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Rethinking process management for the I4.0 era: a theoretical framework for technological and organisational integration

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Abstract

Purpose – This article examines how five process-management paradigms - Reengineering, Total Quality Management (TQM), Lean Manufacturing (LM), Six Sigma (SS) and Lean Six Sigma (LSS) - interact with and enable Industry 4.0 (I4.0), reconceptualising process management (PM) as a strategic lever by mapping technological and organisational variables for its adoption.

Design/methodology/approach – Following PRISMA guidelines for a systematic literature review (SLR), we used Scopus and Web of Science (WoS) and conducted backward snowballing, analysing 120 peer-reviewed journal articles published between 2015 and 2025.

Findings – The results reveal an I4.0 implementation gap due to limited integration between process-management paradigms and socio-technical variables. We identify and systematise these variables in a structured multidimensional input-process-output (IPO) framework.

Research limitations/implications – The inclusion-exclusion criteria excluded grey literature and non-English publications, and framework applicability may differ by sector and firm size, requiring further empirical validation. The IPO framework clarifies the components and interactions between social and technical variables, and provides a roadmap for managing the socio-technical complexity of I4.0 toward holistic integration.

Originality/value – This review integrates PM paradigms within a unified socio-technical IPO framework, which goes beyond existing classifications by revealing paradigm-specific contributions, misalignments and complementarities across organisational and technological dimensions of I4.0 adoption.

Keywords Process management, Industry 4.0, Digital transformation, Socio-technical system, Theoretical framework

Paper type Literature review

Quick value overview

Interesting because - This article examines how PM paradigms (reengineering, TQM, LM, SS, and LSS) enable I4.0 by reframing PM as a socio-technical enabler and going beyond prior research's siloed approaches that analyse paradigms in a fragmented way. It systematically maps socio-technical variables into an IPO framework, highlighting paradigm-specific contributions, misalignments, and complementarities in I4.0 adoption.

Theoretical value - The findings indicate that successful I4.0 implementation depends on the alignment of organisational and technological variables. For instance, top management commitment and digital capabilities enable iterative experimentation and gradual scaling, whereas knowledge and resource gaps increase implementation risks. At the process level, interoperability, data quality, and cybersecurity condition the implementation of digital technologies into efficiency, effectiveness, and resilience outcomes. Moreover, PM paradigms exert stage-dependent effects: TQM and LM support early adoption phases, while LSS

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provides more comprehensive governance in advanced stages, addressing complexity and data integration.

Practical value - Managers should follow a roadmap which prioritises process stabilisation before deploying advanced technology. They should redesign processes, align leadership and culture, and develop digital skills before introducing digital solutions. Interoperable technologies should be tested through small-scale pilot projects and scaled progressively as organisational capabilities mature. Strategically combining process paradigms - for example, reengineering for end-to-end redesign, TQM and LM for incremental improvement, and LSS for data-driven optimisation - helps reduce I4.0 failure risks and strengthen resilient, efficient operations.

1. Introduction

I4.0 represents a fundamental transformation of industry, with significant implications for society and businesses (Tardio *et al*., 2023). Its pervasiveness extends beyond the manufacturing sector into other sectors, where digital technologies are adopted to optimise services and enable cross-sector collaboration.

I4.0 reshapes technological infrastructures and organisational paradigms, fostering a transition from traditional hierarchical structures towards process-oriented forms of organisation, with direct implications for operational efficiency and business performance.

From an operational perspective, I4.0 enhances production and control systems, workflow management, system responsiveness, and resource allocation through real-time information exchange. From a performance perspective, technologies such as IoT, Big Data, Digital Twins, and Artificial Intelligence (AI) enable improvements in productivity, quality, flexibility, customer satisfaction, agility, and data-driven decision-making (Babatunde, 2021; Prashar, 2023). These capabilities are critical in the current economic context, characterised by heightened market volatility, cost pressures, supply chain disruptions, and growing sustainability requirements, which demand resilient, adaptive, and efficient business processes.

Despite I4.0's growing relevance, the existing literature highlights a predominantly siloed and technology-centric approach. Empirical evidence suggests that more than 70% of I4.0 adopters lack the PM capabilities required to fully exploit digital technologies (Antonucci *et al*., 2021; Mohammad Mosadeghrad, 2014), so digital initiatives often fail to translate technological potential into sustained operational and performance improvements. Previous research has frequently overlooked the interaction between social and technical variables, offering fragmented and overly simplistic explanations of how PM can enable effective I4.0 adoption (Ali and Waheed, 2025).

To address this gap, this study reconceptualises PM paradigms - Reengineering, TQM, LM, SS, and LSS - as strategic and integrative enablers of I4.0, extending their theoretical relevance into the digital transformation (DT) domain. Beyond these theoretical limitations, organisations face substantial practical challenges, including limited strategic vision, insufficient leadership commitment, misalignment between business processes and digital technologies, and issues related to interoperability, data quality, and cybersecurity (Psomas and Deliou, 2023). Addressing such complexity requires a systemic and process-oriented approach that supports structured decision-making, continuous improvement, and adaptive transformation (Prashar, 2023).

Accordingly, this study synthesises the fragmented body of knowledge through a SLR and develops a multidimensional IPO framework that aligns PM paradigms with the organisational and technological variables shaping I4.0 adoption. By adopting a transparent and rigorous review protocol, it integrates dispersed empirical and conceptual insights into a coherent socio-technical framework that advances theoretical understanding of the role of PM in I4.0 adoption and offers actionable guidance for practitioners navigating DT under conditions of economic uncertainty. The remainder of the paper is structured as follows: the background section examines the evolution of DT and the role of PM paradigms and presents the research questions; the methodology section details the SLR approach; the findings section discusses theoretical and practical implications; and the conclusion synthesises key insights and outlines directions for future research.

2. Background: I4.0 adoption, PM, and its main paradigms

Today, I4.0 spans several sectors (Briatore *et al*., 2025), focussing on efficiency, agility, and innovation (Meier *et al*., 2023) and fostering smart factories through physical and digital integration (Bahulikar *et al*., 2023; Ganjavi and Fazlollahtabar, 2023). I4.0 technologies enhance supply chain communication and interconnection (Colli *et al*., 2021; Kouatli, 2014), while Cyber-Physical Systems (CPS) optimise production and decision-making (Ghobakhloo and Fathi, 2020), achieving sustainability and resilience (Singh *et al*., 2022).

PM supports I4.0 adoption (Czvetkó *et al*., 2022) as it extends beyond operational improvement by overseeing the business process lifecycle - identification, analysis, implementation, execution, monitoring, and continuous improvement (Baier *et al*., 2022) - prompting horizontal interconnections that synchronise workflows and data exchange within and across organisational boundaries. Enhancing agility and flexibility, it enables rapid responses to market dynamics. Integration with Big Data analytics and IoT infrastructures enhances process visibility and provides actionable insights for proactive, data-driven decision-making (Antonucci *et al*., 2021), fostering inter-organisational collaboration and sustainable competitive advantage.

In this study, PM is conceptualised as a managerial and governance-oriented approach that structures, coordinates, and continuously adapts end-to-end business processes. It therefore differs from operational improvement techniques, which represent specific paradigms operating within the broader PM logic.

Despite its relevance, I4.0 adoption is hindered by cultural, technical, and organisational barriers (Al-Mashari and Zairi, 1999; Mohammad Mosadeghrad, 2014). Some literature highlights that strategy, leadership, and business model readiness represent critical weaknesses (Psomas and Deliou, 2023), also identifying vision deficits and weak connections with I4.0 technologies (Patrucco *et al*., 2020; Fischer *et al*., 2020). These findings reinforce the view that PM is particularly critical for I4.0 adoption because it provides the structural mechanism through which digital technologies are embedded in organisational routines, decision-making processes, and performance management systems. This fragmentation calls for a systematic understanding of the role of PM in I4.0 practices to address these challenges (Amato *et al*., 2021).

