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Critical factors affecting digital transformation in manufacturing companies

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Abstract

Digital transformation represents a compelling opportunity for manufacturing companies to enhance their competitiveness. This transformative journey offers myriad possibilities, including improved connectivity between workers and machines, as well as seamless machine-to-machine interactions. However, many manufacturing companies encounter challenges when attempting to implement digital transformation effectively. The process of digital transformation is often slow, and most companies find themselves in the early stages of adoption, grappling with the ambiguity surrounding the associated technologies. A systematic approach for the implementation of digital transformation is still elusive for many manufacturing companies. The number of studies exploring digital transformation is increasingly growing, encompassing various sectors and domains. However, within the manufacturing sector, there remains a need for further research and clarity on systematic implementation approaches. To address these issues, this research undertakes a comprehensive analysis to identify the critical factors that influence digital transformation in the manufacturing sector. The objective of this research is to identify the factors that drive the success of digital transformation in manufacturing companies while also uncovering factors that, when neglected, could lead to failure. Through a systematic literature review, this research identifies 11 critical factors. These factors serve as the basis for developing the ARTO model, a structured framework comprising four distinct categories: "Awareness-related factors," "Readiness-related factors," "Technology Selection-related factors," and "Operations-related factors." Moreover, this research incorporates expert perspectives gathered through a survey to refine the ARTO model. This study offers the ARTO model and digital transformation definition as practical tools for successfully implementing digital transformation in manufacturing companies, while also delineating the intricate relationships among the crucial factors. By shedding light on the factors underpinning digital transformation

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in the manufacturing sector, this research contributes to the ongoing discourse and facilitates more effective adoption of digital transformation strategies.

Highlights

Digital transformation enhances competitiveness with connectivity and machine interactions.
Challenges in implementing digital transformation necessitate the identification of critical influencing factors.
Developed ARTO (Awareness, Readiness, Technology, and Operations) model for enabling successful digital transformation based on critical factors.
The ARTO model, derived from 11 critical factors, offers a structured framework for successful implementation.
The ARTO model and the proposed DT definition guide manufacturing companies in their digital transformation journey.
This research sheds light on essential factors, contributing to a more effective adoption of digital transformation strategies.

Keywords Digitalization · Industry 4.0 · Digital technologies · Critical factors · Manufacturing industry · Technology integration · Success factors · Smart production · Transition management

Introduction

In recent times, manufacturing companies have experienced significant transformations driven by technological advancements, increased competition, evolving customer demands, and rising apprehension (Choi et al., 2017; Yin et al., 2018). Consequently, digital transformation (hereafter, DT) has become a critical strategic imperative (Kane et al., 2015; Omol, 2023). Digitalization offers innovative opportunities, enabling companies to address issues such as customer satisfaction, resource optimization, workforce utilization, cost reduction, and quality control (Santos & Martinho, 2020). To seize the full potential of digitalization, companies must actively harness technology to achieve superior outcomes (Lee et al., 2015; Chirumalla, 2021; Johansson et al., 2024).

This process of digitalization, coupled with the integration of enabling technologies, introduces enhanced flexibility, adaptability, access to technical systems, increased productivity and efficiency, and reduced labor costs within the market (Synnes & Welo, 2016; Schiffer et al., 2019; Perzylo et al., 2019). The manufacturing industry has witnessed several industrial revolutions, with the most recent being the fourth industrial revolution, often referred to as Industry 4.0 (Santos & Martinho, 2020). Industry 4.0 has led to the rise of DT (Schumacher et al., 2019), which enhances product quality, system monitoring, and shop floor efficiency (Temel & Ayaz, 2019; Merhar et al., 2019). DT encompasses technologies like Internet of Things (IoT), cloud computing, Artificial Intelligence (AI), augmented reality, block chain, 3D printing, big data, and advanced simulations (Illa & Padhi, 2018; Rad et al., 2022; Perzylo et al., 2019).

Despite its advantages, companies face challenges in implementing DT, with many still in the early stages of technology adoption (Johansson et al., 2020). Unclear understanding of the associated technologies and a lack of a clear and effective digital strategy and transformation roadmap hinder progress (Buer et al., 2018; De Carolis et al., 2017; Kane et al., 2015). The complexity of DT results in different interpretations and varying levels of readiness among companies (Santos & Martinho, 2020; Kane, 2019). Companies must embrace DT to remain competitive, adapt to changing customer demands, and enhance efficiency (Zhang et al., 2021). However, a lack of knowledge, high costs, and the need for technical skills hinder adoption (Javadi & Chirumalla, 2024; Sanders et al., 2016; Schuh et al., 2014). Insufficient understanding of technology functionality and investment requirements further complicates the process (Schuh et al., 2014).

To address these challenges, it is essential to identify the critical factors that influence the successful implementation of DT in manufacturing companies. Critical factors are "those few things that must go well to ensure success for a manager or an organization" (Boyton & Zmud, 1984, p. 17) or "factors that would tend to increase the likelihood of success" (Zhang et al., 2022, p. 3). The presence of these key areas within an organization will facilitate the successful implementation of initiatives (Vrchota et al., 2021). Focusing on a few critical factors can reduce the complexity of process implementation and decision-making, allowing for greater emphasis on the most important aspects to achieve the desired outcomes (Bai & Sarkis, 2013). In this research, the term 'successful' in the context of DT within the manufacturing sector refers to the achievement of specific objectives and outcomes that signify progress and value creation (e.g., Delone & McLean, 2003; Ghobakhloo & Iranmanesh, 2021; Pozzi et al., 2023). According to the Cambridge Dictionary, 'successful' means achieving the desired or expected results, while 'unsuccessful' denotes the failure to attain these results. Successful DT is marked by tangible improvements in key performance indicators, such as increased revenue, cost savings, and enhanced operational efficiency (e.g., Bhatia & Kumar, 2022). These metrics serve as benchmarks for assessing the transformative impact on business performance. By adhering to these criteria, organizations can effectively distinguish between unsuccessful and successful DT initiatives, ultimately driving sustainable growth and gaining a competitive advantage in the manufacturing sector. Current research in this domain has predominantly provided generalized insights into critical factors that apply across various sectors (Deepu & Ravi, 2021; Sahu et al., 2018; Schniederjans et al., 2020; Jones et al., 2021; Mhlungu et al., 2019; Steiber et al., 2021; Gurbaxani & Dunkle, 2019; Cichosz et al., 2020; Sony & Naik, 2020). While there are studies addressing small and medium-sized enterprises (SMEs) (Zhang et al., 2022; Eller et al., 2020; Ghobakhloo & Iranmanesh, 2021) and large industrial firms (e.g., Steiber et al., 2021), there is a notable gap in research tailored specifically to the unique needs of manufacturing companies (Vogelsang et al., 2018). Although some studies have explored critical factors associated with Industry 4.0 technologies (Brodeur et al., 2022; Pozzi et al., 2023; Sony & Naik, 2020), including those focused on manufacturing companies (Pozzi et al., 2023), the manufacturing and service sectors (Sony et al., 2021), and the automative manufacturing industry (Bhatia & Kumar, 2022), there remains a lack of research dedicated to developing and validating frameworks and

models specifically designed for DT in the manufacturing sector. Readiness frameworks and maturity models have been proposed to support DT efforts (e.g., De Carolis et al., 2017; Santos & Martinho, 2020; Wagire et al., 2020), yet the application and effectiveness of these models in addressing the particular challenges faced by manufacturing companies remain underexplored. This research aims to fill this gap by focusing on the critical factors specific to manufacturing companies and developing a more nuanced understanding of successful DT within this sector.

To achieve this aim, the authors systematically reviewed the literature to distill the various factors influencing digital transformation. The research examined both factors that contribute to success and those that, if neglected, can lead to failure. By thoroughly evaluating the existing literature, this study aims to establish connections between these factors, providing valuable insights for researchers, practitioners, and stakeholders in the manufacturing industry. To guide our investigation, we pose the following research questions.

RQ1: What are the influential factors for the success of digital transformation in manufacturing companies, and how are these factors interrelated?
RQ2: How can manufacturing companies utilize these factors to achieve successful digital transformation implementation?

Key concepts' background

In this section, we delve into the background of key concepts crucial to this research: digital transformation, and Industry 4.0.

Digital transformation (DT)

Digitalization is a key driver in the evolution of advanced manufacturing, leveraging digital data and technologies to automate data management and optimize processes (Buer et al., 2018). This process goes beyond merely converting analogue information into digital formats; it involves enhancing the interconnectedness of business processes, creating efficient interfaces, and enabling seamless data exchange and management (Bogner et al., 2016). Core digital technologies underpinning this transformation include the IoT, AI, cloud computing, big data analytics, blockchain, augmented reality, automation, advanced robotics, additive manufacturing, simulation, and semantic technologies (Rad et al., 2022; Oztemel & Gursev, 2020). These technologies are characterized by real-time processing, intelligence, interoperability, virtualization, decentralization, connectivity, service orientation, modularity, and advanced analytical capabilities (Ardolino et al., 2018; Oztemel & Gursev, 2020; Chirumalla, 2021). Referred to as digital capabilities (Li et al., 2019), these features are critical for driving digital transformation. They enable machines to cooperate and coordinate, make autonomous decisions, manage and solve problems independently, and even learn from their environments in manufacturing settings (Oztemel & Gursev, 2020; Li et al., 2019).

Companies can develop their digital capabilities across six key areas: research and innovation, production management and control, supply chain management, financial management, operational management, and customer service (Li et al., 2019). Building these capabilities requires a holistic approach that goes beyond merely adopting information and communications technology (ICT) or spreading new technologies. It necessitates a comprehensive strategy that integrates data management, technology, business processes, organizational structures, and strategic planning (Gürdür et al., 2019; Li et al., 2019; Chirumalla, 2021).

DT describes the process by which businesses and organizations fundamentally change their way of operating through technological innovations (Verhoef et al., 2020; Vogelsang et al., 2018). The adoption of digital technologies has enabled the development of new processes across the entire value chain—from manufacturing to sales and services, including product usage (Bogner et al., 2016). DT not only facilitates the reconfiguration and integration of products with other systems (Santos & Martinho, 2020), but also allows for real-time data acquisition, enabling more effective planning and operational control (Buer et al., 2020; Ruiz et al., 2017).

However, integrating DT across an entire organization remains a formidable challenge for practitioners, primarily due to the absence of well-established implementation and monitoring procedures (Illa & Padhi, 2018). This process requires radical changes both internally and externally, necessitating a comprehensive, holistic transformation of the organization (Vogelsang et al., 2018). As a result, many firms continue to struggle with realizing the full potential of DT (Hess et al., 2016), often due to a lack of understanding of its complexities (Ahlskog et al., 2023; Kane et al., 2015).

DT goes beyond merely adopting new technologies; it requires aligning these technologies with the organization's structure, culture, and external environment (Matt et al., 2015). As Vogelsang et al. (2018) noted, "*Technology is a prerequisite for digital transformation. Without secure and reliable technological innovations, digital transformation is not possible. However, driving only technology forward is not enough to gain benefits from digital transformation*" (p. 137). DT is a complex system that involves the interaction of multiple factors, all of which must work together to ensure its success (Zhang et al., 2022).

For companies to navigate this complexity effectively, it is crucial to fully understand the key elements necessary for successful digital transformation. This understanding is essential for steering the organization toward a strategic and effective transformation (Vogelsang et al., 2018). Previous research, such as the information systems success models proposed by DeLone and McLean (2003), has laid the groundwork for identifying success factors. Building on this, studies have discussed various success factor models (Vogelsang et al., 2018; Pozzi et al., 2023; Mhlungu et al., 2019). For instance, Vogelsang et al. (2018) categorized success factors into three major dimensions: technology, organization, and environment. Notably, most success factors are associated with the organizational dimension, highlighting both the challenges and opportunities for companies as they drive their digital transformation.

Many companies, however, find themselves overwhelmed by the multitude of factors to consider, the identification of key points, and the development of a digitization roadmap before embarking on a DT journey (Kiron et al., 2016). Therefore, it is criti-

cal to identify and clarify the key factors and mechanisms that influence the success of digital transformation. This is of great importance for effective resource allocation, as well as for promoting the successful implementation of DT initiatives. A clear understanding of these critical factors can significantly increase the likelihood of success in DT efforts, providing essential guidelines and potentially uncovering the root causes that lead to successful initiatives (Zhang et al., 2022).

Industry 4.0

Industry 4.0, often referred to as the fourth industrial revolution, represents a transformative shift in manufacturing through the convergence of physical and digital technologies (Rußmann et al., 2015; Kagermann et al., 2013). Launched in Germany in 2011, Industry 4.0 emerged from a collaborative effort between the federal government, universities, and private companies aimed at enhancing national industrial productivity and efficiency (Frank et al., 2019). At its core, Industry 4.0 leverages the combination of information, computing, communication, and connectivity technologies to drive innovation in manufacturing (Bharadwaj et al., 2013). It encompasses nine key technological pillars—IoT, horizontal and vertical system integration, simulation, autonomous robots, big data and analytics, augmented reality, additive manufacturing, cloud computing, and cybersecurity—each playing a critical role in transforming traditional manufacturing systems (Rußmann et al., 2015). Together, these advancements present new strategic opportunities for companies to enhance their competitiveness by optimizing costs, improving quality, elevating service levels, and increasing operational flexibility.

