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How lighthouse companies are pioneering Indonesia's Industry 4.0 and 5.0 revolution? A soft system methodology approach

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How lighthouse companies are pioneering Indonesia's Industry 4.0 and 5.0 revolution? A soft system methodology approach

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Abstract: As industries transition toward Industry 5.0, organisations face challenges in balancing automation and digitalisation with human-centric and sustainable principles. Existing Industry 4.0 readiness frameworks primarily emphasise technological adoption while overlooking the role of operational excellence in facilitating structured transformation. This study develops a comprehensive transformation model integrating Soft System Methodology with the INDI 4.0 framework. The proposed model introduces a novel approach by embedding waste elimination, defect reduction, autonomous processes, and total productive maintenance as foundational enablers. This framework establishes a structured sequence for implementation, ensuring that operational excellence serves as a prerequisite for sustainable and adaptive digitalisation. The study highlights the interplay between management commitment, workforce adaptability, and digital integration, offering a pathway toward Industry 5.0. The findings provide actionable insights for policymakers and industry leaders in emerging economies, demonstrating how operational efficiency and human capability development can drive sustainable and socially responsible industrial ecosystems.

Keywords: Industry 5.0; Industry 4.0; operational excellence; soft system methodology; INDI 4.0; Lean Six Sigma; LSS; readiness model; maturity model; digitalisation; sustainability; human-centric; resilience.

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1 Introduction

The industrial revolution has evolved through various stages, with Industry 4.0 representing a pivotal transformation characterised by automation, cyber-physical systems, and intelligent manufacturing (Kagermann et al., 2013). This paradigm aims to enhance flexibility, mass customisation, and operational efficiency across industries. However, its implementation remains uneven globally, particularly in emerging economies where infrastructural and organisational readiness is often limited (Anackovski and Pasic, 2020). While advanced economies such as the USA and Germany benefit from robust digital ecosystems, countries like Indonesia continue to face structural constraints in digital transformation. In response, the Indonesian government introduced the 'Making Indonesia 4.0' roadmap in 2018, prioritising five strategic sectors, including the food and beverage industry, which contributes significantly to national GDP (Central Bureau of Statistics Indonesia, 2023).

However, adoption challenges remain due to global disruption and internal capability gaps (*Business Indonesia*, 2024). This is reinforced by a study that emphasised that although INDI 4.0 helps map readiness, it has weaknesses in terms of prescriptive depth, leaving companies without structured guidance on where to start or how to improve operational maturity (Hasbullah and Bareduan, 2024). Particularly, Indonesia's food and beverage sector, in being a national priority, made slow progress in adopting Industry 4.0 technologies due to limited innovation capabilities and supplier ecosystems, particularly the lack of local digital technology providers and integrated infrastructure (Surindra et al., 2024; Rahmatulloh et al., 2024), inadequate workforce skills, and limited financial resources for implementing smart technologies (Surindra et al., 2024). As of the end of 2022, only four companies in the F&B sector had received the National Lighthouse Industry 4.0 certification, highlighting the ongoing gap in digital readiness and implementation.

Amid the ongoing pursuit of Industry 4.0, the discourse around Industry 5.0 has gained momentum. This new industrial paradigm emphasises human-centricity, sustainability, and resilience, positioning advanced technologies as tools to empower workers and achieve broader societal and environmental objectives (Breque et al., 2021;

Nahavandi, 2019). The transition to Industry 5.0, however, requires more than technological upgrades; it demands strategic alignment between operational excellence, digital capability, and human development. Recent research emphasises the importance of aligning digital transformation with the Sustainable Development Goals (Verma, 2024) and advancing worker-centric technological innovations such as digital twins, XR, and trustworthy AI (Vyhmeister and Castané, 2024; Fernández-Caramés and Fraga Lamas, 2024). In the Indonesian context, companies face challenges in achieving both foundational process efficiency and the maturity of enabling technologies (Rajnai and Kocsis, 2018).

Recent literature has explored the complementarity between Lean Six Sigma (LSS) and digital transformation, suggesting that LSS provides a disciplined methodology for improving process quality and efficiency, which can be enhanced through digital tools such as real-time analytics, automation, and cyber-physical systems (Ibrahim and Kumar, 2024; Tissir et al., 2024). On the other hand, case studies from the manufacturing sector illustrate how hybrid approaches – such as real-time data analytics, IoT, CPS, predictive algorithms, and robotics – are increasingly being implemented to support core Lean principles such as continuous flow, standardised work, TPM, Kanban, and continuous improvement (Dascalu and Pislaru, 2025). That combination increases the possibility of more responsive and adaptive production systems. Simultaneously, the INDI 4.0 model developed by the Indonesian Ministry of Industry offers a strategic framework for assessing digital preparedness across five key dimensions: management, culture, operations, technology, and products. However, this model remains diagnostic in nature and does not offer structured guidance for operational improvements prior to digital implementation. This limits its practical utility, particularly for firms with low maturity levels seeking a phased transformation approach.

