	1.22	2	4.2
Journal of Environmental Policy & Planning	1	1.22	#NV	2.2
Journal of Innovation and Knowledge	1	1.22	1	15,5
Journal Of medical internet research	1	1.22	#NV	6.0
Journal Of organizational change management	1	1.22	2	2.7
Journal of strategic information systems	1	1.22	4	11.8
Managerial and decision economics	1	1.22	2	2.7
Policy sciences	1	1.22	1	3.7
Review of European comparative & international Environmental law	1	1.22	#NV	2.3
Transportation research part D-transport and environment	1	1.22	#NV	7.7
Utilities policy	1	1.22	1	4.4
Total	82	100.00		

Table 4 Sample overview

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Sample DT						
Aerts, R; Pikkarainen, M; Xu, YQ; Andersson, S	Technological Forecasting and Social Change	Overcoming hospital resistance in an international innovation co-creation	2023	Case study with 17 hospitals	Empirical Qualitative Case study	Hospital resistance to innovation is driven by lack of internal resources and concerns about security Co-creation with hospitals helps startups overcome resistance and refine their solutions Startups must develop relational and regulatory skills to navigate hospital bureaucracies COVID-19 positively impacted the adoption of the startup's digital solutions in hospitals
Al-Kahtani, N; Alruwaie, S; Al-Zahrani, BM; Abumadini, RA; Aljaafary, A; Hariri, B; Alissa, K; Alakrawi, Z; Alumran, A	Digital Health	Digital health transformation in Saudi Arabia: A cross-sectional analysis using Healthcare Information and Management Systems Society' digital health indicators	2022	10 healthcare facilities	Empirical Quantitative Mann–Whitney test Kruskal–Wallis test	Private healthcare facilities scored higher in digital health transformation readiness compared to public ones Governance and workforce dimension had the highest score among all dimensions Predictive analytics was the least implemented dimension There is no significant difference in DT between healthcare facility types
Alzghaibi, HA	Frontiers of Public Health	An examination of large-scale EHRs implementation in Primary Healthcare Centres in Saudi Arabia: a qualitative study	2023	17 Interviews	Empirical Qualitative Case study	EHR implementation failed previously because of lack of infrastructure and support A new structured plan emphasizes stakeholder consultation and better-defined processes Training and technical support are crucial for successful large-scale EHR projects User resistance stems from poor technical support and inadequate training

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Anderson, C	Decision Support Systems	Blockchain innovation for consent self-management in health information exchanges	2023	200 survey participants	Empirical Quantitative Design Science Research	Patients prefer a blockchain-based app for self-managing health data consent Interoperability between health information exchanges is improved through blockchain Older consent management systems limit patient autonomy over their health data Blockchain provides a secure, decentralized solution for patient consent management
Basile, LJ; Carbonara, N; Pellegrino, R; Panniello, U	Technovation	Business intelligence in the healthcare industry: The utilization of a data-driven approach to support clinical decision-making	2023	2255 patients' data across 4 institutions	Empirical Qualitative Case study	Data-driven Decision Support Systems (DSS) outperform experience-based models in estimating costs The data-driven model results in more accurate treatment pathway cost assessments for BRCA-mutated patients BI adoption in healthcare leads to better resource optimization and cost savings A wider application of the data-driven model can significantly improve decision-making and financial outcomes in healthcare
Basile, LJ; Carbonara, N; Panniello, U; Pellegrino, R;	Technovation	The role of big data analytics in improving the quality of healthcare services in the Italian context: The mediating role of risk management	2024	173 healthcare professionals	Empirical Quantitative Partial Least Squares Structural Equation Modeling (PLS-SEM)	Big data analytics improves healthcare service quality directly and through risk management. Risk identification and risk monitoring significantly enhance service quality and mediate the analytics–quality link. Risk assessment and treatment do not show significant effects. Managers should integrate data-driven tools with risk management to handle uncertainty and improve care

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Baudier, P; Kondrateva, G; Ammi, C; Chang, VC; Schiavone, F	Technovation	DT of health-care during the COVID-19 pan-demic: Patients' teleconsultation acceptance and trusting beliefs	2023	1233 re-sponses from survey	Empirical Quantitative Unified Theory of Acceptance and Use of Technol-ogy (UTAUT2) model with a partial least squares (PLS) approach	Trusting beliefs and self-efficacy are key predictors of teleconsultation acceptance Performance expectancy and effort expectancy significantly influence behavioral intentions to use teleconsultation Social influence and facilitating conditions had no significant impact on teleconsultation acceptance Teleconsultation proved essential during the pandemic, fostering a resilient healthcare system
Bernardi, R; Exworthy, M	Information Sys-tems Journal	Clinical managers' identity at the crossroad of mul-tiple institutional logics in its in-novation: The case study of a health care organization in England	2020	16 Interviews	Empirical Qualitative Case study	Clinical managers navigate multiple institutional logics in IT innovation Hybrid identities help or hinder the adoption of IT innovation Institutional logics conflict with medical professionalism and managerialism Innovation advocates, brokers, and laggards play distinct roles in IT implementation
Bhatti, A; Malik, H; Kamal, AZ; Aamir, A; Alaali, LA; Ullah, Z	Business Process Management Journal	Much- needed business DT through big data, IoT and block-chain capabilities: implications for strategic perfor-mance in telecom-munication sector	2021	343 responses from survey	Empirical Quantitative Structural Equa-tion Modelling (SEM) and confirmatory factor analysis (CFA)	Data quality and technological competence positively impact strategic performance Big data analytics and IoT capabilities act as significant mediators between independent and dependent variables Blockchain capabilities routinization does not significantly mediate strategic performance The study highlights the need for Chinese telecom firms to focus on big data and IoT for business transformation