Therefore, our first research question (RQ1), aiming to investigate the critical PM variables for I4.0, is: *Which PM variables are most salient for I4.0 adoption?*

Moreover, PM is intertwined with various paradigms (Chountalas and Lagodimos, 2019). Within this broader domain, several paradigms have emerged that operationalise PM principles in different ways (Table 1).

Each paradigm yields different applications by interpreting and incorporating PM principles differently, resulting in paradigm-dependent variables that can significantly differ across I4.0 adoption. A common framework is therefore needed to systematically identify and understand the specific nuances within each paradigm, how they embed PM attributes, and how these can be adopted in the I4.0 context (Chiarini, 2020; Pagliosa *et al*., 2021; Komkowski *et al*., 2023; N Kumar *et al*., 2024). Accordingly, our second research question (RQ2) examines how PM variables are applied across different paradigms to identify specific applications within I4.0: *How are PM variables applied within the different paradigms, and how are they interrelated?* Due to the lack of comprehensive frameworks and implementation roadmaps in the existing literature, we frame variables within an IPO framework by articulating the interrelationships between I4.0 and the specific characteristics of PM paradigms.

Table 1. Process management paradigms

Paradigm	Description	Key components	References
Reengineering	Top-down, radical redesign of processes with intensive Information Technology (IT) use to improve cost, quality, flexibility, and lead time	Change management, leadership, teamwork, IT, efficiency, and employee empowerment	Davenport (1993); Hammer and Champy (1993), Al-Mashari *et al.* (2001); Patrucco *et al.* (2020)
TQM	Bottom-up, evidence-based continuous improvement and waste reduction for zero defects and customer satisfaction	Customer focus, leadership, Kaizen, Statistical Process Control (SPC), ISO 9001, process efficiency, risk/ stakeholder management, empowerment	Deming (1986), Calvo-Mora *et al.* (2014), Margherita and Braccini (2022), Prashar (2023)
LM	Evolution of TQM focused on value, waste elimination and pull production to enhance flexibility and productivity	Plan-Do-Check-Act, 5S, Kaizen, Just in Time , Overall Equipment Effectiveness (OEE), Visual Stream Mapping (VSM), SPC, pull production, Total Productive Maintenance (TPM), Root-Cause Analysis	Womack and Jones (1996), Sanders *et al.* (2016), Tortorella *et al.* (2021), Antony *et al.* (2023)
SS	Data-driven approach to reduce variability and defects	Define, Measure, Analyse, Improve and Control (DMAIC), defect reduction, variance reduction, Suppliers, Input, Process, Output, Customers (SIPOC), Failure Mode and Errors Analysis (FMEA), ANOVA, Design of Experiments, fishbone	Pande *et al.* (2000), Jirasukprasert *et al.* (2014), Chountalas and Lagodimos (2019), Meier *et al.* (2023)
LSS	Integration of LM and SS to reduce waste and variability while aligning strategy and continuous improvement	Value maximisation, strategic alignment, 5S, DMAIC, Kaizen, TPM, VSM, standard ISO/ automotive, and leadership	George (2002), Albliwi *et al.* (2015), Ganjavi and Fazlollahtabar (2023)

Source(s): Authors' own work

Finally, to shed light on future challenges and directions of I4.0 adoption, we explore the following research question (RQ3): *What are the potential avenues for future research in I4.0 studies?*

3. Method section

3.1 Search strategy

We conducted an SLR (Tranfield *et al.*, 2003) to analyse and conceptualise key themes in PM research, along with the limitations and potential of its paradigms in I4.0 adoption.

According to the PRISMA (Moher *et al.*, 2014) and following Dekkers *et al.* (2024), we searched the Scopus and WoS databases, and selected 112 articles (Figure 1). We complemented the search by conducting backward snowballing (Bouwmeester *et al.*, 2022), which, according to SLR best practices (Coulombel and Berkowitz, 2025), helps capture works that may have been excluded due to indexing differences or keyword variability. Thus, we identified 8 additional papers, bringing the total sample to 120. The protocol's

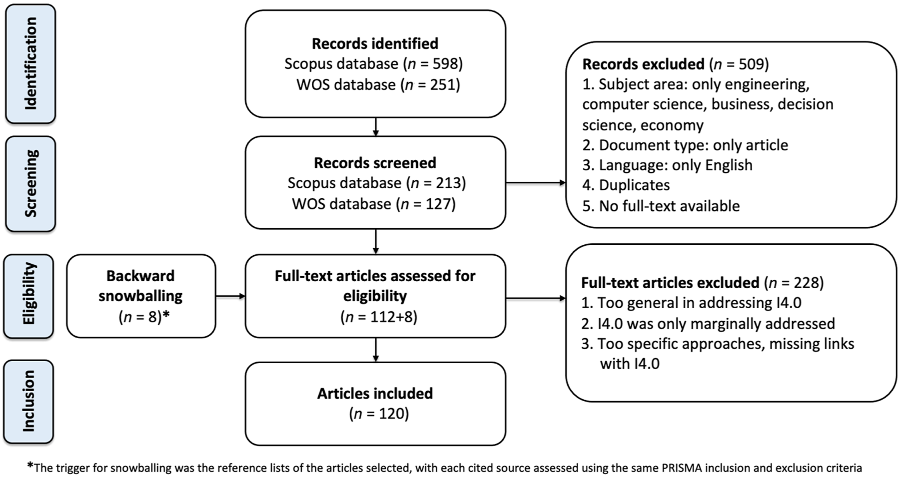


Figure 1. PRISMA Scheme. The full list of articles is available upon request. Source: Authors' own work

preregistration was unnecessary, as our SLR aimed to explore and conceptualise key themes (Rojon *et al.*, 2021).

3.2 Analysis strategy

We conceptualise I4.0 as a socio-technical system (Appelbaum, 1997). Social components include human resources, leadership, teamwork, training, participation, and employees' commitment to quality excellence, while technical variables refer to management tools and technologies aimed at improving production systems, processes, and methods (Babatunde, 2021). These socio-technical elements are integrated through the digitisation, automation, and orchestration of business processes enabled by PM (Dumas *et al.*, 2018).

Using Atlas.ti software, we applied an abductive coding approach based on socio-technical variables (Calvo-Mora *et al.*, 2014, 2015). To ensure methodological rigour, two authors independently coded the studies and iteratively discussed them, resolving disagreements via consensus (Braun and Clarke, 2021), refining categories and incorporating emerging variables such as cybersecurity and data quality.

To further connect the socio-technical perspective with PM, the identified variables were organised according to the IPO model (Section 5). This model supported the classification of socio-technical variables into inputs (e.g. organisational culture), processes (e.g. digital technologies and automation), and outputs (e.g. productivity) (Fischer *et al.*, 2020; Bahulikar *et al.*, 2023; Tripathi *et al.*, 2021b). Finally, gaps in the literature were identified to outline future research directions (Table 5).

4. Findings

4.1 Descriptive analysis

A sample of 120 relevant studies was examined from 2015 onwards. Regarding production and total citations per paper, we observe exponential growth in topic interest after five years, indicating increasing relevance (Figure 2). The temporal trend from 2015 to 2025 shows limited interest initially (2015–2019), but starting from 2020, a marked and rapid increase in scientific output follows an exponential growth pattern, with publication peaks around 2022–2023 and subsequent slight decline.