The current research landscape reveals three critical gaps: First, existing frameworks predominantly emerge from advanced economies with mature digital ecosystems, overlooking the unique constraints faced by emerging economies with nascent digital infrastructure. Second, while Industry 5.0 discourse has gained momentum in theoretical studies (Nahavandi, 2019; Breque et al., 2021), empirical investigations of implementation pathways remain scarce, especially in labour-intensive sectors where human-machine collaboration presents distinct challenges. Third, most studies examine either operational excellence methodologies or digital readiness in isolation, creating a fragmented understanding that fails to capture the sequential relationship between process optimisation and technological adoption. This research aims to fill those gaps by employing a combination of Soft Systems Methodology and INDI 4.0 model.

2 Literature review

2.1 Accelerating Industry 5.0 transformation in lighthouse companies

The transition from Industry 4.0 to Industry 5.0 has attracted growing scholarly attention, particularly as organisations seek to balance technological advancement with human-centric and sustainable manufacturing practices. Numerous readiness models have been developed to guide Industry 4.0 implementation, such as the Kearney framework – which categorises national readiness – and Schumacher et al. (2016), which focuses on organisational-level maturity across strategic and cultural dimensions. In the Indonesian context, the INDI 4.0 model serves as a localised readiness tool developed by the Ministry of Industry to assess firm-level transformation across five key dimensions: management and organisation, people and culture, factory operations, technology, and products and services. While these models provide structured diagnostics, they often lack prescriptive guidance on how companies can operationalise transformation and enhance internal capabilities before adopting advanced technologies. This limitation is especially evident in emerging economies, where firms face resource constraints and capability gaps in implementing Industry 4.0.

Figure 1 Key features of Industry 5.0 (see online version for colours)

Source: Kraaijenbrink (2023)

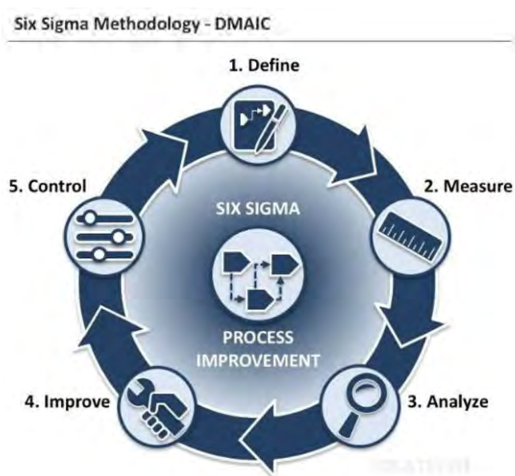
At the same time, the emergence of Industry 5.0 introduces a broader agenda that goes beyond digital automation to prioritise human-machine collaboration, resilience, and sustainability [Kraaijenbrink (2023) as described in Figure 1]. According to the European Commission (2021), Industry 5.0 represents a paradigm shift that places worker well-being, inclusive design, and skills development at the heart of the industrial system. This shift reflects a shift from technology-centric production to human-machine symbiosis. Similar sentiments were expressed in a systematic review by Ali et al. (2025), which highlighted that the human-centred focus in Industry 5.0 leverages collaborative robotics (cobots) and AI to enhance more creative and ergonomic roles for workers. The principles of Industry 5.0, outlined by Rame et al. (2024), emphasise transformative sustainability, integrating digitalisation with a circular economy, resource efficiency, and performance indicators linked to environmental and social outcomes. Additionally, a study emphasised that Industry 5.0 places resilience – the ability to absorb disruption and recover – as a strategic objective and that leveraging Industry 4.0 capabilities continuously builds resilience (Ghobakhloo et al., 2024).

However, most existing frameworks do not provide a clear roadmap for transitioning from efficiency-driven models to these more adaptive and human-centred systems, especially at the firm level. Current models like INDI 4.0 assess readiness but do not offer integrated pathways for transformation. To address this gap, scholars have proposed embedding operational excellence methodologies, such as LSS, into digital readiness models. LSS provides a structured approach for waste reduction, process efficiency, and continuous improvement – critical enablers for successful digital transformation and foundational for Industry 5.0. By aligning LSS with INDI 4.0, this research proposes a stepwise transformation model that prepares firms not only for Industry 4.0 adoption but also for the human-centric and sustainable demands of Industry 5.0.