Industry 4.0 is centered on the collection and analysis of real-time data, utilizing digital technologies to generate valuable insights that enhance manufacturing processes (Frank et al., 2019). By integrating physical objects, production lines, and intelligent machines, Industry 4.0 fosters a more productive, cost-effective, and competitive value chain (Genest & Gemache, 2020). While the implementation of these technologies can be complex, various maturity models and studies have been developed to assess their impact on industrial performance (Frank et al., 2019; Yıldırım & Demirbağ, 2020; Wang et al., 2016; Wagire et al., 2020; Sjobakk, 2018). Researchers have also mapped out patterns of adoption and implementation strategies, as outlined in the framework by Frank et al. (2019), which offers a comprehensive view of how organizations navigate the transition to Industry 4.0. Moreover, Veile et al. (2020) highlight that for Industry 4.0 to be successfully implemented, it is essential to consider seven critical factors: corporate culture and communication, workforce readiness, organizational structure, safety and security protocols, preparatory measures for Industry 4.0 initiatives, the integration of these initiatives, and the financial viability of the transformation. These factors collectively influence the effectiveness of Industry 4.0 adoption and underscore the multifaceted nature of the transformation process.

The implementation of Industry 4.0 aims to develop "smart factories," where emerging technologies converge to enhance manufacturing processes (Stentoft & Rajkumar, 2019). These smart factories leverage advanced integration and automation, enabling the autonomous execution of operations (Jung et al., 2021). This sets

the current manufacturing landscape apart from previous industrial concepts (Fatorachian & Kazemi, 2018). By incorporating technologies like cyber-physical systems (CPS) and human-machine interfaces, smart factories contribute to environmentally, economically, and socially sustainable manufacturing systems. A defining feature of Industry 4.0, the smart factory allows products to navigate the production process independently while maintaining cost efficiency and high flexibility (Hofmann & Rüsch, 2017). In a smart factory, communication and material flows seamlessly across subsystems, integrating end-to-end engineering within traditional manufacturing settings. This integration not only enhances product development and efficiency (Wang et al., 2016) but also intensifies competition by introducing vertical integration to the shop floor. Wang et al. (2016) suggest a four-layer system architecture for smart factories, which includes physical tools, industrial networks, data storage, and a control and supervision layer to meet production demands.

Industry 4.0 serves as the cornerstone for DT strategies, enabling businesses to evolve into smarter, more connected, and flexible production systems (Ghobakhloo & Iranmanesh, 2021). Today, Industry 4.0 is often described as the comprehensive DT of entire industrial value chains (Culot et al., 2020). This transformation is driven by the implementation of specific digital technologies (Indri et al., 2018) and the development of innovative design principles (Frank et al., 2019). DT accelerates businesses into the era of Industry 4.0 by enhancing their understanding of customer needs, boosting operational efficiency, and creating new revenue streams (Schwab, 2017; Frank et al., 2019). However, this shift goes beyond mere technology adoption; it requires a fundamental rethinking of business models, corporate culture, and customer interactions (Gürdür et al., 2019; Li et al., 2019; Kane et al., 2015).

While transformation in manufacturing has long been an evolutionary process, marked by the gradual adoption of new technologies to enhance efficiency and productivity (Matt et al., 2015; Hess et al., 2016; Stentoft & Rajkumar, 2019), the current wave of change is distinguished by the unprecedented pace of technological development (Gurbaxani and Dunkle, 2019; Steiber et al., 2021; Omol, 2023; Oztemel & Gursev, 2020). This rapid evolution is not just about isolated technological advancements; it's about the integration of these technologies into a unified, connected factory floor. This integration allows manufacturers to collect, analyze, and leverage data across the entire value chain—from design and development to production and delivery—resulting in greater efficiency, flexibility, and competitiveness (Oztemel & Gursev, 2020; Pozzi et al., 2023). Therefore, a deep understanding of the critical factors influencing DT under Industry 4.0 is crucial for organizations.

Research method

This study aims to identify the factors that influence the success of DT in manufacturing companies, as well as those whose neglect leads to unsuccessful outcomes. The research approach commenced with a systematic literature review (SLR) (Denyer & Tranfield, 2009), which aimed to comprehensively investigate the factors impacting DT in manufacturing companies. Subsequently, the data collected through

the SLR underwent rigorous analysis, leading to the formulation of a conceptual model, ARTO (Awareness-Readiness-Technology-Operations) (Fig. 5). To validate the ARTO model, a survey was meticulously designed and distributed to industrial practitioners in the manufacturing industry. Respondents were assured of anonymity, enabling them to offer candid insights from their internal industrial perspective. The subsequent phase involved a thorough analysis of the survey results. Finally, the findings from both the systematic literature review and the survey were amalgamated to construct a comprehensive and generic ARTO model (Fig. 19).

Systematic literature review (SLR)

The systematic literature review was conducted to address research questions 1 and 2 (RQ1 and RQ2) and to gain a comprehensive understanding of existing studies in this field. The SLR approach not only consolidates existing knowledge but also aids in theory development on the specific topic (Masrom et al., 2021). An SLR typically involves three stages: planning the review, conducting the review, and reporting the results.

Planning stage

In this stage, the authors established a clear goal for the SLR and created a review protocol to guide the literature collection process. The review protocol not only defines the research method but also serves to reduce research bias (Masrom et al., 2021). To ensure a systematic and efficient review, the authors devised a timetable outlining all the processes and time limits involved in the SLR. The processes integrated into the timetable encompassed various activities such as literature search using logic operators, applying inclusion and exclusion criteria based on abstracts and titles, categorizing articles using an Excel sheet, selecting relevant papers, utilizing snowballing techniques, and making the final selection of papers for inclusion in the SLR.

Conducting the review

The second stage involves the actual search, analysis, and selection of relevant literature (Masrom et al., 2021). Academic databases, including Scopus and Web of Science, were used for this purpose. To identify potentially relevant articles in both databases, we used Boolean logic to combine the search term "*digital transformation*" with various search terms referring to "*manufacturing companies*" and "*factors*". Specifically, we applied the following search string for English language journal articles:

> *"(digital*transformation OR digitali* OR smart* factory OR industry 4.0) AND (manufacturing* companies) AND (factor* OR success factors OR enablers OR capabilities OR prerequisites OR critical success factor OR criteria OR determinants) AND NOT (challenges OR barriers)"*

The criteria for selecting articles were based on keywords, title, and abstract. The search spanned from 2005 to 2021, resulting in the retrieval of 379 articles. Various keywords were employed, and advanced criteria, including narrowing the scope to the engineering field, were used to ensure the selection of relevant papers. Out of the 379 papers, only abstracts were initially examined, resulting in the elimination of irrelevant papers. After this first round of screening, 176 papers were selected for a detailed analysis to ensure their relevance to the study. Inclusion criteria considered papers specific to the manufacturing industry and the engineering field, covering success factors, capabilities, critical success factors, digitalization, and DT across both developed and underdeveloped countries. Exclusion criteria encompassed papers solely focused on digital technology implementation without addressing factors, those lacking specificity regarding digital transformation, articles concentrating on software, and papers discussing barriers and challenges of DT in manufacturing companies. After applying the inclusion and exclusion criteria, a total of 67 papers remained, which underwent full paper reading. This thorough evaluation resulted in the inclusion of 21 studies for the review. Additionally, the snowballing method was employed, leading to the identification of another article, bringing the total number of studies analyzed in the review process to 22. Figure 1 illustrates the article selection process. The selected papers were downloaded into Endnote for further evaluation. These downloaded papers were thoroughly reviewed, and crucial information was highlighted. Additionally, relevant articles were categorized in an Excel spreadsheet, incorporating details such as author names, publication year, addressed factors, and more, to facilitate a deeper understanding of the articles.

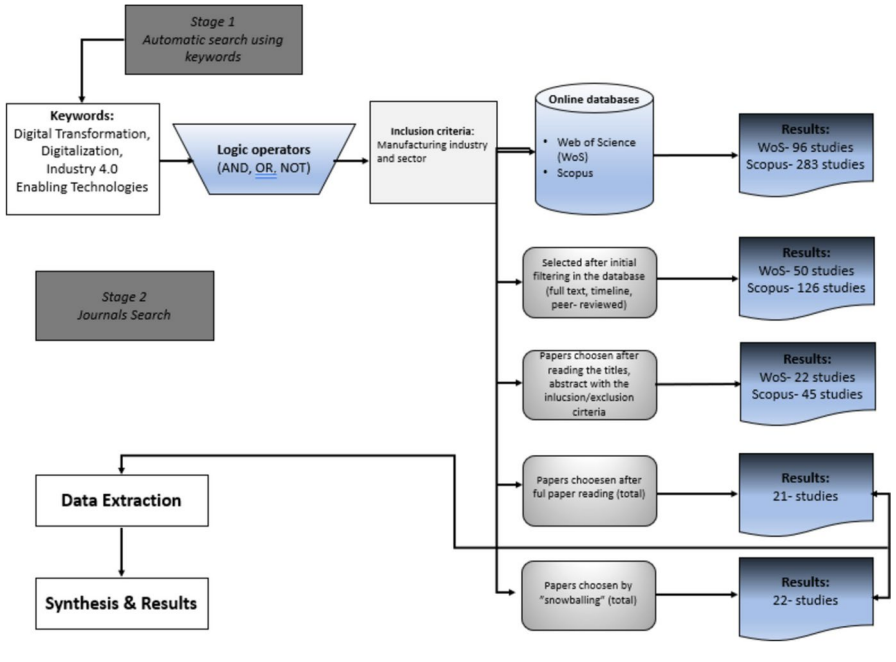

Fig. 1 The screening process of article selection

Reporting the results

The analysis of data obtained from the literature involved reading and examining the content using an Excel sheet, aimed at addressing the research questions. The analysis sheet was organized into categories such as paper type, paper purpose/focus, technology type, factors/capabilities/prerequisites/critical factors of DT, implementation process/maturity model, successful/unsuccessful factors of DT, type of empirical studies/type of industry, year of publication, and various definitions of DT. Pattern matching technique (Miles & Huberman, 1994) and thematic analysis (Braun & Clarke, 2006) were employed for the comprehensive analysis of a wide array of factors. This analytical approach led to the identification of 11 categories of critical factors. In the subsequent phase, an analysis was conducted to understand the relationships between these factors that influence digital transformation. This analysis resulted in the identification of four dimensions based on the nature and type of influence these factors had on digital transformation. The culmination of this analysis was the development of a conceptual model named ARTO (Awareness-Readiness-Technology-Operations), which captures the critical factors affecting DT (Fig. 5).

Survey

To gain first hand insights and a comprehensive understanding of digitalization implementation across different companies, a web survey was developed using SurveyMonkey (See Appendix A). The survey was designed for individuals working in various manufacturing companies, and it was estimated to take 15–20 min to complete. The survey was structured into four sections. The first section focused on general company and individual information. Questions related to the company included type of company, number of employees, and types of products produced. Questions regarding the individual respondent covered educational qualifications, job roles, and relevant experience. In the second section, participants were asked to assess the importance of critical factors for digital transformation. They used a Likert Scale to rate each factor on a scale from 1 to 7, where 1 indicated non-significance, and 7 indicated high significance. Section three addressed subfactors identified through the SLR. Participants were required to select the subfactors that they considered relevant for each key factor from their company's perspective. The fourth and final section focused on a generic model created from various factors and subfactors. This model consisted of four phases: awareness in the organization regarding digital transformation, organizational readiness for digital transformation, technology selection, and the technology's relevance for digital transformation, and operations relevance for digital transformation.

Survey participants were tasked with either confirming the SLR findings or introducing new insights and suggestions. Once all participant responses were collected, they were compiled and analyzed. An ARTO model, showcasing the most highly ranked factors according to the survey participants, was constructed. Furthermore, the results from both the literature study and the survey were amalgamated into new diagrams. A comparative analysis was conducted to identify the most dominant critical factors, considering insights from both the literature study and the survey. This

analysis led to the formulation of a definitive ARTO model (Fig. 19), revealing the relationship between various factors influencing DT.

Results from systematic literature review (SLR)

Descriptive analysis of the SLR

In this section, we delve into key aspects, such as factors derived from the literature, article types, publication years, and the types of industries under study. This analysis is aimed at enhancing our understanding of the depth and breadth of research efforts concerning DT (Kim et al., 2018).

Factors from the literature

The literature we examined falls into two broad categories. Some authors emphasize the critical factors necessary for the successful adoption and implementation of digital technologies, while others outline fundamental criteria that, when overlooked, can lead to unsuccessful DT. Figure 2 illustrates that researchers have dedicated more effort to exploring factors contributing to the success of digital transformation, as opposed to those that hinder its progress. Over 80% of the articles center on the positive outcomes of digital transformation. While this emphasis on success is valuable, we identify a gap that calls for attention. To bridge this gap, we believe it's crucial for practitioners of DT to have a well-rounded understanding of both the factors that lead to success and those that can impede progress. Striking this balance is essential to mitigate potential pitfalls, especially as we differentiate between companies already on the transformation journey and those just commencing.