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Biancone, P; Secinaro, S; Marseglia, R; Calandra, D	Technovation	E-health for the future. Managerial perspectives using a multiple case study approach	2023	N/A	Empirical Qualitative Case study	Telemedicine promotes virtuous experiences of knowledge exchange and social impact Technology acceptance factors like trust and facilitating conditions are crucial for telemedicine success Telemedicine enhances access to care in less developed countries, bridging geographic barriers Resistance to technology is minimal when trust between physicians and patients is established
Carroll, N; Maher, M	MIS Quarterly Executive	How Shell Fuelled DT by Establishing DIY Software Development	2023	18 Interviews	Empirical Qualitative Case study	Citizen development empowers Shell employees to drive DT Low-code/no-code platforms enhance agility and reduce reliance on IT departments Shell's DIY software development improves cost-efficiency and operational safety Senior management support is crucial for sustaining DT initiatives
Chen, W; Zhang, QY	Technological Forecasting and Social Change	Can corporate climate risk drive digital transformation? Evidence from Chinese heavy-polluting enterprises	2025	1,355 firm-year observations from heavy-polluting enterprises (2010–2022)	Empirical Quantitative Dual fixed effects panel regression, mediation analysis	Higher corporate climate risk significantly promotes digital transformation. The effect operates through reduced fixed asset investment and increased diversification. The impact is stronger in high-energy industries, non-state-owned firms, and firms facing financing constraints. Digital transformation serves as an adaptation strategy to climate change, linking digitization and greening
Chwilkowska-Kubala, A; Cyfert, S; Malewska, K; Mierzejewska, K; Szumowski, W	Technology in Society	The impact of resources on DT in energy sector companies. The role of readiness for digital transformation	2023	110 energy companies	Empirical Quantitative Survey-based study SEM	Technological and financial resources significantly impact DT in the energy sector, mediated by DT readiness Human resources influence readiness for DT but not directly on DT itself Organizational culture and governance are critical components of readiness for DT ICT and infrastructure resources show no significant relationship with readiness for DT

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Correia, LMAD; Frank, AG	Technovation	Structuring resources in healthcare digital transformation: a comparison across public, private and research hospitals	2025	3 large hospitals in Brazil (public, private, research-oriented), 7 formal interviewees + document analysis and site visits	Empirical Qualitative Case study	Hospitals manage digital resources differently depending on their business models: public hospitals rely on internal development, private hospitals emphasize external sourcing, and research hospitals adopt hybrid governance. Each approach reflects distinct financial structures, governance logics, and ecosystem strategies. All hospitals maintain complementary resources for resilience. The study introduces hybrid governance in research hospitals as a funding-driven mechanism
Denicolai, S; Previtali, P	Technovation	Innovation strategy and DT execution in healthcare: The role of the general manager	2023	15 Interviews	Empirical Qualitative Case study	DT serves as a key driver of innovation in healthcare, especially post-pandemic General managers play a crucial role in leading digital change and addressing institutional pressures Innovation strategies in healthcare are heterogeneous, showing varying approaches to DT The pandemic accelerated DT, making healthcare organizations more resilient and adaptive
Espinosa Apráez, B; Noorman, M	Review of European Comparative & International Environmental Law	Regulating AI in the 'twin transitions': Significance and shortcomings of the AI	2024	Not applicable (legal analysis, not empirical research)	Legal Analysis	The EU's AI Act, intended to guide the responsible development and adoption of AI, will have limited direct regulatory impact on many AI systems currently being integrated into the digital transformation of the electricity sector This gap in regulation may create challenges for ensuring trustworthy AI adoption as the electricity sector undergoes further digital transformation

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Fernandez-Vidal, J; Gonzalez, R; Gasco, J; Llopis, J	Technological Forecasting and Social Change	Digitalization and corporate transformation: The case of European oil & gas firms	2022	26 Interviews	Empirical Qualitative Case study	DT in oil & gas firms is modest and incremental rather than large-scale Poor governance and piecemeal strategies hinder the effectiveness of transformation efforts Agile innovation, venture building, and M&A are the most used strategic tools Firms struggle to develop a coherent transformation strategy aligned with their business goals
Fox, G; James, TL	Information Systems Frontiers	Toward an Understanding of the Antecedents to Health Information Privacy Concern: A Mixed Methods Study	2021	25 Interviews, 243 Survey Participants, 6 Exploratory Interviews	Empirical Mixed Methods Part A: Exploratory interviews Part B: Quantitative survey Part C: Explanatory interviews	Higher health information privacy concerns (HIPCs) lead to lower intentions to use EHRs systems Age and prior health privacy invasion experiences significantly increase HIPCs Trust in health professionals reduces HIPCs, while trust in technology vendors has a more mixed effect Perceived ownership and sensitivity of health information strongly influence HIPCs
Garcia-Perez, A; Cegarra-Navarro, JG; Sallos, MP; Martinez-Caro, E; Chinnaswamy, A	Technovation	Resilience in healthcare systems: Cyber security and digital transformation	2023	99 survey participants	Empirical Quantitative Structural equation modelling	Healthcare system resilience is influenced by cybersecurity knowledge and risk awareness DT efforts increase the sector's vulnerability to cyberattacks Interdependence in the supply chain is crucial for healthcare digital resilience A comprehensive security strategy is essential for antifragility in healthcare transformation

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Gastaldi, L; Appio, FP; Corso, M; Pistorio, A	Business Process Management Journal	Managing the exploration–exploitation paradox in healthcare: Three complementary paths to leverage on the digital transformation	2018	107 Interviews	Empirical Qualitative Case study	DT balances exploratory and exploitative activities in hospitals Three paths emerged: asset digitization, process integration, and disruptive decision-making through analytics Digitization in clinical domains yields higher results than administrative digitization Combining exploration and exploitation efforts leads to improved hospital performance and innovation
Ghosh, K.; Dohan, M. S..; Veldandi, H; Garfield, M	Journal of Computer Information Systems	DT in Healthcare: Insights on Value Creation	2023	19 Interviews	Empirical Qualitative Case study	DT supports existing value creation and fosters new value propositions Care coordination and patient engagement are key drivers of value creation IT integration and reconfiguration capabilities are crucial for healthcare organizations Sensing and seizing capabilities help organizations align technology with user needs
Giraldo, S; la Rotta, D; Nieto-Londoño, C; Vásquez, RE; Escudero-Atehortúa, A	Energies	DT of Energy Companies: A Colombian Case Study	2021	N/A	Empirical Qualitative Case study	DT at AES Colombia improved risk management and optimized energy trading The platform reduced time for decision-making processes like price projections and offer generation Data normalization and AI-driven analytics enhanced portfolio management and operational efficiency Resistance to change and technical challenges are the main obstacles for successful DT