2.2 Operational excellence and LSS

Operational excellence refers to an organisation's ability to continuously improve operations while executing strategies effectively, efficiently, and consistently (Russell and Koach, 2009; Urick and Adams, 2017). It involves creating value for customers and preventing failures before they occur, emphasising a proactive rather than reactive approach. The core components of operational excellence include strategic focus, disciplined execution, and a culture of continuous improvement. These elements enable organisations to optimise performance and achieve sustainable competitive advantage (Duggan, 2011). In recent discussions, operational excellence is not only identified with process efficiency and reliability but also encompasses the integration of frameworks such as LSS, TQM, and digital innovation. One definition of operational excellence emphasises sustainable alignment with corporate strategy, supported by key management methods and hindered by cultural and resource constraints (Vlachopoulos and Dimitriadis, 2025). Specifically, they emphasise that modern operational excellence extends to sustainability performance, reflecting a broader understanding in the manufacturing context.

Figure 2 Six Sigma framework (see online version for colours)



Source: Stratechi (2024)

LSS combines two complementary approaches that support performance and quality enhancement. Lean focuses on maximising customer value by eliminating waste and improving flow efficiency, guided by principles such as Jidoka, or process autonomy, to halt production when defects are detected (Womack and Jones, 2003; Ohno, 1988). Six Sigma, on the other hand, employs a data-driven method to minimise variation and improve process consistency through a structured approach of define, measure, analyse, improve, and control (Dahlgaard and Dahlgaard-Park, 2006; Wang et al., 2022) as specified also in Figure 3 (Stratechi, 2024). While Lean enhances operational efficiency, Six Sigma strengthens process effectiveness, making their integration a powerful tool for achieving operational excellence across industries (Clancy et al., 2022; Khillar, 2021).

Delahoz-Dominguez et al. (2024) conducted a study highlighting how the structured discipline of Six Sigma provides operational benefits in the parcel management process in service logistics, reinforcing the role of LSS in achieving operational excellence. In the banking sector, Ojha and Deen (2024) uncovered the application of lean practices through workflow mapping, waste identification, and iterative process redesign to reduce loan processing time and improve customer satisfaction. A study identified that investments in digital infrastructure and cultural alignment can enhance the role of LSS in service improvement and process efficiency (Chentoufi and Ennadi, 2023). Additionally, Dave et al. (2015) reveal a fundamental historical account of the evolution of LSS, emphasising its integration with service quality management and highlighting how its structured methodology lays the foundation for future digital practices and smart operations.

2.2.1 Integration of LSS and total productive maintenance

Total productive maintenance (TPM) and LSS represent complementary methodologies that collectively enhance operational excellence in manufacturing environments. TPM, introduced by Nakajima (1988), focuses on maximising equipment effectiveness through autonomous maintenance, planned maintenance, and early equipment management, while LSS combines waste elimination principles (Womack and Jones, 2003) with statistical process control (Montgomery, 2013). A notable study offered a compelling framework integrating TPM and LSS; the combined approach significantly improved overall equipment effectiveness (OEE) in textile manufacturing (Islam et al., 2025). More recently, a study of the combination of LSS and TPM reveals the synergetic result of reducing non-value-added time by up to 60% (Gomaa, 2025). Similarly, Kumar et al. (2021) found that TPM's emphasis on OEE creates the measurement infrastructure necessary for implementing smart manufacturing technologies, as OEE metrics provide baseline data for digital monitoring systems.

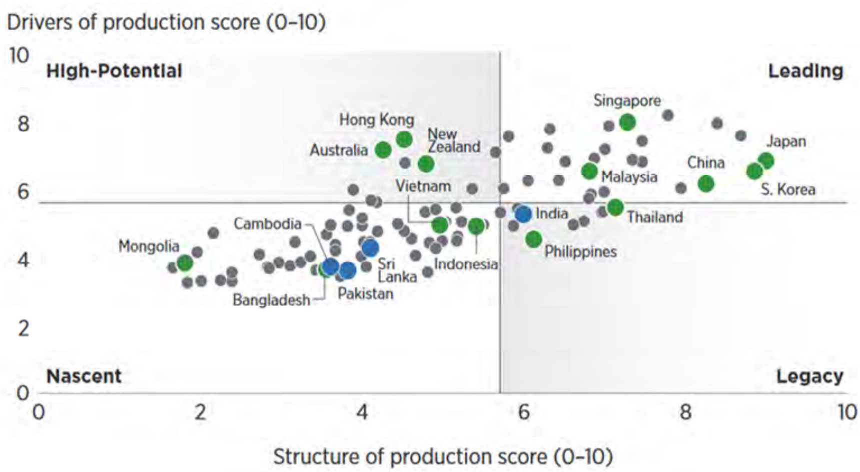
The literature indicates that TPM serves as a precursor to digital manufacturing by establishing both technical capabilities and cultural readiness for transformation. Clancy et al. (2022) found that operational excellence methodologies create the process discipline necessary for successful digitalisation, with 'technology implementation requiring lean workflows before digitalisation'. Moreover, Wang et al. (2022) demonstrated that manufacturers integrating TPM with LSS before digital implementation reported higher success rates in smart factory initiatives compared to those pursuing technology-first approaches. And Tissir et al. (2024) extended this understanding by showing how TPM's autonomous maintenance principles align with the autonomous process requirements of Industry 4.0, creating a natural progression from operator-led equipment care to cyber-physical maintenance systems.