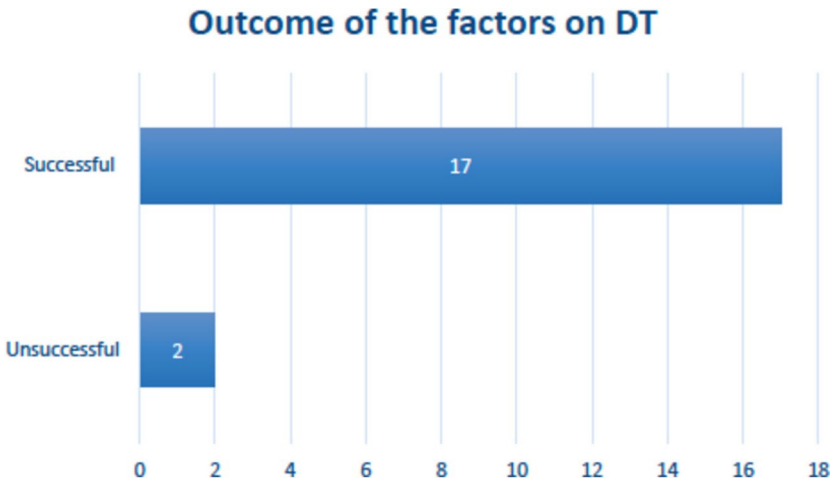

Fig. 2 Successful and unsuccessful outcomes of the factors

Fig. 3 Article types from literature

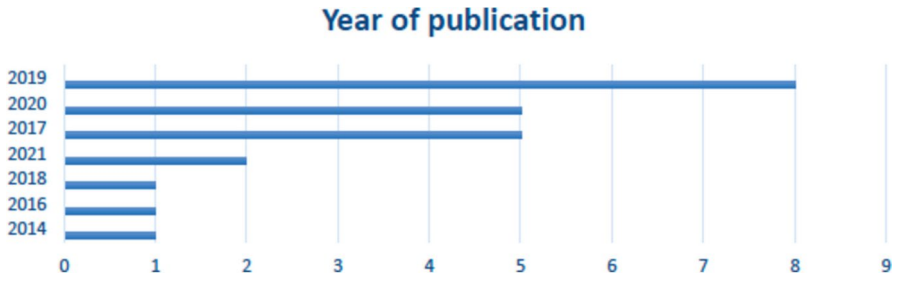

Fig. 4 Year of publication of articles

Article type

Our analysis categorized concluded articles into various types, including empirical studies, surveys, mixed empirical and systematic literature reviews (SLR), literature reviews (LR), conceptual papers, surveys, workshops, systematic mapping studies (SMS), and process models. Figure 3 shows that a significant portion of research efforts have been devoted to empirical studies. While this emphasis on empirical research is commendable, we contend that there is room for increased diversity in article types to offer solutions to the evolving challenges that manufacturing companies face in their DT journey.

Year of publication

Our examination extends to the years of publication of the articles, spanning from 2005 to 2021 as shown in Fig. 4. Notably, the year 2017 experienced a surge in the number of articles concerning factors influencing DT in manufacturing companies,

in contrast to prior years. However, there was a substantial decline in articles published in 2018, followed by a peak in 2019 and another decline in 2020. At present, it remains challenging for us to pinpoint the exact reasons behind these fluctuations.

Thematic analysis of the SLR

Identified critical factors influencing digital transformation

The literature analysis has identified the following list of factors that influence digital transformation:

1. Organizational Culture: This factor centers on an examination of the overall attitude of the organization towards digital transformation.
2. Organizational Structure: Focusing on a functional structure that promotes the achievement of digital transformation.
3. People and Organizational Competence: This factor evaluates the competence levels of the workforce concerning digital transformation.
4. Characteristics, Selection & Integration of Digital Technologies: Addressing the organization's processes for selecting and integrating digital technologies into its transformation efforts.
5. Infrastructural Investment: Considering the necessary infrastructure investments to achieve the organization's DT goals.
6. External Support: Encompassing external influences on the organization, including the need to satisfy customers and collaborate with suppliers to acquire essential technology.
7. Data Security: Pertaining to the safety and proper management of the data collected during the DT process.
8. Design of Production System (DPS): Analyzing the design of the production system within the organization.
9. Organizational Strategies: Addressing the strategies required to achieve DT goals.
10. Organizational Leadership: Evaluating the management and leadership of the organization, including leadership approaches, strategies, and styles.
11. Data Governance (DG): Referring to the organization's ability to comprehend and interpret all collected data effectively.

Factors related to organizational culture In this context, organizational culture refers to the analysis of the behavioral characteristics of employees. It seeks to examine how the leadership of the company works, the mode of communication between teams, adaptation to modern technologies, the company's willingness to collaborate, and its overall attitude towards innovation (Manavalan & Jayakrishna, 2019; Merhar et al., 2019; Mittal et al., 2019; Paschou et al., 2018; Santos & Martinho, 2020; Schumacher et al., 2019; Synnes & Welo, 2016; Temel & Ayaz, 2019). These factors further delve into the preparedness of the company for the implementation of digital equipment, such as sensors, digital monitoring, optimization, automation, and IoT

connection, and its level of readiness towards digitalization (Wagire et al., 2020; Schumacher et al., 2019).

Factors related to organizational structure Organizational structure is connected to the organization's behavioral patterns and management-related issues, aimed at evaluating the approaches employed by the organization's management in directing work while ensuring a functional and agile structure (Santos & Martinho, 2020). Additionally, the company's organizational structure places a strong focus on task orientation, motivation, employee autonomy, flexibility, team skills, customer orientation, and collaboration throughout the value chain (Santos & Martinho, 2020). Important aspects to consider within the context of organizational structure include security issues, reconfigurable layouts, management of innovation, and the degree of openness to innovation (Santos & Martinho, 2020).

Factors related to people and organizational competence The term "people and organizational competence" pertains to the workforce within the organization and their level of competence. This workforce can be divided into two subcomponents: existing abilities and the acquisition of new skills (Santos & Martinho, 2020; Schumacher et al., 2019), which is achieved through the qualification of new employees (Santos & Martinho, 2020). The awareness of Industry 4.0 plays a significant role in companies, as technology simplifies work for employees. For example, the use of Virtual Reality (VR) technology enables suitable training for employees (Wagire et al., 2020). With the transition to digitalization and the adoption of new innovative technologies, it is essential to consider employee qualifications and the continuous updating of management and workforce skills.

The team's willingness to implement innovative technologies, adapt to change, and exhibit flexibility is crucial (Paschou et al., 2018; Santos & Martinho, 2020; Schumacher et al., 2019) for the overall growth of the organization. Simultaneously, the company must have employees with expertise in data collection (Paschou et al., 2018). The lack of this capability often leads to the inability to define starting points and could hinder prompt responses in data-related activities (Nausch et al., 2020). IoT devices bring significant benefits to employees. For example, they can provide warnings to workers before unforeseen situations occur, which can save lives, time, and costs (Manavalan & Jayakrishna, 2019). Additionally, IoT devices enable supervisors to track the location of components remotely, allowing live instructions to be sent to workers on how to handle sensitive materials and special equipment (Manavalan & Jayakrishna, 2019). Furthermore, technological readiness is a crucial factor for the company, as a lack of it can negatively affect economic success.

According to Merhar et al. (2019), to implement digitalization, information, participation, and training are crucial factors for the participants. Also, confirmation from the management is a significant factor for participants' acceptance. Equal distribution of devices, social influence, support from management, influences from colleagues, and being seen as an innovative company are also influential factors (Merhar et al., 2019). Choi et al. (2017) suggest that factors like workers, environmental effects, and material handling systems are more complicated than data acquisition for non-

equipment factors since they are not standardized. Enabling factors for implementing digitalization include innovative education and training, along with compliance with laws and regulations. It is also important to educate knowledge workers about digitalization (Mittal et al., 2019).

Factors related to characteristics, selection & integration of digital technologies This category refers to the methods employed in choosing and integrating digital technologies into the company's DT process. When implementing digital technologies, it is essential to ensure the traceability of data from start to finish within the structure to reduce waste, increase productivity, and facilitate maintenance (Temel & Ayaz, 2019). Smart factories have also been implemented for SMEs through technologies such as AI and Big Data. SMEs have leveraged cloud computing to support smart manufacturing (Jung et al., 2021; Ruiz et al., 2017).

Critical aspects to consider with digitalization include reliability, high functionality, software and device timeliness, rapid data transformation, and exceptional performance (Merhar et al., 2019). Furthermore, the ease of use and perceived usefulness significantly impact users' willingness to adopt technology (Merhar et al., 2019; Synnes & Welo, 2016). Digital technologies empower companies to enhance their competitiveness and productivity. Achieving this requires innovative thinking along with a holistic perspective. It is essential to deliver cost-optimized products based on customer demands. To accomplish this, the company should consider not only production, service, and function but also various organizational aspects, including quality control, logistics, material flow control, and product quality (Jung et al., 2021; Ruiz et al., 2017). Enabling factors to support this approach include the company's ability to embrace modern technologies and increase flexibility. The production system's work environment should maximize capacity utilization. Another crucial factor is product and process development facilitated by teamwork. In addition, supporting tools like knowledge-sharing guidelines between different departments, such as production and product engineering, play a vital role (Jung et al., 2021; Ruiz et al., 2017). A holistic view is vital within a company as it enhances technical capabilities related to services, products, and processes, aligning them with organizational strategy (Santos & Martinho, 2020). Cloud computing contributes to capabilities such as storage and on-demand computing (Bevilacqua et al., 2017).

In recent times, additive manufacturing has gained popularity in companies as automation becomes increasingly preferred in modern industries, leading to increased flexibility and customization within production systems (Qin et al., 2017). To enable big data utilization within a company, an important prerequisite is to strategically address big data and problem-solving related to it (Paschou et al., 2018). Merhar et al. (2019) suggested that users prefer digital devices to be simple and easy to use. Ease of use significantly influences users' willingness to adopt digital technologies. Generally, users' attitudes towards technology are characterized by openness and optimism. Digital system designs should be user-friendly, functional, reliable, and capable of swift data transformation. Additionally, digital technologies are popular to varying degrees, with tablets being the preferred choice in the private sector due to

their excellent display options. Smartphones rank second due to their mobility, and portable devices are popular for their flexibility (Merhar et al., 2019).

Factors related to infrastructural investment Infrastructural investment pertains to the investments that a company must make when transitioning to digital transformation. Companies operating in the goods sector typically exhibit a strong awareness of industry 4.0. Company size plays a pivotal role in assessing the challenges and benefits associated with the shift to industry 4.0. For SMEs, the primary barrier lies in financial resources, while large enterprises face the challenges associated with transitioning to industry 4.0 (Yıldırım & Demirbağ, 2020). Buer et al. (2020) concur that smaller companies are not as financially and technologically prepared for industry 4.0. As a result, the operational break-even point increases in tandem with investments for industry 4.0 implementation. Challenges when implementing digitization encompass factors such as low production volumes, standardization requirements, data security concerns, and limited access to trained employees. Thus, many SMEs may deem the transition to digitization insufficiently profitable. The disparity in implementing digitization between large and small companies warrants further investigation.

However, Buer et al. (2020) argue that the transition to industry 4.0 is not limited to large enterprises, as industry 4.0 encompasses the entire supply chain and offers significant advantages to SMEs, including the creation of new products, services, and innovative business models. Additionally, digitalization can enhance efficiency and reduce costs, irrespective of company size. Buer et al. (2020) claim that smaller companies typically have lower IT expertise compared to larger counterparts. In enhancing IT competence, the actions of managers are pivotal. Managers should engage in activities aimed at expanding their employees' IT skills, such as research projects and participation in knowledge-sharing networks (Buer et al., 2020). Developing countries, which lack sufficient capital accumulation, require tailored approaches and practical models to maximize technology transfer and capacity building through in-depth case studies (Yıldırım & Demirbağ, 2020). In many cases, companies do not view the excessive costs, lack of knowledge, and insufficient benefits as justifying investment compared to the expected returns. Moreover, Schiffer et al. (2019) express agreement with the perspective that excessive costs, a lack of competence, and insufficient benefits deter many companies from investing in digitization. Paschou et al. (2018) also assert that a critical prerequisite for enabling digitization in a company is having the infrastructure for digital systems.

Factors related to external support External support factors in this research encompass all external influences on the organization's transition to digital transformation. The pressing need for customer satisfaction significantly shapes the ongoing transformative shift occurring worldwide, and it must be thoughtfully integrated into the production system's design (Choi et al., 2017). Various factors from outside the organization, including competition, competitors, globalization, suppliers, and regulatory frameworks, wield substantial influence on the DT journey (Ruiz et al., 2017). Suppliers, for instance, impact the supply and delivery of raw materials, equipment, and

machinery to the organization. The accuracy and timeliness of their deliveries play a critical role in the success of this transition (Bevilacqua et al., 2017). The competitive nature of the manufacturing industry and the relentless pursuit of customer satisfaction, driven by the constant threat from competitors, have compelled many organizations to embrace DT as a necessity (Yıldırım & Demirbağ, 2020). External factors, such as rules and regulations governing organizations, can serve as motivators for DT (Mittal et al., 2019). Enabling technologies also play a crucial role in efficiently distributing products from the organization to customers, ensuring that goods reach their destination on time, at the correct price, and in optimal condition (Manavalan & Jayakrishna, 2019).

Factors related to data security Within this research, the concept of Data Security encompasses all aspects related to safeguarding the integrity of data acquired, stored, analyzed, and transmitted within the system. The system's design must effectively repel any unauthorized access to the organization's data, ensuring that data remains inaccessible to intruders. The advent of DT has ushered in the management of vast, intricate datasets, necessitating comprehensive protection. Safeguarding the integrity and security of data and information within the organization stands as a critical imperative for ensuring organizational continuity. The management is tasked with formulating strategies that guarantee the utmost security for the organization's information and all the captured data (Merhar et al., 2019; Ruiz et al., 2017). Ensuring robust data security is considered a hallmark of sound operational practice. The organization's data holds paramount importance and, therefore, must be vigilantly protected. Data security extends beyond secure data transmission to encompass secure computation in the cloud (Santos & Martinho, 2020).

Factors related to design of production system (DPS) Design of the Production System (DPS) pertains to how the production system is structured during the organization's transition from conventional to digitalized production methods. It encompasses elements such as planning, resource allocation, processes, and productivity levels. Data plays a vital role at workstations, ensuring the proper monitoring and accurate operation of the entire system. The ultimate aim of the design is to create an optimized system, making production planning a crucial aspect that demands a substantial time investment (Bevilacqua et al., 2017). The potential for productivity improvement is significant during this transition. For example, the implementation of lean production principles within DPS can significantly reduce waste. The combination of lean principles with enabling technologies leads to the creation of an optimal system (Yıldırım & Demirbağ, 2020).