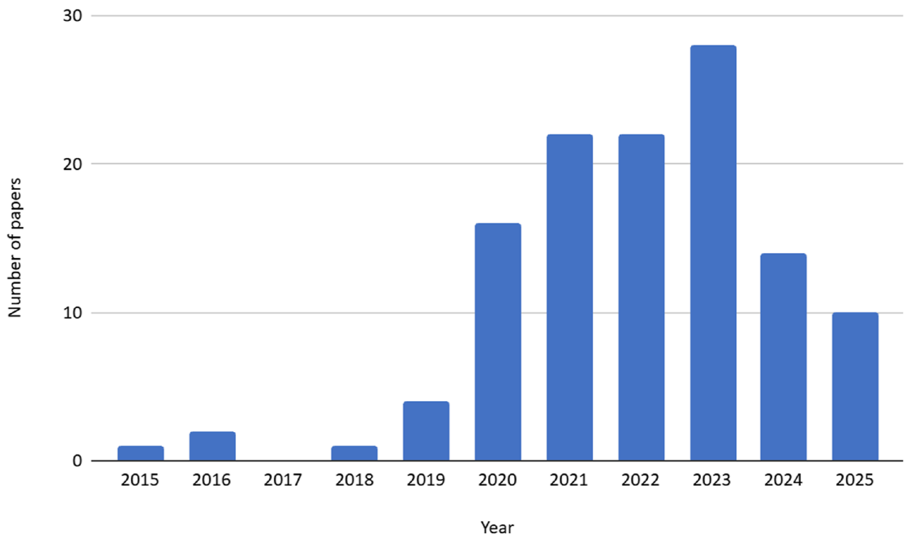


Figure 2. I4.0 and process management topic growth related to n° of articles. Source: Authors' own work

While the descriptive analysis highlights the growth of PM–I4.0 research, the review also shows that a limited number of influential studies have been pivotal in shaping the field. In particular, Antonucci *et al*. (2021), Van Looy (2021), Patrucco *et al*. (2020), and Chiarini (2020) provide the main conceptual foundations for interpreting PM as an enabler of I4.0 across paradigms. These studies are therefore used as key reference points throughout the findings to interpret broader patterns emerging from the literature.

Moreover, we classified studies into four typologies (Figure 3): conceptual papers (36%), surveys (27%), case studies (21%), and literature reviews (16%). Conceptual papers highlight

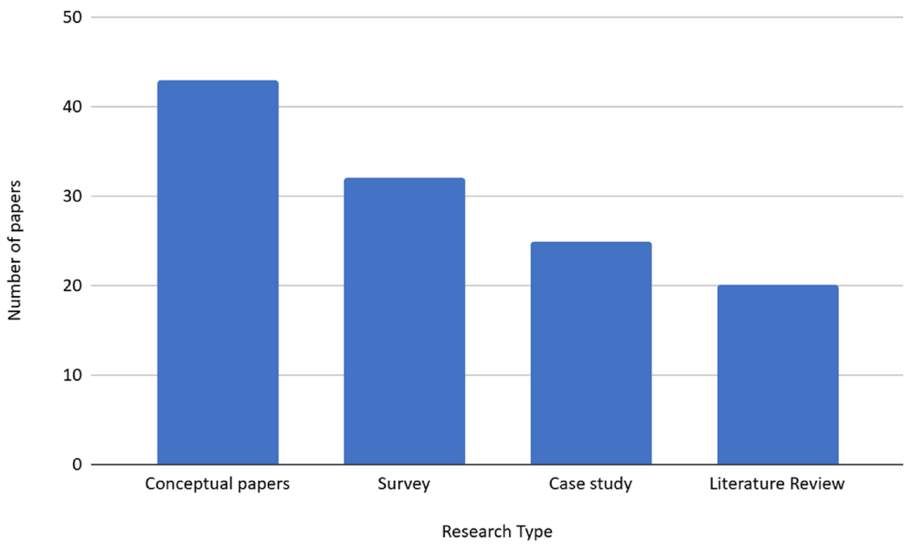


Figure 3. Articles' classification according to the research type. Source: Authors' own work

the lack of standardised frameworks for digital initiatives in manufacturing and I4.0 implementation (Richard *et al.*, 2021; Antonucci *et al.*, 2021; Tripathi *et al.*, 2021a), while surveys examine how I4.0 supports PM and its impact on SMEs' profitability (Amato *et al.*, 2021; Richard *et al.*, 2021). Case studies provide real-world application examples (Sordan *et al.*, 2022; Hosseinzadeh *et al.*, 2023; Shahin *et al.*, 2023a), and literature reviews identify practical integration gaps (Chiarini, 2020; Pagliosa *et al.*, 2021; Pongboonchai-Empl *et al.*, 2023; Kumar *et al.*, 2024).

This distribution of research designs helps explain the field's fragmented nature. Highly cited conceptual studies (e.g. Antonucci *et al.*, 2021; Richard *et al.*, 2021) repeatedly call for stronger theoretical explanations of how PM enables I4.0, while the smaller number of case studies suggests that empirically grounded implementation pathways are still emerging. This imbalance reinforces the need for an integrative synthesis, supporting the relevance of the research questions addressed in this study.

Figure 4 shows the frequency with which PM paradigms are addressed in the literature, highlighting that several articles address multiple paradigms. LM and LSS are the most frequently discussed paradigms, aligning with I4.0's incremental, technology-enabled optimisation. TQM is also addressed, though less frequently. In contrast, reengineering's radical redesigns and SS's statistical focus have received less attention in relation to I4.0's agile and rapid evolution.

We conducted additional screening to identify theoretical perspectives adopted in the sample. The results of the analysis are reported in Table 2, which maps journals, the number of papers, and the main theoretical lenses employed and explicitly declared by authors. The analysis shows that a substantial share of studies does not explicitly ground their analysis in a formal theoretical perspective, instead relying on practice-driven or technology-centric approaches. The theoretical lenses identified include: (1) stakeholder theory (Yadav and Al Owad, 2022), framing LSS implementation as dependent on alignment and engagement of key organisational stakeholders; (2) theories of conservatism, bounded rationality, and path dependence (Dixit *et al.*, 2022), explaining I4.0 adoption as constrained and incremental; (3) contingency theory through the TOE framework (Van Looy, 2021), showing PM's contribution to digital innovation depends on technological, organisational, and

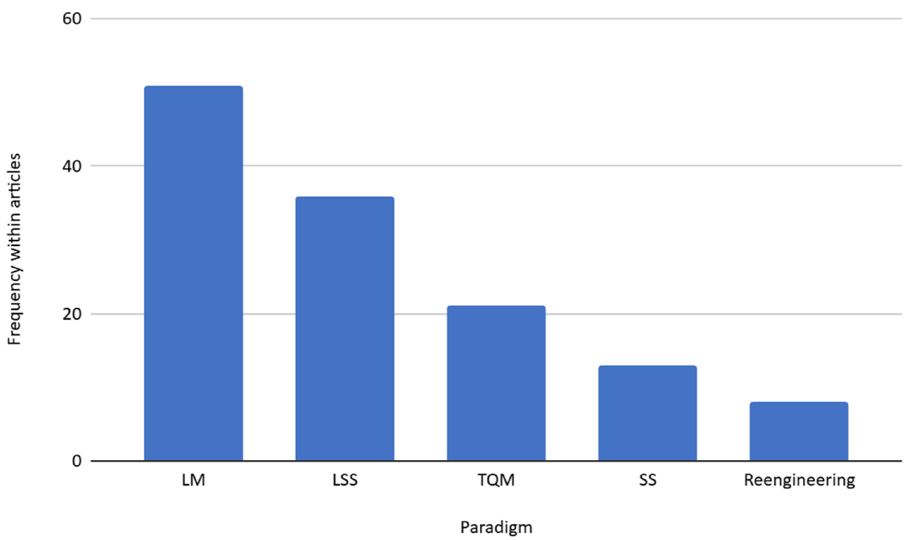


Figure 4. Frequency of the main paradigms. Source: Authors' own work

Table 2. The theoretical lenses employed in the articles analysed

Journal	N° of papers	Theoretical perspective
Journal of Manufacturing Technology Management	3	Socio-technical perspective; Stakeholders' theory; IT-enabled capability perspective
The TQM Journal	2	Socio-technical perspective
IEEE Transactions on Engineering Management	1	Socio-technical perspective
Technological Forecasting and Social Change	1	Theory of conservatism, bounded rationality, and path dependence
Information and Management	1	Contingency Theory
Global Journal of Flexible Systems Management	1	Resource-based view
International Journal of Lean Six Sigma	1	Socio-technical perspective
Others	110	Empirical frameworks
Total	*120*	