2.3 INDI 4.0 model

The assessment uses two terms, maturity and readiness, to gauge the level of Industry 4.0 adoption. Readiness assessment is carried out before engaging in the maturation process, while maturity assessment aims to capture the situation as it is during the maturation process (Schumacher et al., 2016). In 2018, A.T. Kearney developed an assessment of country readiness for Industry 4.0, together with the World Economic Forum. They classified the countries into four categories based on drivers of production and structure of production, as shown in Figure 3. The analysis resulted in a model with four types of countries:

- Leading: countries with a good position to utilise Industry 4.0 driven by a strong production base.
- Legacy: countries with a strong existing production base but having risk due to unsavoury production drivers.
- High potential: countries with limited production bases but strong drivers of production.
- Nascent: countries with a more limited production base and drivers of production.

Figure 3 APAC country readiness for the Fourth Industrial Revolution (see online version for colours)



Source: Kearney (2019)

As part of the Making Indonesia 4.0 program, the Indonesia Ministry of Industry developed INDI 4.0 as presented. INDI 4.0 is a model to assess the readiness of Indonesian companies to do a digital transformation. This model consists of five dimensions: management and organisation, people and culture, factory operation, technology, and the last part is product and service. A company that reaches a minimum level 3 of readiness will be certified as a national Lighthouse Industry 4.0. Companies utilise the assessment result to identify the challenges and determine strategies to enhance the transformation. Meanwhile, the government uses the assessment as a standard to measure and determine policies for Making Indonesia 4.0. Figure 4 shows the INDI 4.0 model as the assessment model for the companies to transform into Industry 4.0.

Further elaboration of INDI 4.0 dimensions is explained as below:

1 Management and organisation: this dimension aims to measure the management's support to develop manufacturing systems to be more efficient.

2 People and culture: the aim of this dimension is to prepare people to open up to the transformation process and to create a conducive culture.

3 Products and services: to provide technology-enabled products and data-based intelligent services.

4 Technology: the implementation of various Industry 4.0 technologies, such as artificial intelligence, 3D printers, augmented reality, robot collaboration, etc.

5 Factory operations: the pillar concerns the use of technology in factory operations, including enterprise supply chain and logistics systems, intelligent maintenance system applications, autonomous production processes, centralised data storage and control systems, and enterprise cybersecurity.

Figure 4 INDI 4.0 model (see online version for colours)

Source: Indonesia Ministry of Industry (2018)

However, according to a systematic review, only 56.86% of respondents agreed that INDI accurately measures Industry 4.0 readiness after comparing it with other maturity models such as IMPULS and SIRI. The narrow focus on factory operations and lack of depth in other dimensions were key criticisms (Hasbullah and Bareduan, 2024). In the other articles, Hasbullah et al., (2022) emphasised that the INDI 4.0 diagnostic is limited in providing actionable insights for companies at different maturity levels, particularly in translating their readiness scores into systematic improvement plans. Furthermore, a plant-level assessment conducted by Surindra et al. (2024) reveals that the current INDI 4.0 design allows for score inflation, where companies may focus solely on well-defined areas such as logistics automation or data warehousing while ignoring broader strategic drivers. This can create a distorted view of digital transformation, weakening the validity of the assessment and the decisions made.

2.4 Conceptual model

The conceptual model in Figure 5 presents an integrated framework combining LSS and the INDI 4.0 model to support a structured transition toward a structured and human-centric progression to Industry 5.0, which emphasises human-machine systems, sustainability through resource optimisation, and resilience to disruptions (Breque et al., 2021). LSS provides a foundation for operational excellence, leveraging systematic tools such as DMAIC, waste elimination techniques, and process flow analysis (Montgomery, 2013; Womack and Jones, 2003). These technologies guarantee that process enhancements are customer-focused and data-driven, offering a solid basis for successful technology adoption. Simultaneously, INDI 4.0 functions as a diagnostic model, assessing readiness across dimensions including management, culture, operations, and technology (Indonesia Ministry of Industry, 2018).