With digital transformation, the production system becomes highly traceable, enabling efficient monitoring and enhancing product quality. The ability to trace the entire system is a critical step that should be meticulously integrated into the designed production system (Temel & Ayaz, 2019). The design of the DPS should also consider aspects like material movement methods within the system and the physical factory layout (Choi et al., 2017). It ensures that the integration of digital technologies results in processes capable of observing real-time events within the

system (Choi et al., 2017; Schumacher et al., 2019). At the core of DPS are the customers whose needs the organization aims to fulfill. Therefore, designing the system with customer satisfaction as the primary objective is crucial. Subsequently, factors such as processes, productivity levels, and factory efficiency should be addressed. Other essential elements include material flow and methods for product distribution between workstations (Choi et al., 2017).

Factors related to organizational strategies Organizational strategies pertain to the methods employed within a company before transitioning to digital transformation. The company's strategies play a pivotal role in the shift from traditional methods to digitalized processes. DT requires strategies that yield long-term results, making it crucial for the company to develop a digital vision that will shape its strategy (Sjobakk, 2018).

The characteristics of an organization's strategy can significantly impact the transition to DT. The organization must thoroughly assess its existing business strategy to determine if it aligns with the transition, or if it necessitates the creation of an entirely new strategy for the digital journey. In most cases, adapting the DT strategy to complement the existing business strategy is the most effective approach (Sjobakk, 2018). Based on current research, establishing a direct connection between the organization's regular strategy and the strategy employed during DT is challenging. Sjobakk (2018) suggests that since the strategies employed during the transition influence the entire process, it's reasonable to conclude that the strategy developed during this transition is influenced by digital technologies (Sjobakk, 2018).

An appropriate strategy is essential for evaluating and assessing the progress of the transition. Without it, the transition can lead to complications and eventual frustration. A clear vision is crucial in guiding the transition process (Sjobakk, 2018). This vision assists in role allocation, resource management, and goal attainment. Strategies such as benchmarking, roadmapping, and lean methodologies can be employed to facilitate a smooth transition (Yıldırım & Demirbağ, 2020). While it's not uncommon for companies to use ad-hoc methods to achieve desired results, it is in the organization's best interest to systematically design strategies that ensure long-term and sustainable outcomes (Yıldırım & Demirbağ, 2020). Customized strategies tailored to the organization's specific needs are vital in helping it achieve its desired objectives (Yıldırım & Demirbağ, 2020).

Factors related to organizational leadership Organizational leadership, in the context of this research, encompasses the roles played by leaders in achieving a digitally transformed organization. The application of enabling technologies positively impacts the leadership's abilities and the outcomes achieved within the organization (Bevilacqua et al., 2017). It is believed that the management and leadership capabilities within the organization hold the potential for significant rewards. Leaders shape the organization's structure, which, in turn, influences the workforce and the results it attains. Management must create a functional structure that accommodates all parties involved while establishing performance benchmarks against which the organization's success can be measured (Santos & Martinho, 2020). During the transition,

the organization must invest in specific infrastructures to ensure a successful transformation. The responsibility for deciding the infrastructure investments lies with the management, contingent on the budget allocation for infrastructure (Yıldırım & Demirbağ, 2020). Consequently, it's accurate to assert that the organization's size significantly affects infrastructure investment, which, in turn, impacts the DT process. Leadership can also harness available resources for enhanced productivity, aided by enabling technologies (Manavalan & Jayakrishna, 2019).

Factors related to data governance Data Governance encompasses the methodologies and practices aimed at ensuring that data gathered within the system is comprehensively interpreted, securely stored, and safely transmitted when required. The process of data governance initiates at the point of data retrieval from various sources within the system. Subsequently, data is meticulously analyzed for a thorough understanding before it is securely stored (Bevilacqua et al., 2017). Data capture presents a significant challenge in the journey of organizations towards digital transformation. When properly extracted, data becomes a valuable tool that assists leaders in making informed decisions (Choi et al., 2017). Smooth and consistent data flow ensures effective communication and simplifies tracking for system operators (Temel & Ayaz, 2019). Accurate speculation and better outcomes result from collecting the right data, as it provides proper and useful information. It is imperative to make efforts for analyzing data collected and stored in the cloud and integrating it further into the system for a successful transition (Qin et al., 2017). The organization must possess the capability to analyze available data and share it appropriately within the system to those who require it, ensuring a successful transition (Mittal et al., 2019).

Previously, data management was relatively straightforward, involving only a few data aggregates when using conventional methods. However, DT has expanded data collection from multiple sources, leading to increased complexity. This complexity arises as users within the system attempt to analyze and interpret data for accurate comprehension. Data can be sourced from both internal (e.g., production department, administrators) and external (e.g., suppliers, customer demands) sources. Data management plays a pivotal role in the organizational decision-making process, including the establishment of policies and techniques to ensure the system's effectiveness and efficiency (Bevilacqua et al., 2017).

Enabling technologies facilitate data connectivity, collection, and transmission, ultimately enhancing decision-making. Technologies such as "Cloud and Big Data" serve as sources of energy in digital transformation, while "IoT" acts as the mastermind (Manavalan & Jayakrishna, 2019). With effective data management, the system can be closely observed, and actual events within the system can be accurately recorded. This ability enables a better understanding and investigation of occurrences within the system, leading to informed decision-making (Ruiz et al., 2017).

Below is a table displaying the comprehensive list of factors discovered in the literature (see Table 1). These factors were grouped based on their level of similarity and subsequently categorized into eleven critical factors.

Table 1 Identified list of critical factors and sub-factors of DT with sources

Critical factors	Sub-factors	Sources
Organizational culture	• Maintained Communication • Readiness of cultural, strategic, organizational, and technical aspects • Organizational culture • Communication network for a large amount of data traffic • Standardization of Communication • Communication • Preparedness to understand analytics, sensors, etc • Usefulness and sensitivity of industry 4.0 transformation • Innovation • Working environment • Environment • Standards	Choi et al. (2017) Merhar et al. (2019) Mittal et al. (2019) Manavalan and Jayakrishna (2019) Pacchini et al. (2019) Ruiz et al. (2017) Schumacher et al. (2019) Santos and Martinho (2020) Synnes and Welo (2016) Temel and Ayaz (2019) Wagire et al. (2020)
Organizational structure	• Organizational structure • Company size • Planning • Value creation • Flexibility capability • Coordination • Creativity and labor enrichment • Openness and change responsivity • Reconfigurable layouts • Integration of products with other systems • Capacity of agile • Reconfiguration of products	Buer et al. (2020) Ruiz et al. (2017) Santos and Martinho (2020) Synnes and Welo (2016) Yildirim and Demirbağ (2020)
People and Organizational Competence	• Workers • People and culture • People/employees • Workforce qualification • Personnel empowered to organize and collect data • Participation • Social influence • Workers • Employees • Skill acquisition • Innovative education and training • Knowledge/ lack of knowledge • Organizational IT competence • Adequate knowledge • Awareness/Awareness of change • Intelligence/Intelligent control • Consciousness • Knowledge of the problems to be solved • Appropriate knowledge • Innovative education and training • Lack of know-how • Skepticism • Support and knowledge in skills development	Buer et al. (2020) Choi et al. (2017) Merhar et al. (2019) Mittal et al. (2019) Manavalan and Jayakrishna (2019) Nausch et al. (2020) Pacchini et al. (2019) Qin et al. (2017) Ruiz et al. (2017) Schumacher et al. (2019) Santos and Martinho (2020) Schuh et al. (2017) Schiffer et al. (2019) Wagire et al. (2020)

Table 1 (continued)

Critical factors	Sub-factors	Sources
Characteristics, Selection & Integration of Digital Technologies	• Usability • Simplification • Integration of MES and ERP • Ease of use of technology • General attitude towards Digital Assistance • Flexibility/ absorb new technologies • Flexibility of technology • Technical/Technical capabilities related to products and services • Automation • IT-based production management systems • Intelligent control • Technology should be treated at the strategic level • Simple • Building blocks • Technology design • Differences between the devices • Essential technologies	Bevilacqua et al. (2017) Jung et al. (2021) Merhar et al. (2019) Mittal et al. (2019) Pacchini et al. (2019) Qin et al. (2017) Ruiz et al. (2017) Synnes and Welo (2016) Santos and Martinho (2020) Temel and Ayaz (2019)
Infrastructural investments	• Company size/ company size affecting investment • Capital accumulation • Capital investment • Fear high implementation costs • Infrastructure for digital systems	Buer et al. (2020) Pacchini et al. (2019) Ruiz et al. (2017) Schuh et al. (2017) Schiffer et al. (2019) Yildirim and Demirbağ (2020)
External Support	• Suppliers • Competition /competitors • Globalization • Laws and regulations • Competitiveness • Provision of manufacturing services • Services management • Supplier management • Supplier collaboration • Customer response adoption	Bevilacqua et al. (2017) De Carolis et al. (2017) Mittal et al. (2019) Manavalan and Jayakrishna (2019) Synnes and Welo (2016) Yildirim and Demirbağ (2020)
Data Security	• Protection of data • Work & data safety • Security • Privacy issues • Security of assets and data protection	Bevilacqua et al. (2017) Choi et al. (2017) Merhar et al. (2019) Mittal et al. (2019) Ruiz et al. (2017) Santos and Martinho (2020)

Table 1 (continued)

Critical factors	Sub-factors	Sources
Design of Production System	• Production planning • Production sites • Factories and processes • Lean production & maturity • Productivity level • Customization • Material handling system • Traceability • Productivity • Manufacturing line • Processes • Factory construction part • Smart products/parts/materials	Schumacher et al. (2019) Temel and Ayaz (2019) Yildrim and Demirbag (2020)
Organizational Strategies	• Iterative product and process development • Add content to Strategies • Identification of company's position in the strategic landscape • Models and goals • Strategies • Roadmap • Leanness strategy • Measurements using benchmarks • The right strategy for lean & maturity index • Lean production & maturity • Alignment with business strategy • Digital vision • Processes that facilitate teamwork • Readiness model • Sustainable Development Perspective • Sustainable growth/ right unit cost • Analyzing products • Integration and analysis • Strategic sourcing • Cost management	Mittal et al. (2019) Manavalan and Jayakrishna (2019) Nausch et al. (2020) Qin et al. (2017) Sjobakk (2018) Synnes and Welo (2016) Santos and Martinho (2020) Schumacher et al. (2019) Yildrim and Demirbağ (2020) Wagire et al. (2020)
Organizational Leadership	• Improving management capacity and efficiency • Leadership • Managerial capabilities related to organizational strategy and culture • Management • Management Strategy and Organization Perspective • Good/Adequate management • Uncertainty of management and stakeholders • Lack of transparency makes benchmarking difficult • Operational management	Bevilacqua et al. (2017) Choi et al. (2017) Manavalan and Jayakrishna (2019) Ruiz et al. (2017) Santos and Martinho (2020) Schumacher et al. (2019) Yildirim and Demirbağ (2020)

Table 1 (continued)

Critical factors	Sub-factors	Sources
Data Governance	Data collection Data sharing systems Data analytics Data/information organized and maintained in secure digital systems Data aggregation Collection and utilization of internal and external data Continuous data flow Level of information Information collection Early and consistent information Flow of information Agile information share across the organization	Bevilacqua et al. (2017) Qin et al. (2017) Mittal et al (2019) Merhar et al. (2019) Nausch et al. (2020) Pacchini et al. (2019) Temel and Ayaz (2019)

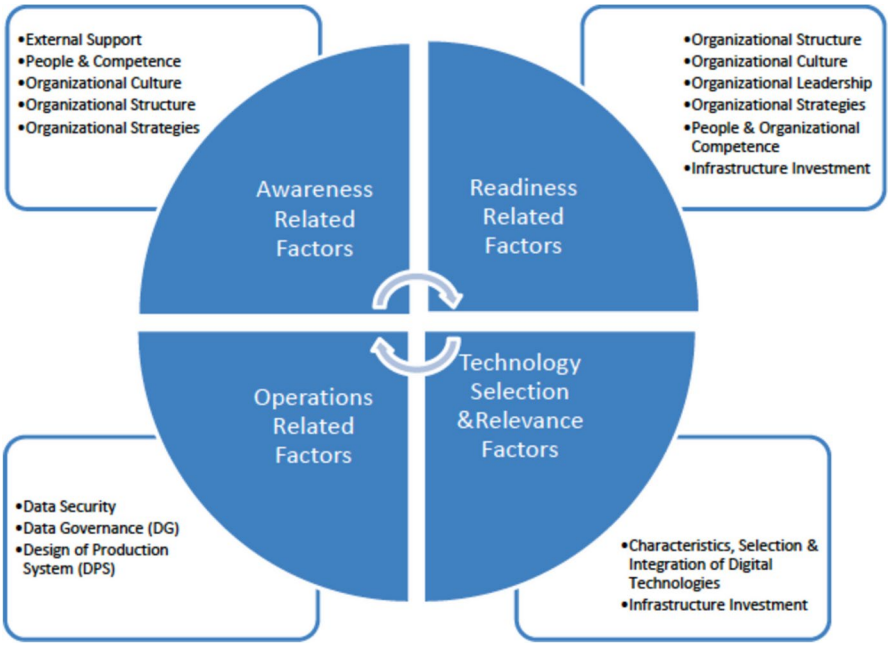

Fig. 5 The developed ARTO model illustrating critical factors across four dimensions

Mapping of 11 critical factors into the ARTO model

Factors affecting digital transformation, as identified in the literature, have been categorized into eleven critical factors. To facilitate understanding and application, these critical factors have been grouped into four dimensions: Awareness, Readiness, Technology Selection and Relevance, and Operations-related factors (ARTO). The ARTO model visually represents the relationships between these critical factors, outlining four stages that practitioners can follow to achieve successful digital transformation. Figure 5 illustrates the ARTO model based on this analysis.

Awareness dimension (A) The Awareness dimension represents the first quadrant, positioned in the left-hand corner of the circle. This dimension is pivotal, as it encompasses the decision-making process regarding the initiation of digital transformation. Several critical factors support this dimension, including external support, organizational culture, organizational structure, organizational strategies, and the availability of people with the necessary competencies, such as top management profiles. These factors collectively influence the decision of management and stakeholders to embark on the journey of digital transformation. External support, which may come from competitors, customers, industry trends, or regulatory pressures, plays a crucial role in signaling the urgency for transformation. For instance, customer demands, intensifying competition, and the pursuit of superior quality by competitors are significant drivers that compel organizations to adopt advanced technologies that promise faster, more efficient results.