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Gizelis, CA; Nestorakis, K; Misargopoulos, A; Nikolopoulos-Gkamatsis, F; Kefalogiannis, M; Palaiogeorgou, P; Christonasis, AM; Boletis, K; Giamalis, T; Charisis, C	Journal of Decision Systems	Decision support using AI: the data exploitation at telecoms in practice	2023	N/A	Empirical Qualitative Case study	AI enables telecoms to optimize network management and customer services Data quality and privacy are critical challenges for AI adoption in telecoms Predictive maintenance using AI reduces hardware malfunctions and service disruptions Chatbots and NLP improve customer satisfaction and operational efficiency
Gnugesser, E; Jöllenbeck, M; Schlenger, W; Ochsmann, E	Journal of Innovation & Knowledge	Navigating the digital shift: Working conditions and employee health in digital social care	2025		Empirical Quantitative Cross-sectional survey	Online counselling adoption in social care remains limited despite COVID-driven digitization High digital use correlates with better working conditions and fewer health complaints, suggesting positive outcomes of sustained digital transformation Support and adaptation are critical for successful integration of digital tools in care settings
Hansen, A; Herrmann, M; Ehlers, JP; Mondritzki, T; Hensel, KO; Truebel, H; Boehme, P	JMIR Public Health and Surveillance	Perception of the Progressing Digitization and Transformation of the German Health Care System Among Experts and the Public: Mixed Methods Study	2019	21 Interviews and 733 survey participants	Empirical Mixed Methods: Part A: Qualitative Grounded theory Part B: Quantitative Delphi method	Physicians show the most resistance to digitization compared to other groups Patients and service providers demonstrate more optimism regarding digital health's potential benefits Digitization is seen to enhance self-monitoring and patient empowerment, but physicians are skeptical Physicians fear that digitization may reduce personal interaction and threaten expert knowledge

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Iyanna, S; Kaur, P; Ractham, P; Talwar, S; Islam, N	Journal of Business Research	DT of healthcare sector. What is impeding adoption and continued usage of technology-driven innovations by end-users?	2022	59 Interviews	Empirical Qualitative Content analysis through open-ended essay-based data collection	End-user resistance to digital health innovations stems from task-related, patientcare, and system barriers Organizational barriers, including threat perception and infrastructural limitations, hinder adoption Patients face usability and resource barriers, particularly with mobile health applications Self-efficacy, tradition, and image barriers contribute to overall resistance among healthcare providers and patients
Jabłoński, M; Jabłoński, A	Energies	Shaping the Safety Culture of High-Reliability Organizations (HROs) through Digital Transformation	2021	28 organizations participated	Empirical Mixed Methods Part A. Analytic Hierarchy Process (AHP) Part B: Vester methods combined with survey-based quantitative research	DT improves safety culture by integrating digital tools into safety processes Monitoring of safety–critical processes and risks is enhanced through digital solutions Employee involvement in safety discussions benefits from digital communication channels Change management in safety culture is more efficient with digital tools for tracking and monitoring
Johansson, PE; Stefan, I.; Axelsson, K.; Söderberg, T.; Forsberg, K	International Journal of Innovation Management	Creating Balancing Spaces for Digital Ambidexterity: Identifying Divergence and Competing Demands in Healthcare Transformation Initiatives	2022	137 survey respondents and 26 workshop participants	Empirical Mixed Methods Regression analysis Workshop transcripts	Balancing DT requires managing divergent views across organizational levels Competing demands between past, present, and future needs create tensions in digital initiatives Balancing practices help organizations achieve digital ambidexterity through structured routines Workshops identified latent and salient tensions that affect digital innovation efforts

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Kattirtzi, M; Ketsopoulou, I; Watson, J	Energy Policy	Incumbents in transition? The role of the 'Big Six' energy companies in the UK	2021	11 Interviews	Empirical Qualitative Case study	The Big Six have shown the ability to adapt given strong policy incentives Decarbonization has been the primary focus, with varying progress across the companies Decentralization has had less impact, with most firms still focused on centralized generation Digitalization remains limited, mainly affecting the retail market but not yet disruptive
Kokshagina, O	Technological Forecasting and Social Change	Managing shifts to value-based healthcare and value digitalization as a multi-level dynamic capability development process	2021	16 Interviews	Empirical Qualitative Case study	Shifts to value-based healthcare (VBHC) require balancing organizational processes and building new dynamic capabilities VBHC and digitalization in healthcare are multi-level processes, requiring alignment between individuals, teams, and the organization Productive dialogue at the meso-level (departments) is crucial for linking micro and macro levels in VBHC implementation Clinicians play a key role in initiating value-based innovations, but top-down support and standardized processes are essential
Körner, MF; Sedlmeir, J; Weibelzahl, M; Fridgen, G; Heine, M; Neumann, C	Energy Policy	Systemic risks in electricity systems: A perspective on the potential of digital technologies	2022	9 Interviews	Empirical Qualitative Case Study	Digital technologies like blockchain and privacy-enhancing tech can mitigate systemic risks Decentralized systems increase complexity and interdependencies, requiring better data exchange Sector coupling and inter-regional electricity system integration increase systemic risk exposure Data governance is crucial for detecting hidden risks and preventing system failures