Source(s): Authors' own work

environmental conditions; (4) the IT-enabled capability perspective (Ghobakhloo and Fathi, 2020), arguing I4.0 adoption depends on firms' ability to transform technologies into organisational capabilities; (5) the resource-based view (Saha *et al.*, 2022), linking I4.0 outcomes to valuable internal resources; and (6) the socio-technical perspective (Pagliosa *et al.*, 2021; Margherita and Braccini, 2022; Alieva and Powell, 2023; Ali and Waheed, 2025) emphasising that missing alignment of social and technical dimensions leads to resistance, digital waste, and low readiness.

4.2 I 4.0 and the "soft variables"

The following section outlines the main soft variables influencing I4.0 adoption.

4.2.1 Culture. Building on influential contributions that frame PM as a socio-technical capability (e.g. Van Looy, 2021; Antonucci *et al.*, 2021), the literature highlights the pivotal role of organisational culture in enabling effective I4.0 adoption through PM.

Studies on reengineering emphasise the need to understand organisational and cultural shifts for successful I4.0 integration (Patrucco *et al.*, 2020). Implementing TQM within I4.0 contexts may be challenging due to rapid technological changes (Canbay and Akman, 2023). A collaborative culture involving employees in selecting digital technologies is essential (Margherita and Braccini, 2022). LM should support continuous improvement and collaborative culture, benefiting I4.0 adoption (Psomas and Deliou, 2023; Sanders *et al.*, 2016) and promoting effective communication with customers and suppliers (Bahulikar *et al.*, 2023). Integrating SS with I4.0 requires a cultural shift towards the adoption of new technologies, although over 60% of SS initiatives fail (Antony *et al.*, 2019). Finally, continuous improvement and employee engagement facilitate LSS adaptation to I4.0 through Kaizen innovation (Yadav *et al.*, 2021; Ganjavi and Fazlollahtabar, 2023).

4.2.2 Managerial support and leadership. Leadership is crucial for implementing I4.0. Top management must set clear goals and strategies in a 3-5-year roadmap (Agarwal and Ojha, 2023), communicating both value and potential risks (Psarommatis *et al.*, 2022; Alieva and Powell, 2023). Reengineering's strong leadership aligns processes with broader goals (Patrucco *et al.*, 2020) and benefits from starting with less disruptive technologies like IoT and Cloud computing. Leadership in TQM should be enhanced by improving system integration, coordination, and communication (Sader *et al.*, 2019; Margherita and Braccini, 2022). LM strategies require long-term vision and overcoming barriers such as capital constraints and customisation demands (Bahulikar *et al.*, 2023). Managers must support key I4.0 technologies such as IoT and AI (Tripathi *et al.*, 2021b; Shahin *et al.*, 2023b). SS demands strong managerial guidance to align process improvements with operational excellence (Ganjavi and Fazlollahtabar, 2023). LSS ensures leadership commitment to innovation and technology adoption (Yadav *et al.*, 2021), which must ensure effective communication, collaboration, and coordination (Samanta *et al.*, 2024; Wankhede *et al.*, 2025; Zulfiqar *et al.*, 2024).

4.2.3 I4.0 knowledge and skills. I4.0 adoption hinges on robust PM, technical knowledge, and high-quality training in digital tools and methodologies (Agarwal and Ojha, 2023; Ooi *et al.*, 2023). Reengineering projects face challenges in digital maturity assessment, contributing to high I4.0 failure rates (Tariq and Khan, 2021). Despite its connection to TQM, I4.0 adoption often fails due to inadequate knowledge and skilled personnel (Antony *et al.*, 2023; Canbay and Akman, 2023). LM practices require substantial understanding and worker training, crucial for overcoming resistance to DT (Psomas and Deliou, 2023). SS domain success depends on organisational expertise in AI and Big Data Analytics (Chiarini, 2020). LSS provides an effective way to develop knowledge and skills for I4.0 implementation, fostering competencies in advanced technologies and data-driven decision-making (Efimova *et al.*, 2021; Wankhede *et al.*, 2025).

4.2.4 Fear of failure. Fear of failure hinders I4.0 adoption. For example, the 85% failure rate of AI-based I4.0 projects amplifies concerns, discouraging investment due to perceived risks and implementation impacts (Meier *et al.*, 2023). Lack of clear frameworks generates anxiety and risk aversion (Oussous *et al.*, 2018), exacerbated by workforce reskilling risks. Managers question the return on investment (ROI) and potential disruption. In reengineering, radical changes expose companies to high risks, particularly when they lack digital maturity assessments, elevating I4.0 failure rates (Tariq and Khan, 2021). TQM, although intended to support I4.0, struggles with high failure rates from insufficient leadership and a weak customer-centric culture, resulting in limited support for DT (Canbay and Akman, 2023; Antony *et al.*, 2024). Similarly, LM faces resistance due to technological complexity, high adoption costs, and employee reluctance towards innovation (Anosike *et al.*, 2021; Shahin *et al.*, 2023b), while SS initiatives often fail to deliver sustained benefits, increasing perceived risk (Antony *et al.*, 2019). LSS mitigates fear through DMAIC, but I4.0 integration is risky, requiring oversight to prevent failures from change inertia and digital system complexity (Yadav *et al.*, 2021). Overall, fear intensifies across paradigms due to I4.0's socio-technical nature, where technological uncertainty and organisational change are interdependent. Overcoming this requires fostering a risk-tolerant culture supporting learning from failure and gradual experimentation.

4.2.5 Readiness. Readiness involves a company's ability and maturity to effectively implement technology. Low digital maturity faces significant implementation challenges (Baier *et al.*, 2022). Readiness encompasses product and service evolution, strategic alignment, and innovation culture (Črešnar *et al.*, 2020). I4.0 technologies, smart sensors, IoT, Cloud computing, and Digital Twins, facilitate integration and performance enhancement through reengineering (Baier *et al.*, 2022). To maximise I4.0 benefits, TQM must evolve into "Quality 4.0", resulting in improved metrics (Singh *et al.*, 2022). LM requires strategic planning for appropriate technology selection (Tardio *et al.*, 2023), while SS uses advanced statistical tools for Big Data management (Giannetti and Ransing, 2016). LSS enhances readiness (Samanta *et al.*, 2024) through SPC to stabilise and optimise processes (Črešnar *et al.*, 2020; Efimova and Briš, 2022).

4.3 I4.0 and technical variables

The following section outlines the main technical variables influencing I4.0 adoption.