Internally, the organization's culture, structure, and strategic orientation are essential in shaping its readiness and approach to digital transformation. A culture that fosters innovation and adaptability, a structure that supports agile decision-making, and strategies aligned with digital goals are all vital in creating an environment conducive to transformation. Moreover, the availability of skilled individuals with the requisite technological competencies, particularly within top management, is crucial in navigating the uncertainties of the awareness stage. These competencies ensure that the organization can make informed decisions and effectively plan the transformation journey. To summarize, the Awareness dimension is foundational in the DT process, as it sets the stage for the entire initiative. The interplay of external pressures and internal readiness determines how effectively an organization can recognize the need for transformation and mobilize the necessary resources and strategies to proceed.

Readiness dimension (R) After establishing awareness of the need for DT and considering the associated factors, the next critical stage is the "Readiness" dimension, situated in the second quadrant of the model. The Readiness dimension pertains to the organization's preparedness to act on its DT goals, supported by six critical factors: organizational structure, organizational culture, organizational leadership, organizational strategies, people and organizational competence, and infrastructure investments. During this phase, the company undertakes a comprehensive self-assessment to evaluate its readiness for DT. This is a pivotal stage where adjustments are made to align the organization's capabilities with the demands of the transformation process (Schumacher et al., 2019). For example, management and leadership may choose to empower employees through targeted training and education programs, equipping them with the necessary skills and knowledge to effectively participate in the transformation (Mittal et al., 2019). Simultaneously, investments in critical infrastructure are made to support the new digital initiatives (Paschou et al., 2018).

In addition to these efforts, the development of a robust transformation strategy is essential. This may involve crafting a clear digital vision if one does not already exist and establishing a digital roadmap to guide the organization through the transformation journey (Synnes & Welo, 2016). Planning and coordination are vital components

at this stage, ensuring that all efforts are aligned and cohesive (Ruiz et al., 2017; Buer et al., 2020). Flexibility is also crucial, as the organization must be prepared to adapt to any necessary changes that arise during the transformation process.

Effective and continuous communication is another key aspect of the Readiness dimension. Transparent and ongoing dialogue among all stakeholders helps to ensure that everyone is aligned with the transformation goals and understands their roles in the process (Mittal et al., 2019; Temel & Ayaz, 2019). Adequate preparation during this phase is vital to prevent the adoption of ad hoc strategies later in the DT journey, which can lead to inefficiencies and missed opportunities (Wagire et al., 2020). Overall, the Readiness dimension is about laying a strong foundation for DT by ensuring that the organization is fully prepared, both in terms of its internal capabilities and its strategic direction. This stage is crucial for setting the stage for a successful transformation that is well-coordinated, strategically aligned, and capable of adapting to evolving challenges.

Technology selection and relevance dimension (T) The third quadrant, located on the right-hand side of the model, is dedicated to the selection of appropriate technologies that align with the company's DT goals. The Technology Selection and Relevance dimension focuses on identifying and integrating suitable technologies, supported by two critical factors: the characteristics, selection, and integration of digital technologies, and infrastructure investments. The choice of technology is crucial for ensuring the effectiveness of the DT process. Selecting the right technology not only enhances operational efficiency but also prevents the wastage of time and resources, which can lead to frustration among stakeholders. The selected technologies should be user-friendly, cost-effective, and time-efficient, ensuring that they are practical and accessible for the organization's needs (Merhar et al., 2019; Temel & Ayaz, 2019).

Once the appropriate technology has been identified, it is integrated into the company's operations to facilitate the digital transformation. This process involves careful consideration of how the technology will interact with existing systems and processes, as well as the necessary infrastructure investments to support its implementation (Merhar et al., 2019). The ultimate goal is to adopt the most suitable technology that not only meets the organization's immediate needs but also positions it for future growth and adaptability in an increasingly digital landscape.

Operations dimension (O) The final quadrant in the model, the Operations dimension, comes into play once the selected technologies have been implemented and are in active use. This dimension focuses on the real-time execution and management of these technologies to achieve the desired goals of DT within the company. It is supported by three critical factors: data security, data governance, and the design of the production system. The integration of various technologies typically results in the generation and acquisition of substantial amounts of data. Proper analysis, secure communication, and uninterrupted storage of this data are crucial to the success of the digital transformation. Ensuring data security is of paramount importance, as breaches or mishandling can have severe consequences for the company. Additionally, effective data governance practices are essential to ensure that information

flows freely and consistently across the organization, enabling smooth and efficient operations (Merhar et al., 2019).

The design of the production system also plays a critical role in the Operations dimension. The use of selected technologies can significantly enhance material handling processes, making them more efficient and allowing for greater product customization (Temel & Ayaz, 2019). Moreover, with advanced technologies in place, the entire production process can be tracked from start to finish, leading to improved productivity and better management of resources (Choi et al., 2017; Merhar et al., 2019). In summary, the Operations dimension is where the practical application of DT efforts is realized. It ensures that the company can leverage the full potential of its technological investments, maintaining data integrity, optimizing production processes, and ultimately achieving the intended outcomes of the DT initiative.

Results from survey

In this section, we present the survey results, with a focus on the critical factors and the validation of the ARTO model.

Overview of participants and companies

The survey received a total of 29 respondents, encompassing a wide range of job profiles within the manufacturing industry. These job profiles reflect the diversity of skills and responsibilities, including strategists, technicians, production planners, research leaders, coordinators, managers, directors, engineers, and seasoned global leaders. In this section, we will examine the respondents' years of experience, company size, and the type of industry their companies belong to.

Years of experience

The years of experience represent the cumulative experience of the respondents in the field, shedding light on their expertise in digital transformation. Out of the 27 respondents, their years of experience were categorized into four main groups. These categories include 1–5 years, which had 17 respondents, 6–10 years with 6 respondents, 11–15 years with 3 respondents, and a single respondent with over 20 years of experience. While the majority of participants have less than 6 years of experience, the inclusion of those in the other categories contributes to a well-rounded and informative set of responses. It's worth noting that respondents with less than 6 years of experience had an average of approximately 3 years.

Company size

A total of 27 respondents participated in the study, representing various company sizes. Categorizing the responses into four groups, which include Small (0–250 employees), Medium (251–500), Large (501–1000), and Enterprise (1001 and

above), will help in drawing more definitive conclusions. The categories for small size had 4 respondents, large had 5 respondents, and enterprise had 18 respondents. This categorization is particularly important because DT is often more prevalent in larger enterprises. Notably, 65% of the participants come from companies with over 1000 employees, offering valuable insights into DT practices.

Type of industry

A total of 28 respondents shared their responses (Fig. 6), representing diverse industries such as construction, energy, mining, pharmaceuticals, telecommunications, automation, and mobility, among others. The automotive industry, the largest represented sector, had a total of 18 respondents, with four other industries closely following with 11% each. This diversity of industries enriches the survey's findings by capturing perspectives from a wide range of sectors.

Critical factors affecting digital transformation

To distinguish the factors influencing DT, participants were asked to rank the critical factors on a scale from 1 to 7, where 1 = Non-significant, 2 = Less significant, 3 = Somewhat significant, 4 = Neither significant nor less significant, 5 = Somewhat significant, 6 = Significant, 7 = Highly significant. Data security received the highest percentage of highly significant rankings at 37.5%, followed by data governance at 33%, and then organizational leadership at 29% (see Fig. 7). Organizational culture received a 42% rating for significant. Three factors, including people and organizational competence, organizational structure, and characteristics, selection, and integration of digital technologies, each received a 37.5% rating for significant.

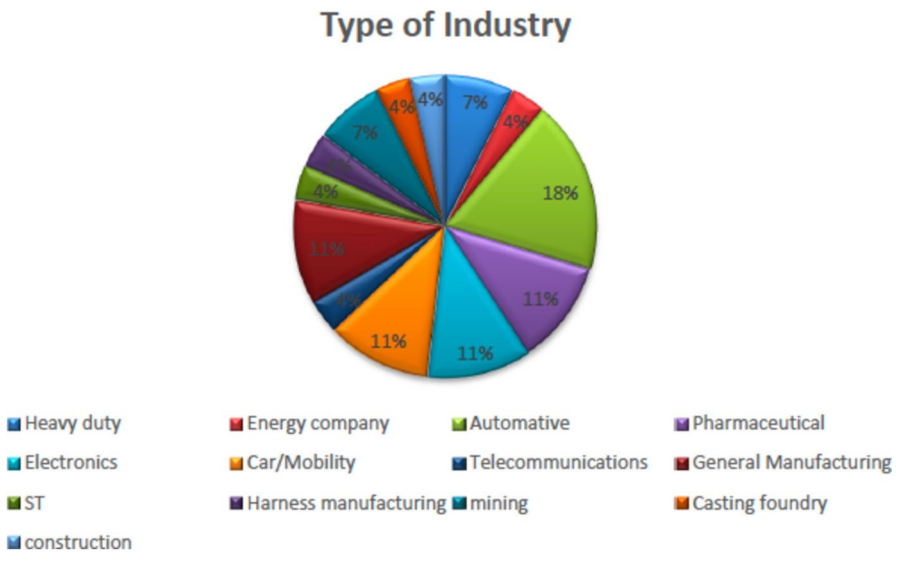

Fig. 6 Type of industries in which survey respondents work

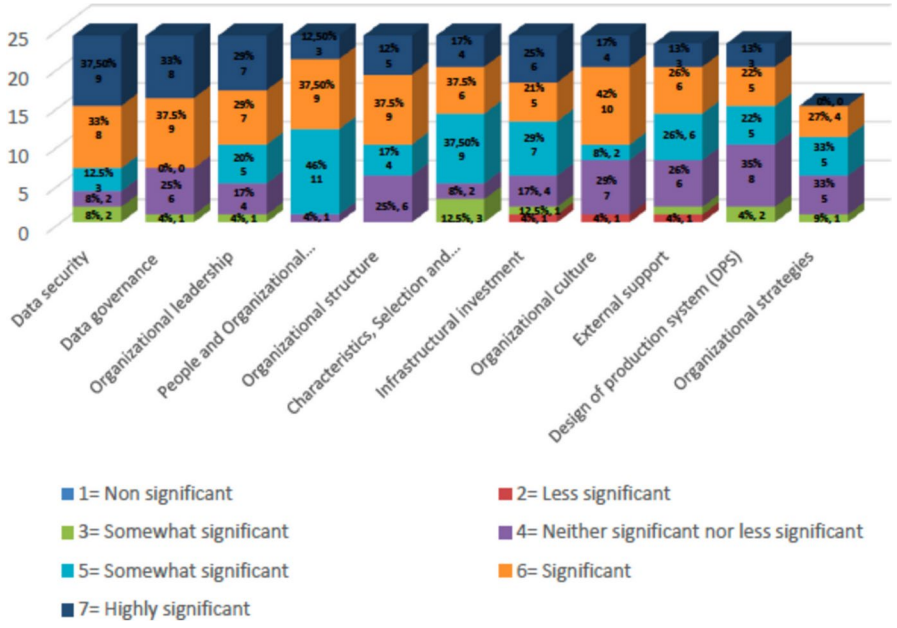

Fig. 7 Respondents view on critical factor affecting digital transformation

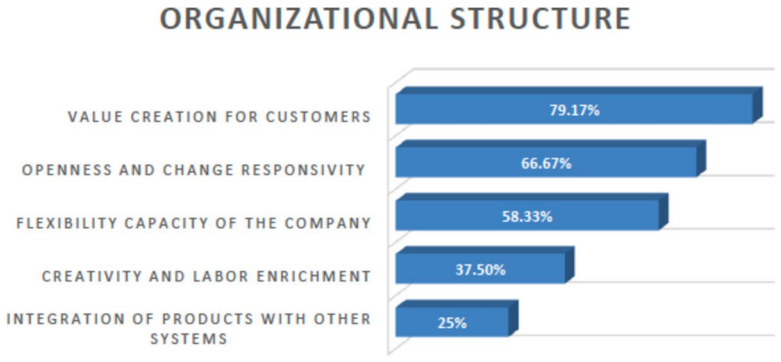

Fig. 8 Respondents ranking on sub-factors of organizational structure

Respondent views on each critical factor details

This section of the survey aimed to identify the sub-factors that align with the main factor based on participants' responses.

Organizational structure According to the responses from the participants (as shown in Fig. 8), creating value for customers is perceived as a highly important aspect of the organization's structure. Additionally, it's crucial for organizations to embrace openness and exhibit a positive response to change while maintaining flexibility dur-

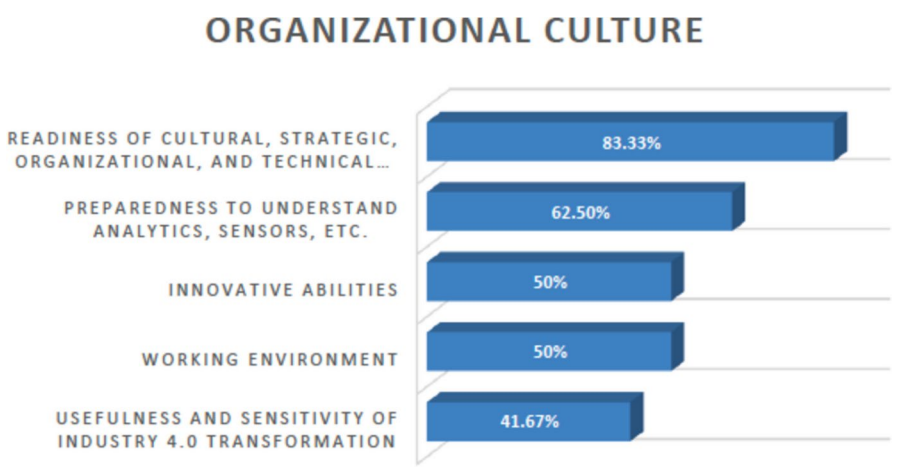

Fig. 9 Respondents ranking on sub-factors of organizational culture

Fig. 10 Respondents ranking on sub-factors of People and Organizational Competence

ing the transition to DT. However, sub-factors such as integration of products and creativity received lower percentage scores.