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Latilla, VM; Frattini, F; Franzo, S; Chiesa, V	International Journal of Innovation Management	Organisational Change and Business Model Innovation: An Exploratory Study of an Energy Utility	2020	9 Interviews	Empirical Qualitative Case Study	Business model innovation in utilities requires decentralization and weak management hierarchies Collaboration with external parties is essential for extending the company's boundaries Digital technologies open up new opportunities for business model innovation but require internal organizational changes Establishing a new organizational division focused on innovation drives business model renewal
Li, H; Yoo, S; Kettinger, WJ	Journal of Management Information Systems	The Roles of IT Strategies and Security Investments in Reducing Organizational Security Breaches	2021	5738 hospitals (45,461 hospital-year observations) over the period 2005–2013	Empirical Quantitative Longitudinal Panel Study	IT security investments reduce security breaches in less digitalized organizations Highly digitalized organizations experience increased breaches because of signaling effects of security investments Technical network control systems reduce external breaches, while identity management systems decrease internal breaches Network embeddedness moderates the effectiveness of IT security systems, particularly in reducing external breaches
Liu, PK; Wu, JH	Sustainability	Game Analysis on Energy Enterprises' Digital Transformation-Strategic Simulation for Guiding Role, Leading Role and Following Role	2023	N/A	Theoretical Simulation Study	Government incentives play a stronger role than enterprise intentions in DT Enterprises with comparative advantages in transformation costs and benefits tend to lead Collaborative DT reduces costs and increases synergies between enterprises Policymaking must carefully balance subsidies and penalties to optimize DT

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Liu, QL; Yang, LJ; Yang, MY	Sustainability	Digitalisation for Water Sustainability: Barriers to Implementing Circular Economy in Smart Water Management	2021	21 Interviews	Empirical Mixed Methods Part A: Case Study Part B: Fuzzy Delphi Method	Lack of awareness about circular economy (CE) and environmental issues hinders adoption Data privacy, security, and inaccurate data analysis are key technological barriers Decentralized wastewater treatment systems are poorly understood by government and enterprises Stakeholder cooperation and public involvement are critical to improve circular water management
Liu, YT; Song, PY	Sustainability	Digital Transformation and Green Innovation of Energy Enterprises	2023	55 energy enterprises in China, using panel data from 2010 to 2020 (total of 605 observations)	Empirical Quantitative Panel data analysis using a double-fixed-effects regression model	DT significantly promotes green innovation in energy enterprises Dynamic capability serves as a key mediator between DT and green innovation State-owned enterprises benefit more from DT in terms of green innovation compared to non-state-owned ones The results emphasize the importance of DT for low-carbon transitions in the energy sector
Lyu, WJ; Liu, J	Applied Energy	AI and emerging digital technologies in the energy sector	2021	Data from 31,920 postings in 2010 and 60,399 postings in 2019	Empirical Quantitative Regression analysis using data from job postings, wage statistics, and firm performance metrics	AI is the most widely adopted digital technology in the energy sector AI brings the highest wage premium to energy firms compared to other digital technologies AI adoption significantly improves firm performance and productivity Big Data and IoT are the fastest-growing emerging digital technologies in the energy sector

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Malewska, K; Cyfert, S; Chwiłkowska-Kubala, A; Mierzejewska, K; Szumowski, W	Energy Policy	The missing link between digital transformation and business model innovation in energy SMEs: The role of digital organisational culture	2024	197 SMEs	Empirical Quantitative Structural Equation Modeling (SEM)	Digital transformation has a limited direct impact on business model innovation in energy SMEs Digital organizational culture plays a crucial mediating role in the relationship between digital transformation and business model innovation, highlighting its importance for successful digital transformation adoption
Manny, L; Duygan, M; Fischer, M; Rieckermann, J	Policy Sciences	Barriers to the DT of infrastructure sectors	2021	23 Swiss sub-states analyzed	Empirical Qualitative Fuzzy-set Qualitative Comparative Analysis (fsQCA)	Lack of vision at the individual level or lack of resources at the organizational level can independently hinder DT in urban wastewater management Digitalization culture and administrative fragmentation do not significantly influence the utilization of data in this context Addressing barriers requires improving resources and fostering individual commitment toward digitalization
Mauro, M; Noto, G; Prenestini, A; Sarto, F	Technological Forecasting & Social Change	Digital transformation in healthcare: Assessing the role of digital technologies for managerial support processes	2024	11 Interviews	Empirical Qualitative Delphi Study	IoT and AI have the strongest perceived impact on healthcare's administrative processes, especially in logistics, forecasting, and operational planning Successful adoption depends on internal factors like employee digital skills, leadership support, and openness to change Support functions, though often overlooked, are critical to healthcare digital transformation and benefit most from measuring, informing, and knowledge-based digital tools
Meske, C; Osmundsen, KS; Junglas, I	MIS Quarterly Executive	Designing and Implementing Digital Twins in the Energy Grid Sector	2021	27 Interviews	Empirical Qualitative Case study	Digital twins facilitate organizational learning and innovation in energy grids Co-creation with multiple stakeholders enhances digital twin development Effective data governance is critical for digital twin success Digital twins optimize grid operations and future-proof energy infrastructure