A critical enhancement to this model is the explicit recognition of human capability as a central component of successful transformation. As Hozdić and Makovec (2023) argue, the evolution of manufacturing systems has progressed from digitalisation and cybernation toward a cognitisation phase, where human cognitive abilities work in harmony with intelligent systems. This alignment recognises that technology adoption alone is insufficient to drive sustainable success; organisations must simultaneously invest in their human capital and cultivate a culture of operational excellence (How and Cheah, 2024). The model bridges these approaches by embedding both efficiency principles and human-centric design into digital transformation efforts, ensuring optimised processes before automation while developing the necessary workforce capabilities. It highlights five transformation principles: waste reduction with a focus on customer value, continuous customer orientation, smooth process flow, understanding real-time operational dynamics, and achieving reliability (Wankhede et al., 2023). These principles act as enablers of Industry 5.0 by fostering human-machine collaboration, resource optimisation, and adaptability to change.

In emerging economies, where industrial digitalisation initiatives frequently suffer from disjointed strategies and inadequate capabilities, this integrated paradigm is especially pertinent. The model offers a two-pronged strategy in this regard:

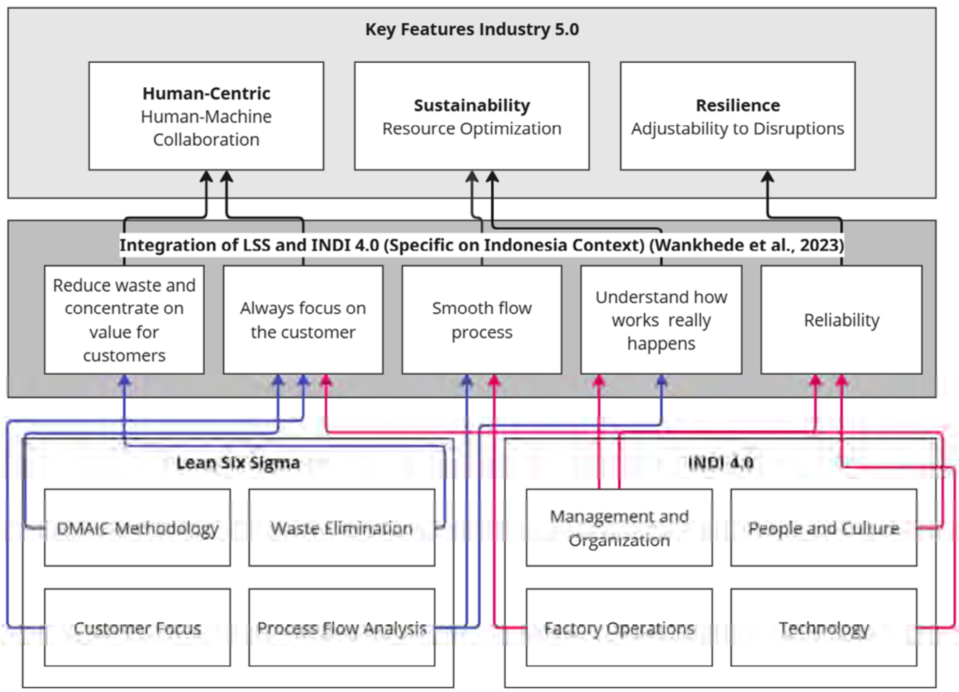
1 use LSS to guarantee the stability and performance of the foundational processes

2 improve human capabilities and INDI 4.0 evaluation to create future-ready capacity.

This kind of integration aids in bridging the sometimes disregarded gap between operational reality and policy aspiration. Moreover, this integrated approach addresses the need for workforce agility in navigating the complexities of new industrial paradigms (Alviani et al., 2024). As organisations transition toward Industry 5.0, they must develop employees' technical skills, problem-solving capabilities, and adaptability to effectively manage advanced systems and extract actionable insights from vast amounts of data.

Ultimately, this model improves management practice as well as theoretical knowledge. In theory, it illustrates how combining the strategic diagnostics of INDI 4.0 with the structured improvement logic of LSS can work in concert. In practice, it provides industry stakeholders – particularly those in developing countries – with a scalable plan to help them manage the shift from Industry 4.0 adoption to Industry 5.0 reality. Through the integration of process excellence, technical maturity, and human growth, the model highlights the multifaceted preparedness necessary to prosper in the upcoming industrial era.