Organizational culture Organizational culture is significantly influenced by its readiness level (as depicted in Fig. 9). Readiness must be pervasive in all aspects of the organization, involving both management and the workforce. This readiness encompasses the organization's strategies, including the adoption of digital technologies for analytics. The organization's level of preparedness and readiness, in turn, affects the working environment and fosters innovative capabilities.

People and organizational competence The sub-factors identified from the literature (as shown in Fig. 10) largely align with the perspectives of the participants. The participants prioritize the creation of awareness among the workforce over factors like educational qualifications and others. This emphasis on awareness is likely because

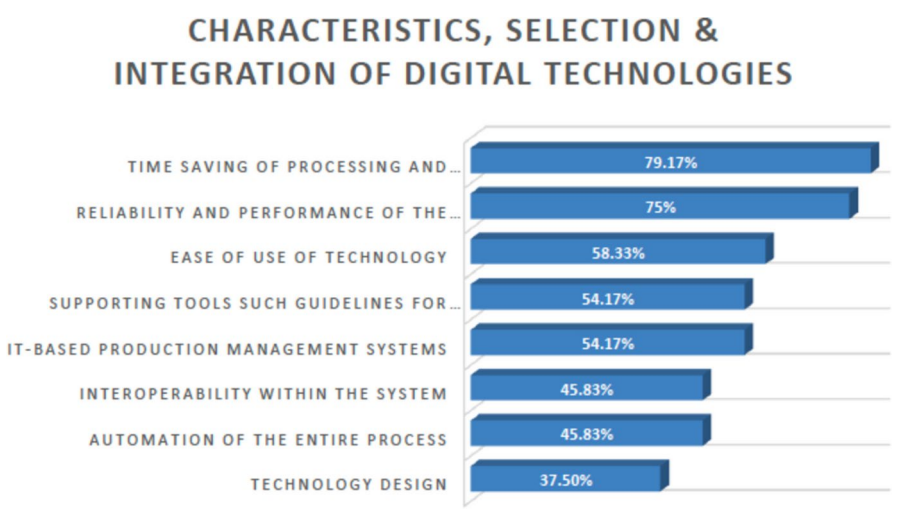

Fig. 11 Respondents ranking on sub-factors of selection and integration of digital technologies

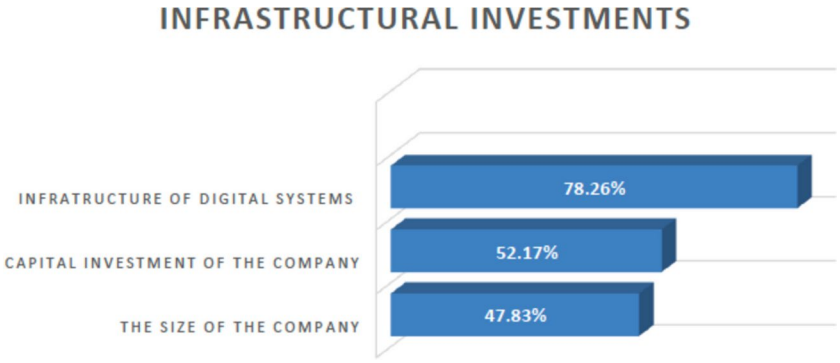

Fig. 12 Respondents ranking on sub-factors of infrastructural investments

it plays a crucial role in preparing individuals for expected changes, making it easier for them to acquire the necessary skills to achieve their goals.

Characteristics, selection, and integration of digital technologies When it comes to the selection and integration of digital technologies, saving time is the foremost sub-factor (as indicated in Fig. 11). Subsequently, the reliability of the technology is another critical consideration. This is in line with the understanding that one of the primary advantages of DT is the reduction of time and improvement in quality (Temel & Ayaz, 2019). Based on these responses, we can infer that the design of the technology is not a top priority in this context.

Infrastructural investments As depicted in Fig. 12, the size of the company appears to be less significant when it comes to infrastructural investment. This finding contrasts with the commonly held belief that the size of the company plays a major role

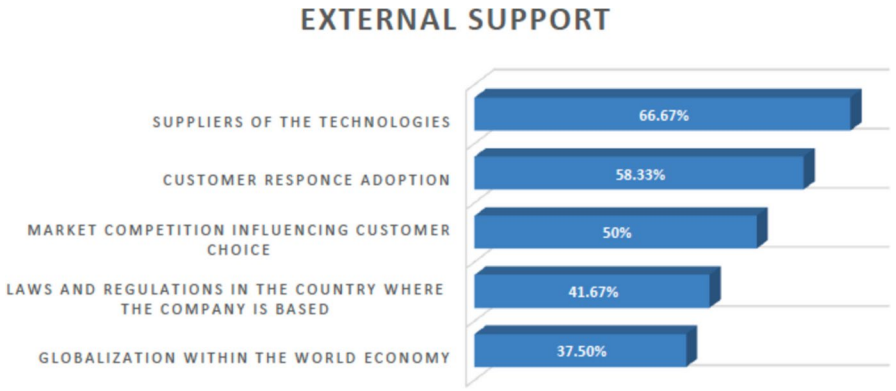

Fig. 13 Respondents ranking on sub-factors of external support

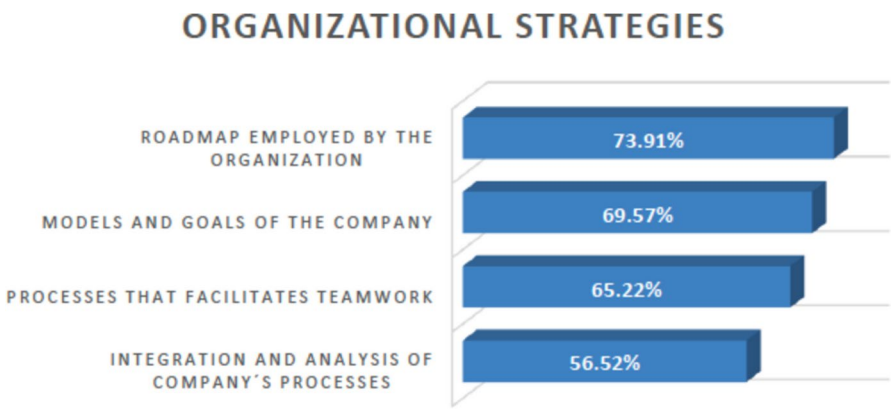

Fig. 14 Respondents ranking on sub-factors of organizational strategies

in its DT journey (Manavalan & Jayakrishna, 2019). It's important to emphasize that investing in digital system infrastructures remains a critical necessity regardless of a company's size.

External support According to the participants, suppliers are perceived as the most significant sub-factor (as shown in Fig. 13) in the context of external support. Furthermore, it's crucial for organizations to adopt methods that facilitate quick responses to customer requests, given that market competition continually influences customer choices. In contrast, globalization is considered less significant as a sub-factor under external support.

Organizational strategies The participants highly value the roadmap employed by the organization, as depicted in Fig. 14. An effective and well-planned roadmap is of utmost importance. Models and goals of the company are also ranked highly. It is clear that the organization's strategies must encourage teamwork while ensuring that the goals are seamlessly integrated into the company's processes.

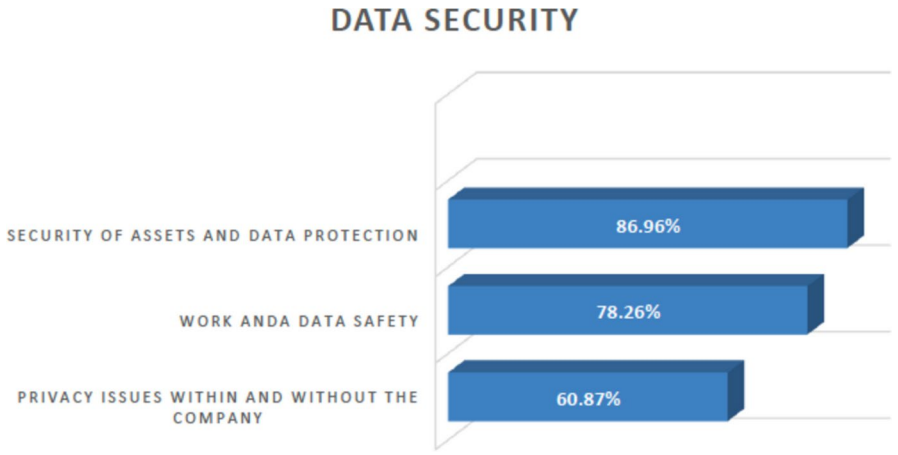

Fig. 15 Respondents ranking on sub-factors of data security

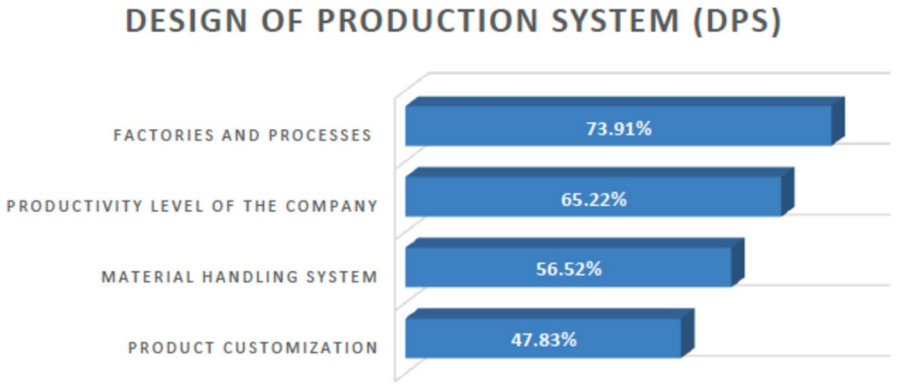

Fig. 16 Respondents ranking on sub-factors of design of production system

Data security The security of assets and data protection, along with work and data safety, ranks very high, with a percentage range of 78.26% to 86.96% (see Fig. 15). Privacy issues within and outside the company also receive relatively high importance, scoring 60.87%. These results emphasize the critical importance of safeguarding assets and data, ensuring that all acquired data are securely protected.

Design of production system In the Design of Production System field, factories and processes are deemed to be the most significant factors (see Fig. 16). The productivity level of the company closely follows as another crucial aspect, as it directly influences the design of the company's production system. These findings align with the idea that efficient factories and processes are essential for enhancing productivity.

Organizational leadership As per the survey participants, managerial capabilities related to organizational strategy and culture (as shown in Fig. 17) play the most sig-

Fig. 17 Respondents ranking on sub-factors of organizational leadership

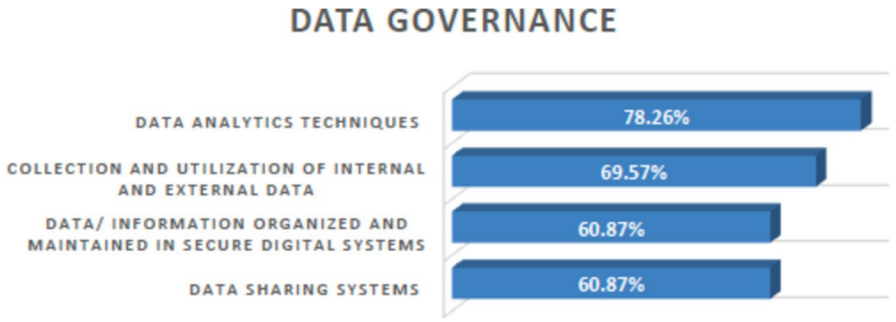

Fig. 18 Respondents ranking on sub-factors of data governance

nificant role, with a high percentage of 86.96%. This highlights that the effectiveness of the management has a substantial impact on the DT process. In contrast, the uncertainty of management and stakeholders is considered insignificant in relation to this key factor. It's crucial to focus on improving management capacity and efficiency, as leadership capabilities can be enhanced to drive successful digital transformation.

Data governance Data analytics techniques are ranked at the top and are considered highly significant by the participants (see Fig. 18). After data collection, effective analysis is crucial for a comprehensive understanding of the information. It's important to emphasize that data analysis is incomplete without the safe and proper transmission of data to the end users.

Additional insights from the survey

Survey participants were given the opportunity to provide additional insights that could impact each key factor. Here's a summary of their feedback:

- Organizational Structure: Participants emphasized the importance of adopting a holistic perspective that considers how digitalization affects various processes such as production and sales support. They recommended placing this perspective under the'organizational structure' factor, as it is often overlooked during risk assessment. Additionally, participants highlighted the need for coordination

between different sites and maintaining a balance among organizational resources. Continuous evaluation by management and the team is seen as essential for a successful transition.