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Mohamad, TA; Bastone, A; Bernhard, F; Schiavone, F	Journal of Organizational Change Management	How AI impacts the competitive position of healthcare organizations	2023	9 Interviews	Empirical Qualitative Case study	AI enhances clinical outcomes by reducing surgical errors and improving patient experience AI-driven surgeries lead to better financial performance by reducing hospital stay times and increasing patient satisfaction Adopting AI optimizes resource allocation, reducing the need for staff and lowering operational costs AI plays a key role in securing a competitive advantage in the healthcare sector by improving organizational efficiency
Nadav, J; Kaihlanen, AM; Kujala, S; Laukka, E; Hilama, P; Koivisto, J; Keskimäki, I; Heponiemi, T	Journal of Medical Internet Research	How to Implement Digital Services in a Way That They Integrate into Routine Work: Qualitative Interview Study Among Health and Social Care Professionals	2021	30 Interviews	Empirical Qualitative Focus group interviews	Comprehensive, continuous communication is crucial for successful implementation of digital services Support from multiple fast and efficient sources is essential for the adoption of new digital tools Training should be targeted individually based on skills and tasks, with a focus on diverse teaching methods Monitoring and feedback mechanisms improve service integration and ensure sustainable usage
Oliveira, M; Zancul, E; Salerno, MS	Technological Forecasting and Social Change	Capability building for DT through design thinking	2024	12 Interviews	Empirical Qualitative Case study	Design thinking fosters the development of DT capabilities Innovation unit structured design thinking workshops to scale innovation efforts Employees gain creative confidence and apply design thinking tools in daily tasks The innovation unit became a central hub for driving digital and innovation strategies

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Ologeanu-Taddei, R; Guthrie, C; Jensen, TB	European Journal of Information Systems	DT of professional healthcare practices: fitness-seeking across a rugged value landscape	2023	22 Interviews	Empirical Qualitative Case study	Doctors adapted digital technologies like teleconsultations based on individual patient needs Professional autonomy plays a key role in driving the DT process in healthcare The COVID-19 pandemic accelerated the adoption of digital tools, transforming healthcare delivery Doctors' fitness-seeking behavior is crucial for combining resources and achieving value creation
Ozturk, I; Ullah, S; Sohail, S; Sohail, MT	Energy Policy	How do digital government, circular economy, and environmental regulatory stringency affect renewable energy production?	2025	27 European countries (panel data, 2010–2022)	Empirical Quantitative Smoothed Instrumental Variable Quantile Regression (SIVQR)	Digital government and circular economy practices significantly increase renewable energy production across Europe Environmental regulatory stringency (proxied by environmental taxes) shows mixed effects, with some negative associations at higher production levels Digitalization supports green energy governance by enhancing transparency, policy efficiency, and investment attraction
Pohlmann, S; Kunz, A; Ose, D; Winkler, EC; Brandner, A; Poss-Doering, R; Szecsenyi, J; Wensing, M	Journal of Medical Internet Research	Digitalizing Health Services by Implementing a Personal EHRs in Germany: Qualitative Analysis of Fundamental Prerequisites from the Perspective of Selected Experts	2020	33 Interviews	Empirical Qualitative Case study	Documentation standards are still influenced by analogue bureaucratic processes Interoperability between various systems and actors remains a major challenge Political structure lacks clear regulations and incentives to drive implementation Stakeholder cooperation and strong patient involvement are critical for success

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Poláková-Kersten, M; Khanagha, S; van den Hooff, B; Khapova, SN	Journal of Strategic Information Systems	DT in HROs: A longitudinal study of the micro-foundations of failure	2023	92 employees involved (21 semi-structured interviews, 6 workshops with 10–25 participants, and additional data from observations and archival documents)	Empirical Qualitative Case study	Identity misalignment between HROs and DT leads to threat perceptions among IT staff Self-protective behaviors from the IT workforce can undermine DT initiatives DT requires balancing between reliability and innovation, which creates tensions in HROs The IT function's resistance to change can derail DT processes
Pundziene, A; Gutmann, T; Schlichtner, M; Teece, DJ	California Management Review	Value Impedance and Dynamic Capabilities: The Case of MedTech Incumbent-Born Digital Healthcare Platforms	2022	18 Interviews	Empirical Qualitative Case study	MedTech incumbents face significant challenges in building digital healthcare platforms because of DT gaps Value impedance, caused by these gaps, limits MedTech incumbents from benefiting fully from digital innovations Dynamic capabilities like sensing the internal environment and orchestrating silos can mitigate value impedance The development of new dynamic capabilities is essential for the success of MedTech incumbents in the digital platform space
Raimo, N; De Turi, I; Albergo, F; Vitolla, F	Technovation	The drivers of the DT in the healthcare industry: An empirical analysis in Italian hospitals	2023	103 hospitals	Empirical Quantitative OLS regression analysis	Hospital size, measured by the number of beds, positively influences the level of DT Hospitals with emergency rooms show higher levels of DT compared to others Older hospitals are also more likely to undergo DT processes Affiliation with universities boosts DT by fostering greater technological knowledge and resources

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Renukappa, S; Kamunda, A; Suresh, S	Utilities Policy	Impact of COVID-19 on water sector projects and practices	2021	12 Interviews	Empirical Qualitative Case study	COVID-19 delayed water sector construction projects and led to operational changes The pandemic accelerated DT in water utilities, improving remote work capabilities Water demand shifted from business to residential use, requiring real-time data adjustments Compliance with COVID-secure regulations slowed project delivery but improved safety standards
Ruan, TS; Gu, Y; Li, XH; Qu, R	Sustainability	Research on the Practical Path of Resource-Based Enterprises to Improve Environmental Efficiency in Digital Transformation	2022	46 resource-based enterprises in China	Empirical Qualitative Fuzzy-set Qualitative Comparative Analysis	Enterprises with strong digital capabilities achieve higher environmental efficiency Government support and environmental regulations drive green innovation Digital technology helps reduce production costs and improve sustainability Two models for green development: "capability-oriented" and "environment-oriented."
Saad, EA; Tremblay, N; Agogué, M	Technovation	A multi-level perspective on innovation intermediaries: The case of the diffusion of digital technologies in healthcare	2024	85 Interviews	Empirical Qualitative Case study	Innovation intermediaries play a pivotal role in facilitating the diffusion of digital technologies Intermediaries help align ecosystem actors with the needs of new technologies Effective intermediation requires managing technology and ecosystem levels Intermediaries can accelerate DT by fostering collaboration across the healthcare ecosystem