4.3.1 Costs. The COVID-19 pandemic and geopolitical conflicts have strained company resources and impeded I4.0 adoption (Psomas and Deliou, 2023). Many businesses opt for smaller pilot projects that leverage smart sensors, IoT, and Cloud (Patrucco *et al.*, 2020). High costs of innovation, technology acquisition, and reskilling are significant barriers, especially for SMEs (Bahulikar *et al.*, 2023; P. Kumar *et al.*, 2023). Fear of financial failure deters firms from pursuing I4.0 innovations due to substantial investment requirements (Agarwal and Ojha, 2023). While I4.0 enhances performance, following reengineering and TQM can be costly (Sader *et al.*, 2019). The integration into LM, SS, and LSS also involves considerable expenses, which can be balanced by long-term benefits, such as improved process performance and operational excellence (Efimova and Briš, 2022; T. Komkowski *et al.*, 2023). Careful planning and a clear understanding of potential ROI are crucial for justifying investments (Margherita and Braccini, 2022; Tripathi *et al.*, 2021b).

4.3.2 Complexity. The increasing complexity of production environments, driven by the expansion of I4.0, poses significant challenges for organisations. IoT-enabled data analytics are crucial for enhancing decision support systems and improving LM processes (Efimova and Briš, 2022). I4.0-related complexity leads to high reengineering failure rates (Tariq and Khan, 2021; Czvetkó *et al.*, 2022). Effective management of technological and human aspects is essential for TQM in supporting I4.0, addressing socio-technical challenges (Margherita and Braccini, 2022; Canbay and Akman, 2023). LM complexity arises from managing data, technology, and human factors. While I4.0 reduces people-related complexity, LM simplifies processes (Psomas and Deliou, 2023; Yadav *et al.*, 2020). SS complexity involves managing Big Data with advanced statistical tools to minimise variation (Efimova *et al.*, 2021). LSS tools, DMAIC, and Fishbone diagrams are suitable for DT as they streamline and optimise processes (Efimova and Briš, 2022), as complexity reduction is essential (Wankhede *et al.*, 2025).

4.3.3 Integration. Integration merges digital technologies with manufacturing operations to achieve data transparency across the value chain (Ghobakhloo and Fathi, 2020). Aligning business models with I4.0 initiatives is critical for driving innovation and collaboration (Ghobakhloo and Fathi, 2020; Psarommatis *et al.*, 2022). Reengineering focuses on advanced IT integration to enhance cost-efficiency, quality, and flexibility (Patrucco *et al.*, 2020). TQM benefits from real-time Big Data analytics, supports evidence-based decision-making, automates production, and CPS (Lepistö *et al.*, 2022; Canbay and Akman, 2023), improving quality control and customer satisfaction (Margherita and Braccini, 2022). LM principles are advanced by IoT, Big Data, and Cloud, enhancing productivity, sustainability, and resource utilisation (Tripathi *et al.*, 2021b) while SS leverages IoT, AI, and Big Data to build robust data foundations (Chiarini, 2020). LSS combines LM and SS strengths, facilitating smooth digital transitions and human-centric approaches (Psomas and Deliou, 2023). Across paradigms, the literature converges on the view that digital technologies integration represents a process governance challenge rather than a purely technical issue. Influential studies such as Antonucci *et al.* (2021) and Chiarini (2020) emphasise that PM capabilities are essential for translating digital infrastructures and data analytics into measurable improvements in process performance in I4.0 contexts.

4.3.4 Interoperability. Interoperability is essential for I4.0 adoption alongside PM paradigms (Bahulikar *et al.*, 2023), encompassing IoT, Cloud, and CPS. It ensures seamless vertical and horizontal integration of company functions. Lack of interoperability leads to coordination failures and suboptimal adoption (Agarwal and Ojha, 2023). Therefore, regular checks are necessary, even within bottom-up strategies (Bahulikar *et al.*, 2023). In reengineering, interoperability maximises DT benefits (Baier *et al.*, 2022). In TQM, it requires enhancing Big Data analysis, coordination, and collaboration, optimising processes and quality (Sader *et al.*, 2019). In LM, it ensures seamless system operation, enabling efficiency, real-time Big Data flow, process integration, and digitalisation (Sanders *et al.*, 2016). In the SS domain, systems and technologies work together seamlessly to achieve integration benefits (Meier *et al.*, 2023), while LSS improves through communication and employee involvement (Yadav *et al.*, 2021).

4.3.5 Data quality. I4.0 implementation requires stringent data quality standards emphasising availability, consistency, and validity. Effective data governance includes rules for privacy, security, compliance, lifecycle management, and clear roles as well as designing an architecture for data capture, storage, integration, and utilisation (Meier *et al.*, 2023). Value chain transparency is critical for maintaining high data quality, though it remains challenging (Ghobakhloo and Fathi, 2020; Alieva and Powell, 2023).

High-quality data is crucial for successful I4.0 initiatives, particularly reengineering. Poor data quality hinders effectiveness (Patrucco *et al.*, 2020). TQM leverages Big Data and AI to enable root cause analysis and improve decision-making (Sader *et al.*, 2019). LM benefits from high-quality, real-time IoT, which is crucial for process optimisation and waste reduction (Sanders *et al.*, 2016; Tripathi *et al.*, 2021b), while SS relies on high-quality data to enhance process performance. LSS uses DMAIC and statistical methods, with AI improving data accuracy and reliability (Meier *et al.*, 2023).

4.3.6 Cybersecurity. Cybersecurity threats can hinder adoption, requiring ongoing vigilance (Kouatli, 2014; Khan and Al-Yasiri, 2016). Systems must be scalable, interoperable, and compliant with privacy regulations (Meier *et al.*, 2023) as insufficient cybersecurity erodes customer trust (Sader *et al.*, 2019). Security lapses disrupt operations, causing delays and extra costs (Agarwal and Ojha, 2023). In reengineering, cybersecurity underscores the importance of a robust IT infrastructure and the role of IT experts to ensure data security to prevent breaches (Patrucco *et al.*, 2020). Integrating I4.0 with TQM requires intensifying with real-time data and interconnected systems (Sader *et al.*, 2019). Moreover, while LM depends on interconnected systems, requiring robust security (Dixit *et al.*, 2022), SS and LSS need cybersecurity to safeguard data, though LSS offers limited direct support (Meier *et al.*, 2023).

4.4 Variables paradigms matrix

Building on soft and technical variable analyses and descriptions, we investigated the five paradigms to assess whether each supports the adoption of I4.0 for the different soft and technical variables and to identify specific factors supporting each of them (Tables 3 and 4). These factors, emerging from the literature, offer insights into the nature of the relationship between individual paradigms and the contextual variables under consideration, highlighting misalignments and gaps and outlining future research directions, which are discussed in *section 6.3*.

5. Discussion: the IPO framework

The findings indicate that successful I4.0 implementation depends on orchestrating technical and soft dimensions through PM. Rather than treating technologies as isolated enablers, the results align advanced digital solutions with specific organisational, managerial, and human factors for sustainable adoption. To capture these dynamics, we organise variables using the IPO framework (Figure 5). While Tables 3 and 4 report paradigm-specific evidence at a granular level, the IPO framework abstracts from detail to highlight recurring patterns across paradigms and specify what PM models need to effectively integrate I4.0: articulation of organisational requirements, processual mechanisms, and I4.0-enabled outcomes within an integrated pathway. By structuring interplay between organisational preconditions, operational mechanisms, and I4.0-enabled outcomes, the model provides a comprehensive roadmap that clarifies which elements are required and how they sequentially interact to support socio-technical transformation associated with I4.0. Consistent with PM, the IPO framework is a self-regulating and adaptive system, inherently cyclical and iterative (Coronel, 2024). Feedback loops from outcomes to inputs capture how I4.0-enabled performance informs subsequent managerial decisions, capability development, and technology investments. This dynamic interpretation clarifies that the value of the IPO model lies in explaining the iterative learning and adjustment mechanisms that characterise I4.0 adoption