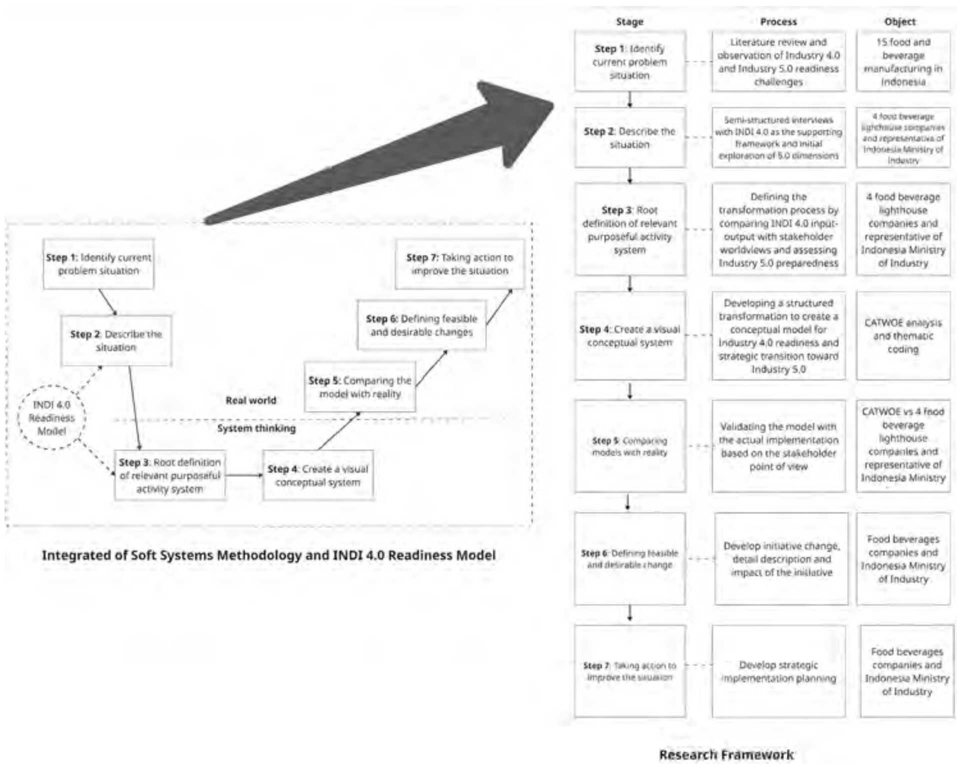
Figure 5 Conceptual model LSS and Industry Revolution 4.0–5.0 (see online version for colours)



3 Methodology

This study employs a qualitative case study approach using Soft Systems Methodology (SSM) combined with INDI 4.0 model to analyse the complex transformation process of Industry 4.0 and its transition toward Industry 5.0, as presented in Figure 6. Four lighthouse companies were selected based on their recognition by the Ministry of Industry, progress in smart manufacturing technology implementation, and willingness to participate in the research. Checkland (1990) created the action-oriented inquiry methodology known as SSM to use a structured inquiry process to address social problems that are difficult to define. Because it accommodates various worldviews and inter-organisational intricacies, it is especially well-suited to situations involving multiple stakeholder perspectives (Al Harassi, 2017).

Figure 6 Research framework: integrated SSM framework (Checkland, 1990) and the INDI 4.0 model (Indonesia Ministry of Industry, 2018)



A case study approach enables an in-depth exploration of real-world industrial transformation using multiple data collection methods, including semi-structured interviews, document analysis, and direct observations (Yin, 2018; Sekaran and Bougie, 2016). By integrating the INDI 4.0 model, this study applies seven key SSM steps: analysing the unstructured problem situation, expressing the messy system, defining root problems, developing a conceptual transformation model, comparing the model with reality, defining feasible and desirable changes, and taking action to improve the situation.

To enhance the validity and reliability of the finding, semi-structured interviews were conducted with key stakeholders from the lighthouse companies and the Indonesian Ministry of Industry. This method provides structured yet flexible discussions, capturing insights into the motivations, barriers, and strategic decisions influencing Industry 4.0 implementation (Yin, 2018; Saunders et al., 2019). Thematic coding was employed to analyse interview transcripts, systematically identifying recurring patterns, transformation challenges, and key enablers. The analysis aligns stakeholder perspectives with the INDI 4.0 dimensions, ensuring that both technological and organisational aspects of transformation are incorporated. The overall research framework and expected outcomes at each stage are depicted in Figure 6.

Table 1 Stakeholders overview

ID	*Sector*	*Institution*	*Years of institutional*	*Years of experience*	*Rank/firm*
P1	Food and beverage company	Nutrition Company	42 years	20 years	Factory Manager
P2	Food and beverage company	Nutrition Company	42 years	24 years	Digitalisation Manager
P3	Food and beverage company	Nutrition Company	42 years	22 years	Engineering Manager
P4	Food and beverage company	Nutrition Company	42 years	21 years	Quality Manager
P5	Food and beverage company	Nutrition Company	42 years	12 years	Human Capital Manager
P6	Food and beverage company	Nutrition Company	42 years	10 years	Performance Manager
P7	Food and beverage company	Formula Milk Company	17 years	24 years	Manufacturing Manager
P8	Food and beverage company	Formula Milk Company	17 years	22 years	Engineering Manager
P9	Food and beverage company	Formula Milk Company	17 years	20 years	Human Capital Manager
P10	Food and beverage company	Formula Milk Company	17 years	16 years	Operations Systems Manager
P11	Food and beverage company	Formula Milk Company	17 years	14 years	Quality Manager
P12	Food and beverage company	Formula Milk Company	17 years	14 years	PPIC Manager
P13	Food and beverage company	Food Company	14 years	30 years	Operations Director
P14	Food and beverage company	Food Company	14 years	17 years	Engineering Manager
P15	Food and beverage company	Food Company	14 years	12 years	Quality Manager
P16	Food and beverage company	Dairy Company	57 years	32 years	Operations Director
P17	Food and beverage company	Dairy Company	57 years	26 years	General managers of supply chains
P18	Government	Ministry of Industry of Indonesia	78 years	17 years	Head of Technology Optimisation and Industry Service Policy