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Santarsiero, F; Schiuma, G; Carlucci, D; Helander, N	Technovation	DT in healthcare organisations: The role of innovation labs	2023	55 Interviews	Empirical Qualitative Case study	Innovation labs foster collaboration between healthcare organizations and startups They help address DT challenges by offering co-creation opportunities Innovation labs act as platforms for prototyping and testing new healthcare solutions They play a key role in bridging the gap between technology development and practical healthcare needs
Spanò, R; Massaro, M; Iacuzzi, S	Technovation	Blockchain for value creation in the healthcare sector	2023	33 healthcare startups	Empirical Qualitative Case study	Blockchain enhances compliance, efficiency, and collaboration among healthcare actors It improves data security and reduces fraud in healthcare transactions Blockchain enables end-to-end integration of information, improving operational efficiency Smart contracts and decentralized systems foster shared value creation among stakeholders
Steinhauser, S; Doblinger, C; Hüsig, S	Journal of Management Information Systems	The Relative Role of Digital Complementary Assets and Regulation in Discontinuous Telemedicine Innovation in European Hospitals	2020	1753 acute care hospitals across 30 European countries	Empirical Quantitative Binary logistic regression analysis	Digital complementary assets are more influential in telemedicine adoption than regulatory frameworks Provider-to-provider (B2B) applications like teleradiology see higher adoption than provider-to-patient (B2C) applications Regulation for security and privacy of data positively influences telemedicine adoption, especially for B2B applications Restrictive regulation impacts the adoption of provider-to-patient innovations negatively, shifting focus to provider-to-provider applications
Teixeira, L; Cardoso, I; Sá, JOE; Madeira, F	Healthcare	Are Health Information Systems Ready for the DT in Portugal? Challenges and Future Perspectives	2023	14 Interviews	Empirical Qualitative Case study	Health Information Systems in Portugal are not yet fully integrated or interoperable Stakeholder engagement and digital literacy are key challenges for HIS implementation Emerging technologies like AI and IoT can drive improvements in healthcare delivery Resistance to change and lack of standardized systems remain major barriers

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Tortorella, GL; Fogliatto, FS; Sunder, MV; Vergara, AMC; Vassolo, R	International Journal of Production Research	Assessment and prioritisation of healthcare 4.0 implementation in hospitals using Quality Function Deployment	2022	N/A	Empirical Qualitative Case study	Digital applications in hospitals are prioritized based on problem-solving potential Healthcare 4.0 adoption remains limited to specific departments or processes Systemic integration of digital technologies shows promising improvements in patient care Public and private hospitals face different challenges but share common improvement priorities
YahiaMarzouk, Y; Jin, JF	Journal of Organizational Change Management	Renew or die amidst COVID-19: investigating the effect of organizational learning culture on strategic renewal through strategic reconfiguration and digital transformation	2023	264 survey participants	Empirical Quantitative Structural equation modelling	Organizational learning culture positively influences strategic renewal in hospitals Strategic reconfiguration and DT mediate the relationship between organizational learning culture and strategic renewal Hospitals need to reconfigure resources and adopt digital technologies to adapt during crises DT enhances the long-term sustainability of hospitals amidst crises like COVID-19
Yu, FF; Zhang, Q; Jiang, D	Managerial and Decision Economics	The impact of regional environmental regulations on DT of energy companies: The moderating role of the top management team	2023	238 energy enterprises from 2016 to 2021	Empirical Quantitative Regression analysis	Regional environmental regulations promote DT Older management teams resist DT More educated teams are less likely to implement DT Longer-tenured teams resist strategic changes

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Yu, Y; Ren, FR; Ju, Y; Zhang, JY; Liu, XY	Sustainability	Exploring the Role of DT and Breakthrough Innovation in Enhanced Performance of Energy Enterprises: Fresh Evidence for Achieving Sustainable Development Goals	2024	92 A-share listed energy companies in China (from 2010–2021)	Empirical Quantitative Fixed-effects panel model and mediated effects model	DT significantly enhances the core business performance of energy companies Breakthrough innovation is a crucial mechanism for improving firm performance through DT There is a nonlinear relationship between DT and firm performance with diminishing returns after a certain threshold DT fosters cross-border cooperation and resource integration, boosting corporate performance
Zhao, Y; Canales, JI	Technological Forecasting and Social Change	Never the twain shall meet. Knowledge strategies for digitalization in healthcare	2021	40 Interviews	Empirical Qualitative Case study	Divergent professional groups must align their knowledge to achieve DT Knowledge strategies evolve through phases of conflict, compromise, and collaboration Healthcare digitalization success depends on integrating clinical, management, and IT knowledge A coherent knowledge strategy promotes knowledge creation, sharing, and application across professional groups
Zheng, X; Zou, F; Liu, Z; Nepal, R	Energy Economics	How does digitalization affect capacity utilization in the energy sector? Evidence from China	2025	902 listed energy companies (panel data from 2011–2019)	Empirical Quantitative Fixed-effects panel model and mediated effects model	Digitalization significantly improves capacity utilization in the energy sector by reducing labor misallocation and enhancing innovation The impact is stronger in competitive markets, labor-intensive firms, and non-state-owned companies Human capital quality, digital infrastructure, and market vitality positively moderate the relationship between digitalization and capacity utilization

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Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Akadiri, SS; Ozkan, O; Kirikkaleli, D	Technology in Society	Synergistic impact of renewable energy technology, governance, digitalisation, and human capital on sustainable development and load capacity factor in Germany's energy landscape	2025	Annual data 2000–2022, transformed into quarterly (≈ 92 observations)	Empirical Quantitative Kernel-based Quantile Regression (KRQR)	Renewable energy technology and digitalization strongly support sustainable development and ecological resilience, especially at higher performance levels. Governance and human capital show nonlinear, context-dependent impacts. Combined effects are stronger than isolated ones, underlining the need for integrated policies
Bjerkan, KY; Ryghaug, M	Technological Forecasting and Social Change	Diverging pathways to port sustainability: How social processes shape and direct transition work	2021	25 Interviews	Empirical Qualitative Case study	Transition pathways are shaped by networks, expectations, and learning processes Ports with more extensive networks show more coordinated sustainability efforts Electrification is a key pathway but lacks broad innovation support Social learning enhances transition work in port sustainability
Bortoleto, AP	Journal of Cleaner Production	A Water-Energy Nexus analysis to a sustainable transition path for São Paulo State, Brazil	2021	22 Interviews	Empirical Qualitative Case study	Water-energy nexus is crucial for São Paulo's sustainability High urbanization pressures water availability and energy demand Wastewater treatment improvements are needed Renewable energy is essential for future water supply