Table 3. Variables/Paradigms matrix: Soft variables

	Reengineering	TQM	LM	SS	LSS
Cultural and organisational readiness	SUPPORTIVE Employees' empowerment*Focus on collaboration* NOT SUPPORTIVE Risk of resistance [1]	SUPPORTIVE Synergistic relationships between people and technologies.Big Data for communication and coordination.Employees' involvement in technological decision-making.Kaizen, if aligned with fast-tech development [4]	SUPPORTIVE Improved safety and health Employees' involvement Problem-solving culture Kaizen, if aligned with fast-tech development [10]	No suggested evidence	SUPPORTIVE Better communication Improved safety and health** Employees' involvement ** problem-solving culture ** Kaizen, if aligned with fast-tech development* NOT SUPPORTIVE Need for coordination and employees' involvement [1]
Managerial commitment	NOT SUPPORTIVE Risk of ideal projects imitation [1]	SUPPORTIVE Integrated systems evidence-based approach [4]	SUPPORTIVE Easier 4.0 adoption NOT SUPPORTIVE Lack of involvement [5]	NOT SUPPORTIVE Lack of involvement*	NOT SUPPORTIVE Lack of involvement [1]
Knowledge and skills	SUPPORTIVE Focus on IT competencies [2]	SUPPORTIVE Focus on employee education and supervision [9]	SUPPORTIVE Focus on employee education [7]	SUPPORTIVE Contribution of Green, Black, Master Black Belts* NOT SUPPORTIVE Statistical competences acquiring*	SUPPORTIVE Focus on employees' education contribution of Black, Master Black Belts* NOT SUPPORTIVE SS and LM competencies requirement* [2]

(*continued*)

Table 3. Continued

	Reengineering	TQM	LM	SS	LSS
Fear of failure	NOT SUPPORTIVE Rate of failure [2]	SUPPORTIVE Risk management approach* NOT SUPPORTIVE Rate of failure [5]	SUPPORTIVE Proved effectiveness* NOT SUPPORTIVE Adoption barriers* Replication difficulties [5]	SUPPORTIVE FMEA * NOT SUPPORTIVE Rate of failure [1]	SUPPORTIVE Overall knowledge management system NOT SUPPORTIVE: risk perception*
Readiness	NOT SUPPORTIVE Need for overall system evaluation [1]	SUPPORTIVE Synergistic relationships between people and technologies Soft practices adoption [5]	NOT SUPPORTIVE Needs for system evaluation [2]	SUPPORTIVE SPC and statistics DMAIC* [5]	SUPPORTIVE Field application evaluation SPC and statistics** [5]

Note(s): The tables include evidence based on the systematic review, except for: * = sources from paradigms definition; ** = directly connected to LM and SS paradigms *** = depending on short vs long-term. The number of papers supporting each variable/paradigm combination is indicated in square brackets

Source(s): Authors' own work

Table 4. Variables/Paradigms matrix: Technical variables

	Reengineering	TQM	LM	SS	LSS
Complexity	SUPPORTIVE END-2-END analysis*	SUPPORTIVE Processes standardisation*	SUPPORTIVE Search for simplification [4]	SUPPORTIVE DMAIC Big Data and AI management Fishbone diagrams*	SUPPORTIVE DMAIC Overall knowledge management system [1]
Integration	SUPPORTIVE Synergies with IoT and Cloud Strong IT competencies [2]	SUPPORTIVE Evidence-based approach supported by IoT, CPS, AI [8]	SUPPORTIVE SPC, JIT, TPM, preventive maintenance supported by IoT, Big Data, Cloud, AI people, processes, and products interaction Human-centric view [8]	SUPPORTIVE DMAIC SIPOC [9]	SUPPORTIVE Synergies with IoT and Big Data Improved interconnection human-centric view** DMAIC** SIPOC** [7]
Interoperability	SUPPORTIVE IoT and DT in SCM END-2-END analysis* [1]	SUPPORTIVE Evidence-based approach supported by IoT, CPS, AI Data sharing better communication [10]	SUPPORTIVE IoT, Big Data, Cloud, AI exploitation OEE, pull production, and employees' involvement [8]	SUPPORTIVE IoT, DT, CPS, AI integrated with Manufacturing execution system [7]	SUPPORTIVE OEE, pull production, and employees' involvement** Better communication [4]
Data quality	SUPPORTIVE Focus on IT competences*	SUPPORTIVE Focus on employee education and supervision*	SUPPORTIVE Big Data analytics for TPM customer involvement in decision-making [6]	SUPPORTIVE Big Data and AI exploitation statistics DMAIC SIPOC [7]	SUPPORTIVE Big Data exploitation customers involvement statistics** NOT SUPPORTIVE The need for data quality* [3]
Cybersecurity	SUPPORTIVE Focus on IT competences*	No suggested evidence	No suggested evidence	No suggested evidence	No suggested evidence
Costs	SUPPORTIVE Llimited IoT projects NOT SUPPORTIVE Large projects [1]	SUPPORTIVE Kaizen Small projects* [2]	SUPPORTIVE Kaizen* NOT SUPPORTIVE Needs for funds [4]	No suggested evidence	SUPPORTIVE Kaizen* Cost-effective in the long-term*** Savings* NOT SUPPORTIVE Need of funds*** [1]

Note(s): The tables include evidence based on the systematic review, except for: * = sources from paradigms definition; ** = directly connected to LM and SS paradigms
*** = depending on short vs long-term. The number of papers is indicated in square brackets
Source(s): Authors' own work

Table 5. RQs referred to soft and technical variables

Paradigm	RQs
Reengineering	What reengineering IT skills are needed for I4.0, and how can they be developed to improve technological readiness? How can reengineering IT skills strengthen cybersecurity in connected and automated production environments?
TQM	How can organisations adapt TQM principles to enhance managerial readiness, training, and skills development programs for the successful integration of I4.0 technologies? What are the barriers hindering the effective utilisation of real-time data for supporting TQM decisions?
LM	How can LM create a culture of safety and human-centredness and enable the development of the skills required for I4.0? How can LM be adapted to Big Data management, real-time data analysis, and the generation of actionable information?
SS	How can I4.0 support SS training, and how can DMAIC be integrated into an I4.0 roadmap? How can I4.0, Big Data, and AI be combined?
LSS	How can LSS skills support I4.0? What upskilling strategies can improve the preparation of LSS professionals for I4.0? How can I4.0 be used to improve LSS system knowledge?