4 Results and analysis

4.1 Step 1: unstructured problem situation

Interviews revealed that lighthouse companies accelerate Industry 4.0 adoption through benchmarking and collaboration, sharing best practices to support industry-wide transformation (Frank et al., 2019). Many firms still view automation as a replacement for human labour rather than a tool for enhancing workforce capabilities. Additionally, while sustainability is acknowledged, cost-efficiency remains the primary focus, limiting long-term investments in eco-friendly and socially responsible practices. These barriers suggest that companies lack a structured roadmap for balancing technological efficiency with human and environmental factors.

The study examined these challenges through semi-structured interviews with 18 key stakeholders from four lighthouse companies and the Ministry of Industry, covering management, operations, HR, supply chain, technology, and quality management (see Table 1).

While lighthouse firms have successfully implemented Industry 4.0, findings indicate that their transformation remains focused on automation, with limited emphasis on human-centric innovation and resilience. Addressing these gaps requires a shift toward integrating Industry 5.0 principles, ensuring that efficiency-driven digitalisation aligns with workforce adaptability and sustainability goals. This study provides a foundation for assessing transformation strategies, helping companies navigate beyond Industry 4.0 and build future-ready manufacturing ecosystems. These four companies are pioneers of Industry 4.0 transformation in Indonesia's food and beverage sector, representing various subsectors, including dairy, nutrition, infant formula, and processed foods. Their participation ensures sectoral coverage and practical insights across a range of industry contexts.

Furthermore, the panellists can provide authoritative perspectives on organisational transformation, with extensive experience – ranging from 10 to over 30 years – holding senior positions. Their leadership within their respective functional areas allows them to provide comprehensive information and insights into the various aspects of Industry 4.0 and Industry 5.0. Furthermore, other manufacturers frequently benchmark these lighthouse companies, demonstrating the strong influence and relevance of their strategies within the Indonesian industrial context. The sampling approach, drawn from a group of practitioners who exemplify best practices and are experienced in navigating the complex realities of industrial transition, minimises bias in the research.

4.2 Step 2: expressing the messy system (rich picture)

Industry 4.0 transformation requires a structured approach to align strategic objectives with operational realities, yet findings indicate a clear disconnect between top management and implementation-level concerns. Top management, represented by general managers and operations directors, primarily focuses on strategic issues such as competitive positioning, manufacturing efficiency, customer expectations, management commitment, and environmental challenges. These concerns emphasise the long-term vision and roadmap for Industry 4.0 adoption, highlighting the importance of leadership in aligning digital transformation with broader business goals (Schumacher et al., 2016).

> "Support from top management is important. Top management leads and aligns the people; hence, the organization can move together towards the vision in manufacturing and supply chain." (Operations Director, Company 3)

> "Top management needs to have a vision of the manufacturing in the future, determine a road map for the transformation, and execute the road map gradually." (Manufacturing Director, Company 4)

Despite these strategic directives, managers responsible for production, engineering, quality, and human capital reported that 'implementation issues' dominate their concerns, including pain points in manufacturing, digital competency gaps, management's commitment, data validation, and cybersecurity risks. These findings underscore the reality that technological adoption alone is insufficient without organisational alignment and workforce readiness (Sony and Naik, 2020). One significant challenge is the digital knowledge gap between senior and younger employees, which slows adoption and creates resistance to transformation (Kiel et al., 2017).

> "The integration of auto-accept and auto-disposition features in the QA process signifies a transformative leap, harnessing technological advancements to streamline and expedite quality assurance, effectively replacing manual tasks with automated efficiency." (Quality Manager, Company 2)

> "The digital knowledge challenges among senior generations pose hurdles in technology adoption, especially in the context of digital knowledge. Integrating digital tools into a predominantly senior workforce environment becomes intricate, emphasizing the contrast between the tech-savvy younger generation and the challenges faced by seniors." (Performance Manager, Company 1)