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Bosman, R; Loorbach, D, Rotmans, J, van Raak, R	Sustainability	Carbon Lock-Out: Leading the Fossil Port of Rotterdam into Transition	2018	33 Interviews	Empirical Qualitative Case study	The Port of Rotterdam faces high dependence on fossil fuels, creating a carbon lock-in A shift in leadership within the Port Authority opened space for sustainability transitions Transition management was applied to help destabilize the fossil regime The process contributed to rethinking strategies and creating a transition unit within the Port Authority
Damman, S; Steen, M	Transportation Research Part D	A socio-technical perspective on the scope for ports to enable energy transition	2021	39 Interviews	Empirical Qualitative Case study	Ports function as intermediaries in sustainability transitions Local contexts influence ports' transition efforts Ports use roles like regulator and landlord to drive change Engagement with innovations depends on local opportunities
Haezendonck, E.; Van den Berghe, K	Sustainability	Patterns of Circular Transition: What Is the CE Maturity of Belgian Ports?	2020	5 Belgian ports covering CE initiatives	Empirical Qualitative Case study	Most ports focus on energy recovery as the first step in CE transitions Larger ports have more resources and circular initiatives than smaller ports Recycling is more common in urban ports like Brussels Orchestrating new cargo streams is still a lower priority in circular transitions
Hansen, AS; Manniche, J; Topsø Larsen, K	Environmental Innovation and Societal Transitions	Navigating sustainable transition processes at the local level: The case of Energy Island Bornholm	2024	14 Interviews and numerous documents	Empirical Qualitative Case study	Explores the opportunities and challenges that local communities face in sustainable transition processes when large-scale sustainable energy infrastructure projects are introduced Emphasizes the necessity of addressing economic opportunities, demographic shifts, democratic involvement, and governance capacity to navigate sustainable energy transitions effectively at the local level

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Kirkegaard, JK; Cronin, T; Nyborg, S; Karnoe, P	Journal of Environmental Policy & Planning	Paradigm shift in Danish wind power: the (un) sustainable transformation of a sector	2021	37 Interviews	Empirical Qualitative Historical analysis Case study	Danish wind power shifted from community-owned to large-scale, centralized developments Changes in technology, finance, and ownership marginalized local actors Centralization reduced local participation and raised social acceptance issues
Li, C; Zhang, Y; Liu, X; Sun, J	Energy Economics	Does artificial intelligence promote green technology innovation in the energy industry?	2025	Panel data of Chinese listed energy firms from 2007 to 2022	Empirical Quantitative Regression analysis	Artificial intelligence promotes green technology innovation in energy firms, which is crucial for the energy sector's sustainability transformation AI's positive influence on GTI is achieved by enhancing human capital and alleviating financial pressures, both of which are essential for driving sustainable practices in the energy industry The impact of AI on GTI is more significant in regions with stricter environmental regulations, highlighting the importance of policy in leveraging technology for sustainability transformations
Lieberherr, E; Truffer, B	Environmental Innovation and Societal Transitions	The impact of privatization on sustainability transitions: A comparative analysis of dynamic capabilities in three water utilities	2015	48 Interviews	Empirical Qualitative Case study	Private and mixed governance modes foster dynamic capabilities more than public modes Private utilities are more focused on efficiency but may neglect environmental and social goals External collaborations help public utilities compensate for lower internal dynamic capabilities Governance modes present trade-offs between efficiency and broader sustainability goals
Lindberg, MB; Kammermann, L	Environmental Innovation and Societal Transitions	Advocacy coalitions in the acceleration phase of the European energy transition	2021	34 Interviews	Empirical Qualitative Case study	Coalition structure has evolved with five distinct coalitions Increasing fragmentation in renewable energy support preferences Progressive incumbents favor less market shielding and more competition Collaboration across coalitions is common despite distinctions

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Lippolis, S; Ruggieri, A; Leopizzi, R	Business Strategy and the Environment	Open Innovation for sustainable transition: The case of Enel Open Power	2023	5 Interviews	Empirical Qualitative Case study	Open Innovation accelerates Enel's sustainability efforts Enel integrates sustainability and innovation through strategic leadership Enel uses external stakeholder collaboration for shared value creation The SKiN framework highlights skill and knowledge exchanges in Enel's innovation ecosystem
Lorenc, S; Kustra, A	Sustainability	Distributing Enterprise Value to Stakeholders in the Range of Sustainable Development on the Basis of the Energy Industry in Poland	2021	Financial data from 4 companies over a 10-year period (2009–2018)	Empirical Quantitative Case Study/ Comparative analysis	Suppliers benefited the most from the distributed value Temporary lack of profitability did not prevent benefits distribution to stakeholders
Lutz, LM; Fischer, LB; Newig, J; Lang, DJ	Energy Policy	Driving factors for the regional implementation of renewable energy—A multiple case study on the German energy transition	2017	18 Regions in Germany	Empirical Quantitative Case Study/ Rough set analysis Performance analysis	Regional energy plans are crucial for successful renewable energy implementation Knowledge exchange with experts improves regional energy outcomes Formal networks significantly enhance regional energy transitions Diverse funding structures contribute to economic benefits from renewable energy
Ngar-yin Mah D; Wu Y; Ronald Hills P	Energy Policy	Explaining the role of incumbent utilities in sustainable energy transitions: A case study of the smart grid development in China	2022	21 Interviews	Empirical Qualitative Case study	China's smart grid development follows an incumbent-led model Incumbent grid companies function as enablers and barriers to innovation Grid companies leverage extensive networks for infrastructure building but resist structural changes Lack of incentives hinders the adoption of distributed energy sources in the smart grid