Source(s): Authors' own work

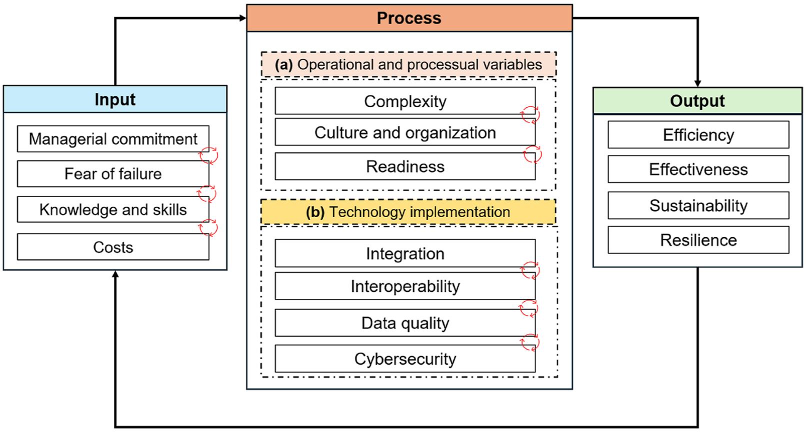
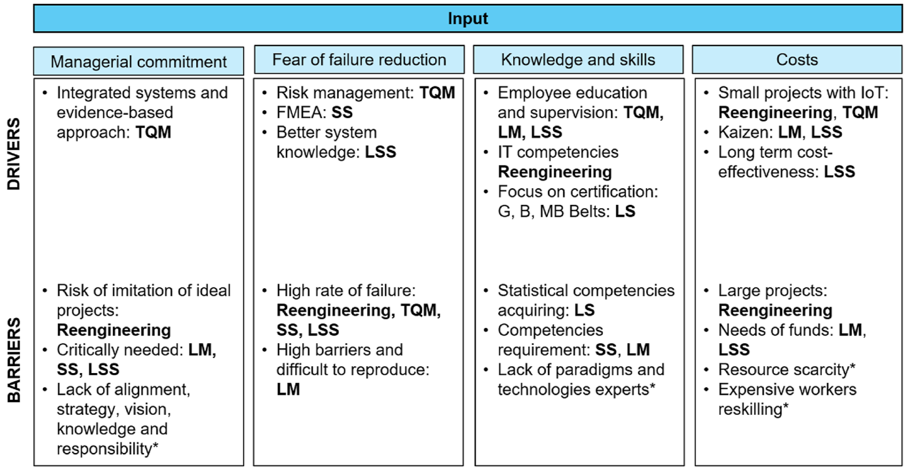


Figure 5. The IPO framework synthesising the soft and technical variables. Source: Authors' own work

over time. In this sense, the framework clarifies both what elements are required and how they interact to support the socio-technical transformation associated with I4.0.

Going deeper into the framework elements, input variables (Figure 6) capture organisational and managerial requirements shaping readiness for I4.0 adoption. Top management commitment plays a pivotal role in defining digital vision, allocating resources, and legitimising experimentation with I4.0 technologies. Managerial commitment reduces uncertainty and fear of failure by signalling tolerance for calculated risk and framing setbacks as learning opportunities, thereby enabling iterative, small-scale experimentation (Agarwal and Ojha, 2023). Such experimentation supports organisational learning and resilience and allows I4.0 initiatives to be gradually scaled as benefits become tangible (Canbay and Akman, 2023). Knowledge, skills, and costs act as critical enablers or constraints of I4.0 adoption. Insufficient expertise increases implementation costs and failure risks, while constrained

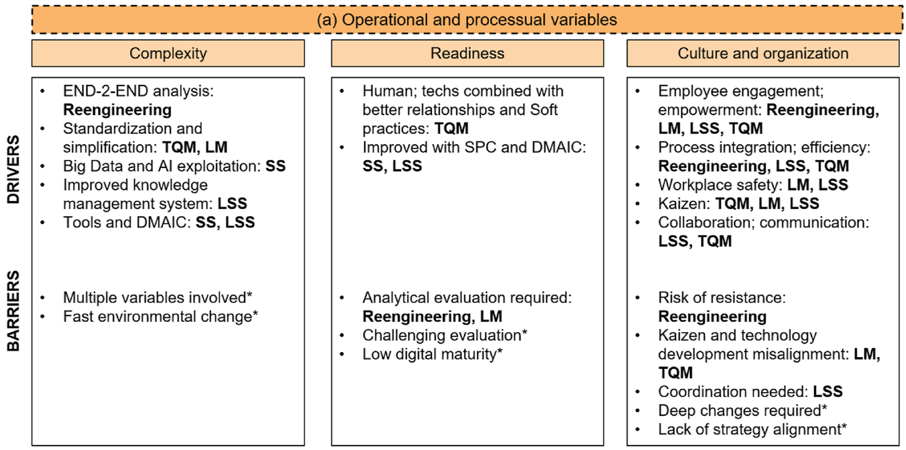


*Common to all the paradigms

Figure 6. Input variables. Source: Authors' own work

resources heighten risk aversion. A balanced assessment of costs and benefits, combined with incremental project initiation, supports a more controlled pathway towards I4.0 implementation.

Process variables (Figure 7) reflect the mechanisms through which I4.0 technologies are prepared, integrated, and governed. The first block of variables includes complexity, assessing technological readiness, culture, and organisation. In more detail, managing complexity and assessing technological readiness guide early decision-making by identifying interdependencies between legacy systems and emerging technologies. Digital maturity assessments provide a structured basis for identifying capability gaps and guiding adjustments. Aligning organisational culture with digital objectives requires employee involvement, training, and structural flexibility, collectively reducing resistance to change.



*Common to all the paradigms

Figure 7. Process variables (a). Source: Authors' own work

The second block concerns technology implementation (Figure 8), which involves selecting appropriate technologies, integrating them with existing systems, and deploying pilot projects. Interoperability becomes central, as effective implementation relies on secure and seamless data flows across I4.0 technologies. Data quality and cybersecurity emerge as cross-cutting variables: high-quality data underpins analytics-driven decision-making, while robust cybersecurity protects system integrity and organisational trust.

Output variables capture I4.0 adoption effects through PM (Figure 5). The literature highlights efficiency gains from improved processes, organisational structures, and human-technology interaction, leading to enhanced performance, reduced costs, and shorter lead times (Patrucco *et al.*, 2020; Prashar, 2023). Advanced technologies support efficiency through real-time monitoring and continuous optimisation (Baier *et al.*, 2022; Singh *et al.*, 2022; Hosseinzadeh *et al.*, 2023). Effectiveness includes quality improvements, customer satisfaction, and mass customisation aligned with quality 4.0 (Anosike *et al.*, 2021; Cifone *et al.*, 2021). Moreover, sustainability emerges as a key output, with digitally enabled processes reducing waste and improving resource efficiency (Tortorella *et al.*, 2021; Psarommatis *et al.*, 2022). Finally, I4.0 strengthens resilience by enabling predictive responses through data-driven decision-making (Singh *et al.*, 2022; Hosseinzadeh *et al.*, 2023).

From a comparative perspective, the analysis allows us to identify the differences between paradigms in I4.0 implementation. Overall, this comparison indicates that no single paradigm is optimal for I4.0 adoption. Instead, the effectiveness of each of them depends on the organisation's digital maturity level and implementation stage. The findings suggest that TQM and LM are particularly suitable in the early phases of I 4.0 adoption, where cultural alignment, employee involvement, and incremental change are essential to reduce uncertainty and resistance. In contrast, LSS emerges as the most comprehensive paradigm for more advanced stages of adoption, as it simultaneously addresses process complexity, data quality and management, technological integration, and continuous improvement through a structured, data-driven approach. Taken together, the comparative mapping of variables across paradigms allows for an integrated interpretation of the findings.

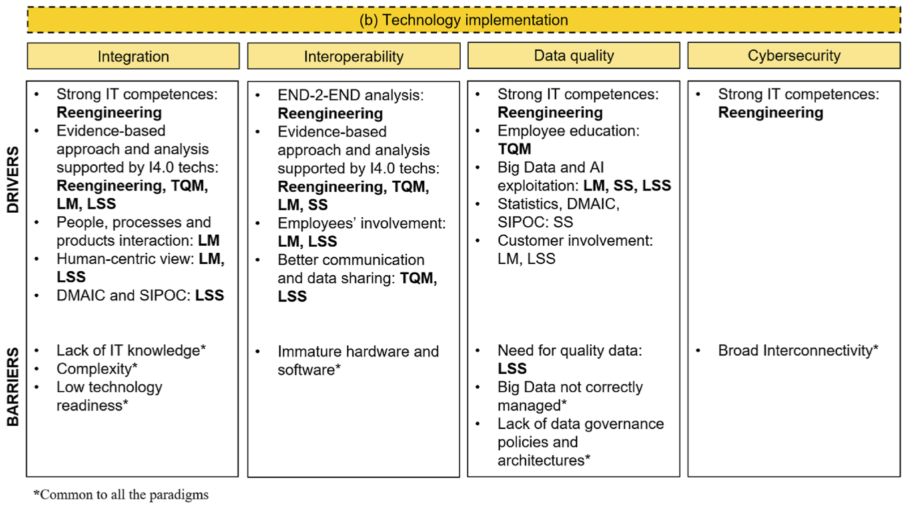


Figure 8. Process variables (b). Source: Authors' own work

6. Implications

6.1 Theoretical implications

From a theoretical perspective, this study contributes to I4.0 and PM research by reconceptualising PM as a socio-technical enabler of I4.0 and by developing an IPO-based explanatory framework grounded in socio-technical systems theory.