- Organizational Culture: Participants stressed the significance of organizational culture and suggested that management should lead by example. Involving people at all levels in decision-making processes was considered vital for both short-term and long-term success in digitalization. Openness and transparency in analytics and reporting shortcomings were also recommended.
- People and Organizational Competence: Participants pointed out that competence goes beyond knowledge and skills and includes values and attitudes towards change from management. They highlighted the importance of developing competence at all levels and fostering a change-driven mindset.
- Characteristics, Selection, and Integration of Digital Technologies: Participants recommended that each responsible unit should connect to a larger store using digital technologies rather than treating digitalization as a peripheral aspect. They emphasized the need to evaluate value-added and ease of use for all stakeholders. Human-machine interaction during emergencies should be carefully considered. Infrastructural investment should account for the rapid changes in hardware and software, maintenance issues, and licenses. Interoperability between old and modern technologies and applications is crucial.
- External Support: Participants believed that customers are the most critical external support factor, whereas suppliers and competitors are less influential, especially since their offerings are already visible. They suggested renaming this key factor to'external communication'. Participants also provided a ranking for companies at various digitalization stages: Customers (7), Suppliers (6), and Competitors (4). They emphasized the need to consider the company's exact digitalization level, geographical location, and whether it operates in a developing or industrialized country. Purchasing guidelines for engaging the right partners is essential to avoid stress resulting from contracts with less competent partners.
- Organizational Strategies: Participants recommended the development of strategies, allocation of resources, experimentation with scope, and the creation of backup plans to address organizational challenges.
- Data Security: Participants noted that data security is often overlooked and highlighted the potential damage unprofessional partners can cause to a company's brand. They emphasized the importance of logical access control and not solely relying on EU rules. Some participants argued that laws and regulations should be considered before embarking on digitalization. Practicing backup plans through role-plays was recommended.
- Design of Production System: Participants emphasized the significance of how an organization perceives its product or service. They pointed out that traditional and new production methodologies can add complexity and lead to the blame of human factors rather than analyzing human-machine interactions. Consideration of production flow changes and new technologies is crucial.
- Organizational Leadership: Participants suggested analyzing management turnover, as it can significantly impact project continuity. Management accountability was considered crucial to mitigate the negative effects of personnel changes.

- Data Governance: Participants recommended including cybersecurity considerations when outsourcing IT development and support services to external partners.

In addition to specific insights, participants provided general comments as follows. Participants emphasized the importance of aligning digitalization efforts with the company's needs and clearly defining the problems that digitalization aims to solve. They stressed the need to assess whether the budget is realistic and to create a comprehensive project plan. Involving individuals from all functions at the outset was seen as essential. Participants recommended providing adequate training for both managers and team members involved in digitalization implementation. Maintaining a balanced and collaborative team environment was highlighted, with an emphasis on active listening, professional responses to feedback and critical questions, and well-documented risk assessments and risk reduction measures. Effective communication with all stakeholders and flexibility in testing new technologies were considered essential. Respect and accountability between individuals at all organizational levels were identified as significant factors contributing to the success of digitalization initiatives.

The proposal of ARTO model for critical factors affecting digital transformation

The ARTO model presented below (see Fig. 19) has been formulated after a meticulous comparison of the findings derived from both the Systematic Literature Review (SLR) and the survey. This model carefully selects factors that demonstrated appropriateness and consensus in both the SLR and survey data. Additionally, factors that garnered substantial agreement, falling within the range of 65% to 100% consensus from the survey, were incorporated. Notably, this includes key aspects such as "organizational leadership" and "organizational culture," particularly within the realm of operations-related factors.

It's important to consider the stage of digitalization that a company finds itself in when applying these factors. The relevance of certain factors, notably those categorized under readiness in the ARTO model, may vary depending on whether a company has initiated its digitalization journey or is still at a distance from this phase. Geographical location also plays a pivotal role, with developed countries being significantly advanced in digitalization compared to developing countries, which are often grappling with the process.

Survey participants have emphatically affirmed the critical significance of "organizational culture" in the successful implementation of digital transformation. This factor extends its influence across three of the four categories in the ARTO model, underscoring its central role in the transformation process. Notably, participants' comments regarding "organizational culture" highlight the paramount importance of involving every member of the organization in the DT endeavor. Early-stage knowledge acquisition and learning about DT processes are considered essential prerequisites for success.

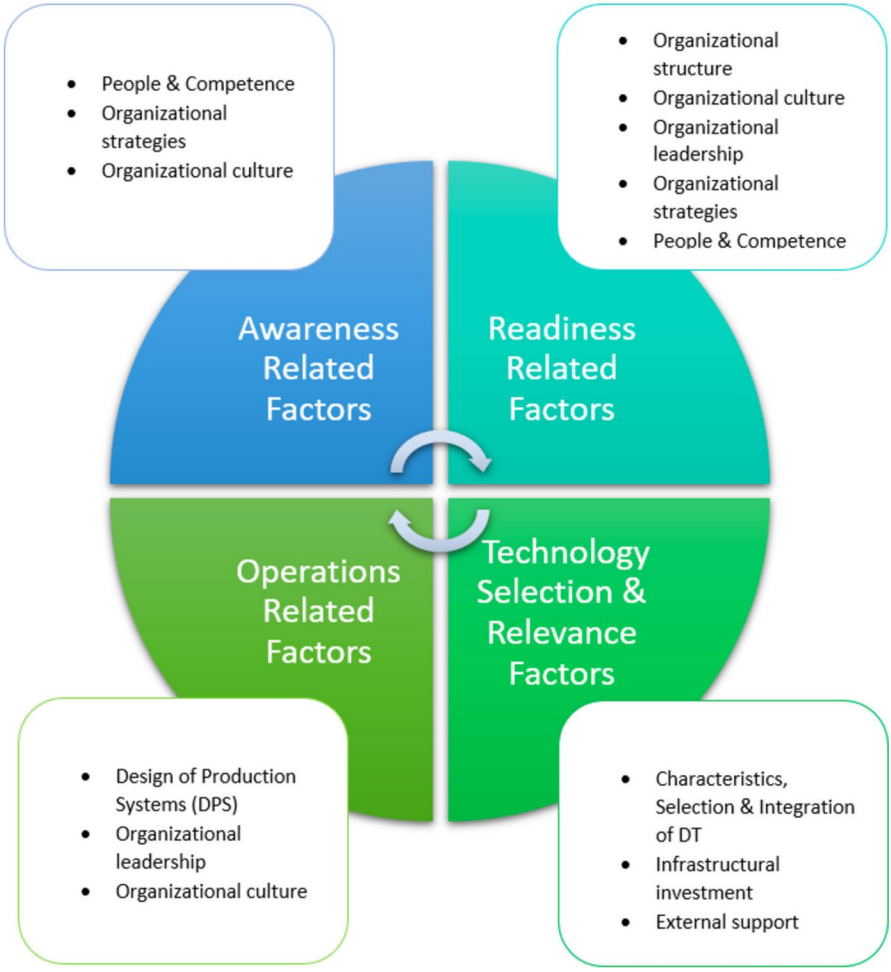

Fig. 19 The proposed ARTO- model for critical factors affecting digital transformation in manufacturing companies

In conclusion, the proposed ARTO model serves as a comprehensive framework that reflects the collective wisdom derived from the SLR and survey results, offering valuable insights into the multifaceted landscape of digital transformation.

Based on our analysis and the insights derived from the ARTO model, we propose the following definition of digital transformation (DT) in manufacturing companies.

Digital Transformation (DT) in manufacturing companies is a structured, multi-dimensional process that integrates advanced digital technologies into organizational operations, strategies, and culture. It encompasses four critical dimensions—Awareness, Readiness, Technology, and Operations (ARTO)—to enable the creation of value for customers, improve organizational adaptability, and optimize production systems.

From a process perspective, DT in manufacturing involves:

- Awareness: Building knowledge and fostering a culture of innovation throughout the organization, ensuring all stakeholders understand the purpose, challenges, and benefits of the transformation.
- Readiness: Establishing the necessary infrastructure, leadership capabilities, and strategic roadmaps while aligning organizational structure and culture to support digital initiatives.
- Technology: Systematically adopting, integrating, and optimizing digital technologies to enhance production processes, improve collaboration, and maintain robust data security and governance.
- Operations: Continuously evolving operational systems to utilize real-time data, optimize factory designs, and achieve long-term productivity and sustainability goals.

This process-driven approach emphasizes holistic and inclusive engagement across all organizational levels, promoting interdepartmental collaboration, customer-centric strategies, and resilience in navigating the complexities of the digital era. The ARTO model serves as a guiding framework, reflecting the interplay between technological, organizational, and human factors critical for a successful digital transformation journey.

Discussion

Theoretical implications

This research provides significant contributions to the body of knowledge on digital transformation (DT) in the manufacturing sector by addressing critical gaps in literature. The key added values of this study are as follows:

Firstly, existing research often generalizes success factors for DT across multiple industries, including manufacturing, service, and SMEs (Deepu & Ravi, 2021; Sahu et al., 2018; Schniederjans et al., 2020; Jones et al., 2021; Mhlungu et al., 2019; Steiber et al., 2021; Gurbaxani & Dunkle, 2019; Cichosz et al., 2020; Sony & Naik, 2020). However, these studies lack a sector-specific focus, particularly for manufacturing companies, which face unique challenges such as technological complexity, resource-intensive operations, and workforce adaptation issues (e.g., Pozzi et al., 2023; Vogelsang et al., 2018). Our research fills this gap by systematically identifying 11 critical factors tailored specifically to manufacturing (answering RQ1), offering insights and practical guidance unique to this industry.

Secondly, prior studies have often emphasized either success factors (Mhlungu et al., 2019; Pozzi et al., 2023; Sony & Naik, 2020; Zhang et al., 2022) or barriers to DT (Ahlskog et al., 2023; Eller et al., 2020; Hess et al., 2016; Jones et al., 2021; Kane, 2019) without exploring their interconnectedness. This research not only identifies success enablers but also investigates factors that, if neglected, can lead to failure. By systematically mapping these factors (answering RQ1), the study provides a bal-

anced and nuanced understanding of the determinants of successful DT, offering a novel perspective that enriches existing theoretical discussions.

Thirdly, unlike existing DT readiness frameworks and maturity models (De Carolis et al., 2017; Santos & Martinho, 2020; Wagire et al., 2020), which are often broad and under-validated for specific industries, this study introduces the ARTO model—a structured framework categorizing critical factors into Awareness-related factors, Readiness-related factors, Technology Selection-related factors, and Operations-related factors (answering RQ2). The ARTO model uniquely integrates insights from literature and expert surveys, providing a cohesive, validated, and practical guide for DT implementation in manufacturing. This focus on contextual relevance and inter-factor relationships advances the theoretical understanding of how specific critical factors interact and contribute to success.

Existing studies often analyze critical factors in a quantitative manner (e.g., Eller et al., 2020; Zhang et al., 2022; Deepu & Ravi, 2021; Mhlungu et al., 2019) or, less frequently, in a qualitative manner (e.g., Pozzi et al., 2023; Vogelsang et al., 2018). However, there is limited focus on examining these factors from a process-oriented perspective. This study uniquely investigates the intricate relationships among factors within the ARTO model (answering RQ1 and RQ1), adopting a system-based process perspective. By doing so, it deepens the theoretical understanding of how different factors interact to shape DT outcomes, offering a robust foundation for future research on holistic DT strategies. Furthermore, this research integrates expert perspectives through a survey, enhancing the practical relevance of the ARTO model. This approach not only validates theoretical insights with real-world data but also bridges the gap between academic research and industrial practice.

Finally, by addressing the specific needs of manufacturing companies, this study contributes to the growing body of literature focused on sector-specific DT strategies. It builds on foundational work (Ghobakhloo & Iranmanesh, 2021; Pozzi et al., 2023; Vogelsang et al., 2018) and advances discourse by introducing a validated, context-driven framework that captures the nuances of DT in the manufacturing sector. Moreover, it proposes a specific definition of DT tailored for manufacturing companies. The ARTO model, grounded in systematic literature review and expert insights, represents a novel contribution to both theory and practice, offering actionable strategies that manufacturing companies can employ to successfully navigate their DT journey. This work not only fills gaps in existing literature but also sets the stage for further research and practical applications in the manufacturing sector.

Managerial implications

Our study identifies 11 critical factors that significantly influence the process of DT within manufacturing companies. These factors, rigorously validated through extensive literature review and comprehensive surveys, provide a holistic foundation for navigating the complexities of transitioning into the digital era.

Manufacturing companies often face ambiguities in selecting DT technologies and defining effective implementation strategies. Professionals engaged in DT initiatives—including managers, engineers, team leaders, developers, and technicians—can utilize these critical factors as a structured starting point. They can map their

business or factory needs, addressing challenges such as unclear technological functionality, cost constraints, and workforce skill gaps.

For industrial practitioners across all management levels—top, middle, and operational—the proposed ARTO model and definition serve as practical tools for systematic DT implementation. Specifically, the model enables:

1. Identifying and prioritizing challenges unique to their organizational context.
2. Map interdependencies between various challenges.
3. Developing actionable strategies by leveraging critical factors categorized within the ARTO framework.

The structured categorization within the ARTO model offers clear, scalable guidance, aligning different management levels and facilitating effective decision-making throughout the DT journey.

A roadmap for practical implementation

The ARTO model meets the growing demand for practical frameworks tailored to the manufacturing sector. By translating critical factors into actionable strategies, it provides a comprehensive roadmap to help companies systematically navigate their DT journey. Outcomes such as increased revenue, cost reductions, enhanced operational efficiency, and alignment with sustainability goals serve as benchmarks for success, ensuring both short-term and long-term competitiveness.

Key aspects of effective DT implementation highlighted by our study include the following:

- Leadership Development: Leaders must develop capabilities to champion DT. Training programs and continuous professional development are essential to equip managers with the skills to inspire and guide teams effectively.
- Organizational Restructuring: A flexible and customer-focused organizational structure is critical for DT success. Adjusting roles, responsibilities, and workflows to align with digital goals can foster an environment of readiness and agility.
- Strategic Roadmapping: Clear strategies, roadmaps, and goals simplify the DT process and provide a unified direction for all stakeholders. These documents ensure alignment across the organization and help maintain focus on long-term objectives.
- Supplier and Technology Selection: Choosing the right suppliers and digital technologies is pivotal. Managers must perform thorough evaluations to ensure selected technologies align with organizational needs and transformation objectives.
- Workforce Engagement and Upskilling: A cooperative and adaptable workforce is indispensable for DT success. Management must actively foster a positive attitude towards change, provide reskilling opportunities, and engage employees at all levels to secure their buy-in.
- Interdepartmental Collaboration: Breaking down silos and fostering collaboration

across departments is essential. Management should encourage cross-functional teamwork to ensure a seamless and unified transformation process.
- Data Governance and Cybersecurity: Effective data management and strong cybersecurity measures are critical in DT initiatives. Organizations must ensure secure collection, storage, transmission, and analysis of data to protect their digital assets and unlock the full potential of integrated technologies.