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Ruan, TS; Gu, Y; Li, XH; Qu, R	Sustainability	Research on the Practical Path of Resource-Based Enterprises to Improve Environmental Efficiency in Digital Transformation	2022	46 resource-based enterprises in China	Empirical Qualitative Case Study/ Fuzzy-set qualitative ratio method	Enterprises with strong digital capabilities achieve higher environmental efficiency Government support and environmental regulations drive green innovation Digital technology helps reduce production costs and improve sustainability Two models for green development: "capability-oriented" and "environment-oriented."
Tan, H; Thurbon, E; Kim, SY; Mathews, JA	Energy Policy	Overcoming incumbent resistance to the clean energy shift: How local governments function as change agents in coal power station closures in China	2021	N/A	Empirical Qualitative Case study	Local governments in China can function as change agents in coal power station closures Developmental motives and industrial upgrading drive coal plant retirements Push and pull mechanisms are used to overcome resistance from power companies Coal exit policies in Guangdong are more ambitious than national-level policies
Tong, KK; Ramaswami, A; Feiock, R	Journal of Cleaner Production	Environmentally sustainable transitions of US district energy systems: Perspectives from infrastructure operators/designers through the co-evolutionary lens	2020	14 Interviews	Empirical Qualitative Case study	District energy systems (DES) are at the first- and second-generation stages Local policies play a more significant role than federal policies in promoting DES transitions DES operators foresee transitions toward more sustainable systems but face technical and financial challenges User engagement and local champions are essential for DES transitions

Table 4 (continued)

Authors	Journal	Article Title	Year	Sample Size	Category Method Technique	Key Findings
Waring, J; Bishop, S; Black, G; Clarke, JM; Exworthy, M; Fulop, NJ; Hartley, J; Ramsay, A; Roe, B	Journal of Health Services Research & Policy	Navigating the micro-politics of major system change: The implementation of ST Partnerships in the English health and care system	2023	83 Interviews	Empirical Qualitative Case study	Political fault lines exist in system change because of differing meanings and values Sustainability and Transformation Partnerships (STP) leaders used to listen and engagement strategies to reconcile stakeholder views Power imbalances influence system collaboration efforts STP leaders navigate opposition with negotiation and political skills

Table 5 Coding Examples

Example Quote	1st Order Concept	2nd Order Theme	Aggregate Dimension
DT			
"DT provides an important entry point for energy enterprises to improve their innovation ability."	Developing green innovation abilities	Build innovation capabilities for risk-tolerant advances	Adaptation and flexibility for DT
"Deep cultural change will also be needed with a focus on people and agile ways of working."	Delivering IT agile	Build innovation capabilities for risk-tolerant advances	Adaptation and flexibility for DT
"This is particularly challenging, given that […] different departments use systems that are not interoperable."	Balancing current operations with the drive towards fundamental transformation	Develop digital business models adapted to high-stakes environments	Adaptation and flexibility for DT
"Having a separate unit for innovation allows for an environment within the mainstream organization in which learning and experimentation are encouraged, and failure is tolerated."	Managing tensions between innovation/transformation and reliable operations	Develop digital business models adapted to high-stakes environments	Adaptation and flexibility for DT
"The participants suggested that implementation be facilitated by involving professionals from different professional groups […]."	Building interdisciplinary knowledge in cross-functional teams	Establishing strategic agility for digitalization	Adaptation and flexibility for DT
"Bringing together different stakeholders to sense opportunities and threats is a means of doing this."	Sensing opportunities and threats	Establishing strategic agility for digitalization	Adaptation and flexibility for DT
ST			
"[…] one is to force them to do so through environmental regulation, […]."	Political regulatory system driving potentials for radical change	Enforce radical change through regulation and guarantee operational stability	Governmental regulations and stakeholder dynamics demanding sustainable transformation
"The ownership of the local governments in some of the major power utilities in the province provide the governments another mechanism to push the closures."	Increasing control for public owners	Enforce radical change through regulation and guarantee operational stability	Governmental regulations and stakeholder dynamics demanding sustainable transformation
"[…] encourage them through market mechanisms."	Navigating economic pressure and loss	Economic incentives driving ST	Governmental regulations and stakeholder dynamics demanding sustainable transformation
"[…] we find that the focus of such reforms remains on cost-efficiency, rather than to engage in radical innovations."	Balancing cost-effectiveness and sustainability	Economic incentives driving ST	Governmental regulations and stakeholder dynamics demanding sustainable transformation

Table 5 (continued)

Example Quote	1st Order Concept	2nd Order Theme	Aggregate Dimension
"[…] carry out green innovation activities through digital technology to adapt to the trend of digital development and improve the environmental efficiency of enterprises."	Promoting the generation of new technologies and enhancing green technology innovation through digital technology for improved innovation efficiency	Technology innovation driving green transformation	Governmental regulations and stakeholder dynamics demanding sustainable transformation
"[…] the global economy has seen decreasing prices on renewables and a rapid development of low-emission technologies."	Rapidly developing low-emission technologies	Technology innovation driving green transformation	Governmental regulations and stakeholder dynamics demanding sustainable transformation

Acknowledgements Johanna Gast is member of LabEx Entrepreneurship, funded by the French government (LabEx Entreprendre, ANR-10-Labex-11-01).

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Nils Kleinschmidt and Lysander Weiss. The first draft of the manuscript was written by Nils Kleinschmidt and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. The authors received no financial support for the research, authorship, and/or publication of this article.

Data availability The data that support the findings of this study are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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