The first key contribution advances understanding of I4.0's adoption by shifting the focus from a technology-driven perspective to a PM perspective. While existing literature emphasises digital technologies' role in supporting paradigms, our findings underscore that PM paradigms themselves enable effective I4.0 implementation. Several studies explored technological enablers within paradigms such as LM (Cifone *et al.*, 2021), TQM (Prashar, 2023), zero-defect manufacturing (Psarommatis *et al.*, 2022), and LSS (Ganjavi and Fazlollahtabar, 2023). However, research explicitly focussing on PM paradigms as I4.0 drivers often remains general and lacks in-depth methodological comparison (Van Looy, 2021; P. Kumar *et al.*, 2023). Although valuable, comprehensive frameworks integrating technological and methodological perspectives remain limited. This study addresses this gap by systematically identifying and classifying key socio-technical variables through a process paradigm lens, offering a structured understanding of methodological support for I4.0 adoption.

The second theoretical implication concerns the development of the IPO-based framework (Figure 5), which contributes to the literature by evaluating how PM paradigms and socio-technical variables interact to support I4.0 integration. While prior research highlighted the need for comprehensive implementation frameworks and roadmaps (Psarommatis *et al.*, 2022; Bahulikar *et al.*, 2023; P. Kumar *et al.*, 2023; Utiyama *et al.*, 2025), a consistent and systematic classification of these variables has remained underexplored. Therefore, variables' organisation within the IPO structure provides an explanatory understanding of how organisational, human, and technological factors jointly shape successful adoption strategies.

The third contribution advances the literature by organising and integrating the dispersed insights into DT challenges coming from several recent studies (Fischer *et al.*, 2020; Yadav *et al.*, 2021; Van Looy, 2021; Cifone *et al.*, 2021; Bahulikar *et al.*, 2023; P. Kumar *et al.*, 2023) within a unified, process-based framework.

6.2 Practical implications

Our SLR provides a comprehensive roadmap for implementing a PM-based approach, helping organisations overcome high I4.0 failure rates (Giannetti and Ransing, 2016; Antony *et al.*, 2024) and adoption barriers (Psarommatis *et al.*, 2022; Bahulikar *et al.*, 2023).

The IPO framework organises variables in logical order that practitioners should follow to guide the DT of their company. By outlining an operative sequence and clearly distinguishing inputs and processes' variables, the proposed model supports a structured implementation path that reduces internal resistance and enables coherent progression of I4.0 initiatives. More specifically, by systematically mapping and refining processes, clarifying roles, and eliminating inefficiencies before introducing advanced technologies, organisations can minimise operational disruptions and resistance. Early involvement of employees and managers in process redesign fosters engagement, addresses fears related to job changes and technology failure, and builds openness towards innovation. In addition, small and manageable pilot projects play a crucial role in gradually developing organisational capabilities. Accordingly, PM paradigms support complexity management, data quality, leadership preparedness, and digital skills development, making them essential prior to advanced technological integration. Reengineering proves valuable for analysing end-to-end business processes, managing complexity, strengthening cybersecurity, and developing IT skills required for system integration and interoperability (Patrucco *et al.*, 2020). TQM is particularly effective in reducing fear of failure through incremental improvement and Kaizen-oriented projects, while enhancing managerial effectiveness, technological readiness, organisational culture alignment, data quality, and interoperability (Sanders *et al.*, 2016). Integrating TQM with reengineering yields complementary benefits, improving both process analysis and implementation effectiveness (Patrucco *et al.*, 2020). LM contributes to reducing resistance to change and fear of failure (Meier *et al.*, 2023) while fostering the cultural and knowledge foundations required for I4.0 adoption and supporting interoperability across systems and processes (Sanders *et al.*, 2016; Patrucco *et al.*, 2020). **SS** addresses complexity through the DMAIC methodology (Kumar *et al.*, 2023), enhances technological readiness, improves integration, and ensures high data quality standards (Sanders *et al.*, 2016; Patrucco *et al.*, 2020). LSS combines structured problem-solving with continuous improvement, supporting employee education, complexity management, technological readiness, and integration, while reducing fear of failure through small-scale, cost-effective improvement initiatives (Sanders *et al.*, 2016; Kumar *et al.*, 2023).

7. Conclusion, limitation, and future research direction

This study examines the evolving I4.0 landscape and challenges associated with its adoption across five PM paradigms (Table 1). It offers a key theoretical contribution by reconceptualising PM as a dynamic socio-technical enabler of I4.0.

In response to RQ1, the study systematically identified and classified socio-technical variables related to managerial, organisational, and technological dimensions, mapping them across the paradigms (Sections 4.2 and 4.3). Key variables include managerial commitment, skills and knowledge, organisational culture, complexity, and cybersecurity. This classification enabled the development of an IPO-based theoretical framework providing a structured representation of how these variables interact within the I4.0-driven process transformation, addressing the lack of integrated frameworks in prior literature (Kumar *et al.*, 2024; Utiyama *et al.*, 2025). Indeed, when integrated through the IPO framework, PM connects operational routines with digital innovation by harmonising organisational, human, and technological variables within a cohesive strategy. This integrative perspective brings together previously fragmented PM-I4.0 discussions, thus positioning PM as a central driver of adaptability, sustainability, and competitive advantage in the digital era.

Addressing RQ2, the comparative analysis (Tables 3 and 4) reveals both strengths and gaps across paradigms. SS shows limited connections with critical variables for I4.0 adoption, including managerial commitment, skills and knowledge, organisational culture, costs, and cybersecurity. Despite their effectiveness in process improvement, LM and TQM show limited engagement with complexity and cybersecurity, two central dimensions of the I4.0 landscape. Reengineering also appears underexplored, indicating opportunities for future research to strengthen its role in DT.

The study outlines future research directions (Table 5) to enhance PM paradigms' contribution to I4.0 adoption (RQ3). These include explicitly addressing digital complexity and cybersecurity within traditional paradigms (e.g. TQM and reengineering), exploring integrated or hybrid approaches (e.g. LSS-TQM), and developing process-centric roadmaps incorporating interoperability and security. Moreover, future research should focus on investigating underexplored factors within the context of PM paradigms, such as fear of failure, interoperability, complexity, data quality, and cybersecurity. Indeed, such factors are frequently acknowledged as critical challenges, yet the literature offers limited guidance on systematically addressing them. Therefore, examining these constructs more deeply within PM contexts, developing mitigation strategies, and empirically validating their role in supporting sustainable and effective I4.0 adoption, is essential.

Finally, to extend the theoretical and practical relevance of the IPO framework, future research should adapt and empirically test it in non-manufacturing contexts. Indeed, our findings are primarily grounded in manufacturing, reflecting the dominant focus of existing I4.0 and PM research. Sectors such as healthcare and services face distinct DT challenges involving distinct regulatory, technical, and human dynamics. Empirical studies could help assess the framework's transferability, identify context-specific variables, and explore its applicability to emerging paradigms beyond manufacturing.

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