Holistic DT integration Leadership plays a central role in driving DT. Leaders must not only possess the vision but also foster a culture that encourages readiness, innovation, and adaptability. A strong leadership focus ensures alignment across all levels of the organization, creating synergy between technological advancements and human capital. As digital technologies are integrated, their infrastructure requirements will shape production systems, necessitating significant investments. Additionally, the vast amounts of data generated must be effectively analyzed and interpreted to derive actionable insights. Robust governance frameworks for data security are essential to safeguard confidentiality and integrity, ensuring uninterrupted benefits throughout the DT process.

Incorporating these managerial implications into a comprehensive DT strategy can greatly enhance manufacturing companies' ability to navigate the complexities of digital transformation. By aligning leadership, organizational structures, technology choices, workforce strategies, and data management within the ARTO framework, companies can:

- Overcome ambiguities in their DT journey.
- Address and resolve key challenges systematically.
- Build sustainable competitive advantages in a rapidly evolving, digitalized economy.

This approach fosters innovation, resilience, and long-term adaptability, supporting manufacturing companies as they transition into the future of smart factories.

Conclusions and future work

This study delved into the multifaceted realm of digital transformation (DT) in manufacturing companies, drawing on an extensive systematic literature review and a comprehensive survey. It aimed to identify the factors impacting DT and the intricate relationships among them. While these factors may exhibit variations across different companies, this research provides valuable insights into the dynamic landscape of DT in manufacturing companies. "Organizational culture" emerged as a standout factor, featuring prominently in three of the ARTO model's categories. This underscores its profound influence on the DT process, making it a pivotal aspect. Nonetheless, the question arises: are there factors that manufacturing companies can afford to disregard in their pursuit of DT?

The survey results reaffirmed the centrality of people in digital transformation. They play pivotal roles in "organizational leadership", "people and organizational competence", and are integral to the success of virtually all other crirical factors in implementation. This extends to data collection, analysis, transfer, usage, and safety, which reverberate throughout an organization, affecting leadership, customers, suppliers, and overarching strategies. However, the extent to which these factors vary between large companies and SMEs remains a complex question. The significance of external factors, particularly customers, cannot be overstated.

The culmination of this study is the development of the ARTO model, which encompasses four categories and a total of 11 critical factor groups relevant to DT in manufacturing. The model is intended to guide companies through the implementation process, emphasizing the importance of systematically progressing through its stages. By recognizing the intricate interplay between these factors, it promotes a holistic approach that is essential for a successful DT. The ARTO model presents an intriguing perspective, as it does not prioritize a specific factor but instead seeks to integrate various factors within each category. This highlights the interconnectedness that exists between these factors and the respective categories. However, for companies already embarking on the transition process and seeking guidance, discretion is crucial to avoid redundancy and inefficiencies.

Limitations and future work

This study has certain limitations. The restriction to the Web of Science and Scopus databases in the systematic literature review may have led to the omission of relevant documents do not present in these databases. The exclusive focus on engineering literature may have overlooked insights from articles outside the engineering field. It is essential to recognize these limitations when interpreting the findings. Nevertheless, this study underscores the significance of all identified factors in the progress of manufacturing companies.

Building on these conclusions, future research should explore the influence of company size and specific organizational types in determining the principal factors impacting digital transformation. Understanding which factors exhibit varying degrees of dominance, particularly in small and medium-sized enterprises (SMEs), could offer critical insights. Moreover, as technology continues to evolve rapidly, future studies should delve into how these dynamic factors adapt to accommodate emerging technologies. Understanding the synergies between established factors and the latest technological trends will be vital for organizations seeking to remain at the forefront of digital transformation. In terms of survey research, conducting follow-up studies with larger and more diverse participant groups is recommended. This approach can yield a more comprehensive and precise understanding of the DT landscape, accommodating varied perspectives and insights.

Appendix A - Survey questionnaire

1. Company background

1. Which type of industry does your company belong to e.g., electronics, aerospace, railway, heavy- duty vehicle, steel manufacturing etc.
2. What is your educational qualification?
3. What is your job profile?
4. How many years of experience do you have in this role?
5. What type of products does your company produce?
6. How many employees are there in your company? Is your company an SME or a large manufacturing company?

2. Critical factors for digital transformation

Based on an extensive review, we have found 11 categories of critical factors that are affecting digital transformation in manufacturing companies. These factors are:
Organizational structure, Organizational culture, People and organizational competence, Characteristics, Selection & Integration of digital technologies, Infrastructural Investment, External support, Data security, Design of production system (DPS), Organizational strategies, Organizational leadership, Data governance (DG). The description of each factor is provided below.

Now, we want you to rank the above 11 factors in a preferential order from scale 1-7 from your company's perspective. The scale is represented with stars and each star represents a number, where 1= non-significant, 2 = less significant, 3 = somewhat less significant, 4 = neither significant nor less significant, 5 = somewhat significant, 6 = significant, 7= highly significant.

7. **Organizational Structure:** focuses strongly on task orientation, motivation, employee autonomy, flexibility, and team skills, customer orientation, and collaboration through the value chain. If you want to add any explanation related to this factor, please provide a comment here.
8. **Organizational Culture:** analyzes the behavioral characteristics of employees and management. If you want to add any explanation related to this factor, please provide a comment here.
9. **People and Organizational Competence:** refers to the workforce and their level of competence. If you want to add any explanation related to this factor, please provide a comment here.
10. **Characteristics, Selection and Integration of Digital Technologies:** refers to the methods employed in choosing and integrating digital technologies into the company's digital transformation process. If you want to add any explanation related to this factor, please provide a comment here.
11. **Infrastructural Investments:** refers to the infrastructures that the company must invest in while transiting to digital transformation. If you want to add any explanation related to this factor, please provide a comment here.
12. **External Support:** deals with factors such as customers, suppliers, competitors. If you want to add any explanation related to this factor, please provide a comment here.
13. **Organizational Strategies:** refers to how strategies are employed within the company before transiting to digital transformation. If you want to add any explanation related to this factor, please provide a comment here.
14. **Data Security:** deals with everything that has to do with ensuring the safety of all data obtained, stored, analyzed, and transmitted within the system. If you want to add any explanation related to this factor, please provide a comment here.
15. **Design of Production System (DPS):** refers basically to how the production system is designed as the organization transitions from the conventional to the digitalized production system. If you want to add any explanation related to this factor, please provide a comment here.
16. **Organizational Leadership:** deals basically with the roles played by the leaders in attaining a digitally transformed organization. If you want to add any explanation related to this factor, please provide a comment here.
17. **Data Governance:** refers to the ways of ensuring that data gathered within the system is adequately interpreted, securely stored and safely transmitted when necessary. If you want to add any explanation related to this factor, please provide a comment here.
18. Kindly add any additional factor(s) that are affecting digital transformation in your company which are missing in the theory or in our review.

3. Details of sub-factors for each key factor

From our literature review, we obtained several sub-factors for each key factor. Below we listed them for 11 critical factors. Now, we would like you to choose the sub-factor(s) that are relevant for each key factor from your company's perspective.

19. **Organizational structure:** focuses strongly on task orientation, motivation, employee autonomy, flexibility, and team skills, customer orientation, and collaboration through the value chain.

- ◯ Flexibility capacity of the company
- ◯ Value creation for customers
- ◯ Creativity and labor enrichment
- ◯ Openness and change responsivity
- ◯ Integration of products with other systems

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

20. **Organizational culture:** analyzes the behavioral characteristics of employees and management.

- ◯ Readiness of cultural, strategic, organizational, and technical aspects
- ◯ Preparedness to understand analytics, sensors, etc.
- ◯ Usefulness and sensitivity of Industry 4.0 transformation
- ◯ Working environment
- ◯ Innovative abilities

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

21. **People and Organizational Competence:** refers to the workforce and their level of competence

- ◯ Innovative education and training
- ◯ Workforce qualification
- ◯ Organizational IT competence
- ◯ Adequate knowledge of the workforce
- ◯ Awareness of change within the company
- ◯ Intelligence/Intelligent control employed by the workforce

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

22. **Characteristics, Selection & Integration of Digital Technologies:** refers to the methods employed in choosing and integrating digital technologies into the company's digital transformation process.

- ◯ Reliability and performance of the technology
- ◯ Time saving of processing and production time
- ◯ Supporting technologies such guidelines for sharing knowledge
- ◯ Interoperability within the system

- Automation of the entire process
- IT-based production management systems
- Technology design
- Ease of use of technology

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

23. **Infrastructural Investments:** refers to the infrastructures that the company must invest in while transiting to digital transformation.
    - Capital investment of the company
    - The size of the company
    - Infrastructure of digital systems

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

24. **External Support:** deals with factors such as customers, suppliers, competitors.
    - Suppliers of the technologies
    - Laws and regulations in the country where the company is based
    - Globalization within the world economy
    - Customer response adoption
    - Market competition influencing customer choice

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

25. **Data Security:** deals with everything that has to do with ensuring the safety of all data obtained, stored, analyzed, and transmitted within the system.
    - Privacy issues within and without the company
    - Security of assets and data protection
    - Work & data safety

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

26. **Design of Production System (DPS):** refers basically to how the production system is designed as the organization transitions from the conventional to the digitalized production system.
    - Productivity level of the company
    - Material handling system
    - Product customization
    - Factories and processes

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

27. **Organizational Strategies:** refers with how strategies are employed within the company before transiting to digital transformation

- ◯ Models and goals of the company
- ◯ Processes that facilitate teamwork
- ◯ Integration and analysis of company's processes
- ◯ Roadmap employed by the organization

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

28. **Organizational Leadership:** deals basically with the roles played by the leaders in attaining a digitally transformed organization

- ◯ Managerial capabilities related to organizational strategy and culture
- ◯ Uncertainty of management and stakeholders
- ◯ Improve management capacity and efficiency

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

29. **Data Governance (DG):** refers to the ways of ensuring that data gathered within the system is adequately interpreted, securely stored and safely transmitted when necessary.

- ◯ Collection and utilization of internal and external data
- ◯ Data sharing systems
- ◯ Data/information organized and maintained in secure digital systems
- ◯ Data analytics techniques

(If you have any comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

4. Proposal of a model for factors affecting your company's digital transformation

From our review, we developed a generic model for digital transformation based on the consideration of 11 identified factors.

The generic model will support companies in understanding critical factors that are affecting digital transformation in a structured way, making a proper action plan for the successful digital transformation.

The generic model consists of four phases such as:

- Awareness in the organization for the digital transformation: Awareness represents the first phase, which basically refers to the point where the organization realizes the need for digital transformation.
- Organizational Readiness for the digital transformation: The second phase is organizational readiness, which refers to the phase where the company examines itself to determine how ready they are for the transformation.
- Selection of technologies and their relevance for digital transformation: The third phase is the selection of technologies and their relevance for digital transformation. In this phase, the organization decides the technology that is most suitable for its activities after considering all available alternatives.

- Method of operations (or mode of operations) for digital transformation: The last and final phase is the mode of operations. In this phase, the company examines their modes of operations and the safety of their data.

Based on the above explanation, we would like you to critically examine the 11 identified critical factors and give your honest opinion on their inclusion in the respective phases of the generic model.

In the questions below, kindly select the critical factors that could be included in each phase of the generic model.

30. **Phase 1: The Company's Awareness of the Digital Transformation**

- ◯ Organizational structure
- ◯ Organizational culture
- ◯ People and organizational competence
- ◯ Characteristics, Selection & Integration of digital technologies
- ◯ Infrastructural Investments
- ◯ External Support
- ◯ Data Security
- ◯ Design of Production System (DPS)
- ◯ Organizational Strategies
- ◯ Organizational Leadership
- ◯ Data Governance (DG)

(If you have any other comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

31. **Phase 2: The Company´s Readiness for Digital Transformation**

- ◯ Organizational structure
- ◯ Organizational culture
- ◯ People and Organizational Competence
- ◯ Characteristics, Selection & Integration of Digital Technologies
- ◯ Infrastructural Investment
- ◯ External Support
- ◯ Data Security
- ◯ Design of Production system design (DPS)
- ◯ Organizational Strategies
- ◯ Organizational leadership
- ◯ Data Governance (DG)

(If you have any other comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

32. **Phase 3: The Company's Selection of Technologies and its Relevance for Digital Transformation**

- ○ Organizational Structure
- ○ Organizational Culture
- ○ People & organizational competence
- ○ Characteristics, Selection & Integration of Digital Technology
- ○ Infrastructural Investment
- ○ External Support
- ○ Data security
- ○ Design of Production system (DPS)
- ○ Organizational Strategies
- ○ Organizational Leadership
- ○ Data Governance (DG)

(If you have any other comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

33. **Phase 4: The Company´s Method of Operations after Digital Transformation**

- ○ Organizational Structure
- ○ Organizational Culture
- ○ People and Organizational Competence
- ○ Characteristics, Selection & Integration of Digital Technologies
- ○ Infrastructural Investments
- ○ External Support
- ○ Data Security
- ○ Design Production System Design (DPS)
- ○ Organizational Strategies
- ○ Organizational Leadership
- ○ Data Governance (DG)

(If you have any other comments or if you see/experience any sub-factor that is missing or can be included in the above list, please specify it.)

34. What do you think about this generic model as a reference to communicating the critical factors affecting digital transformation in manufacturing companies?
35. If you have any general comments on the survey, its structure and content, please comment below.

Thank you so much for your time.

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Declarations

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