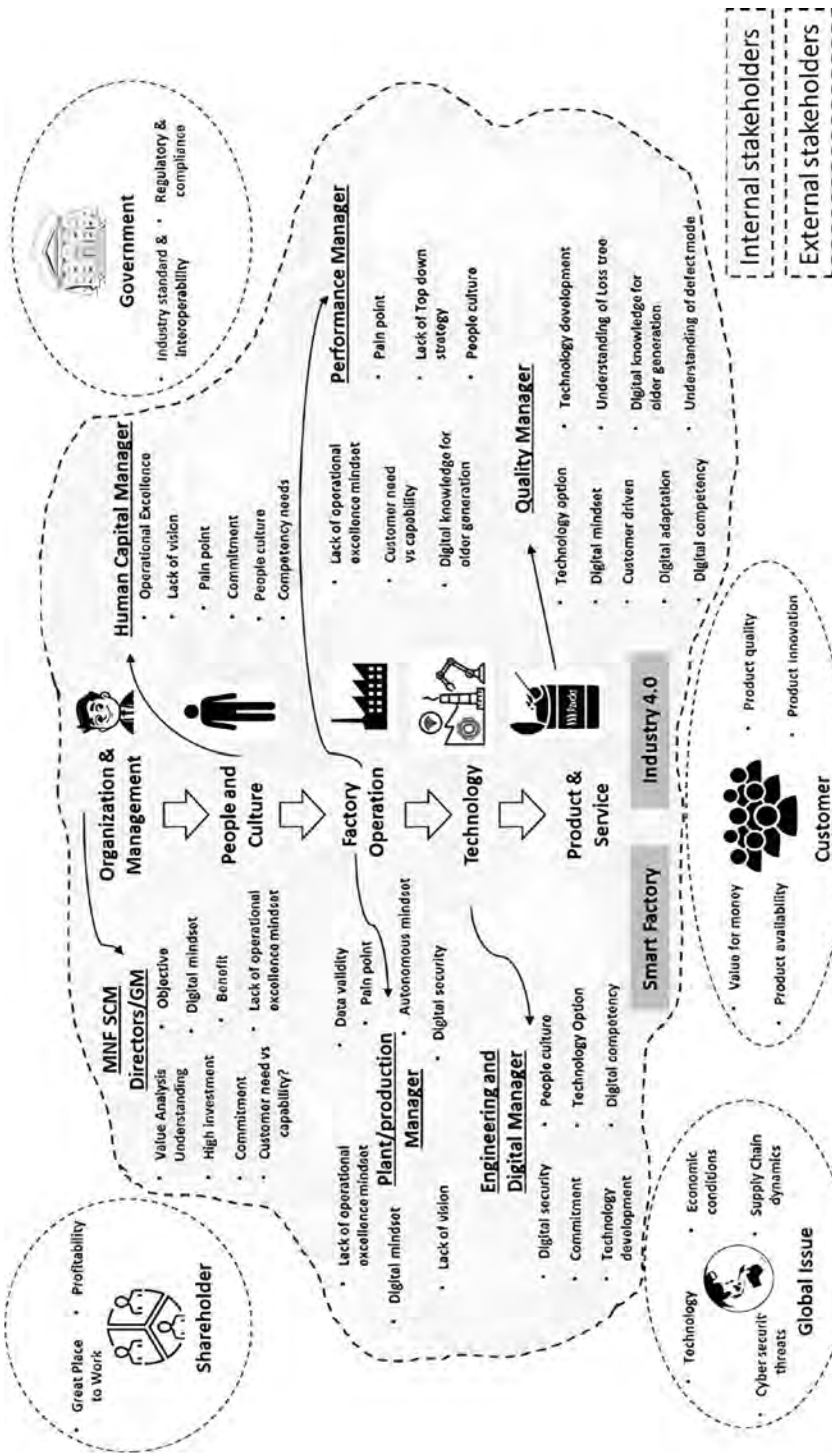
Beyond these differences, both top management and operational managers emphasised the role of mindset and workforce capabilities in achieving operational excellence, particularly through LSS principles. Four critical factors – waste elimination, defect reduction, autonomous processes, and productive maintenance – were identified as the foundation for continuous improvement. These elements play a crucial role in reconciling the efficiency-driven approach of Industry 4.0 with the human-centric and sustainability-focused principles of Industry 5.0 (Breque et al., 2021).

> "The portion of people and culture is bigger because what needs to be changed is the habit, for example, the mindset of the ability to run machines autonomously, meaning minimum resources on the machine, minimizing downtime, defects, and waste." (Supply Chain Manager, Company 2)

> "Operational Excellence principles wield transformative influence in the realm of Industry 4.0, shaping Factory Operation 4.0 through the integration of total productive maintenance principles, the implementation of smart maintenance, and ushering in organizational and managerial changes that significantly accelerate the Industry 4.0 landscape." (Quality Manager, Company 2)

To further understand the macro perspective, an interview with the Head of the Industrial Technology Application Study Division at the Indonesian Ministry of Industry was conducted. The government's focus extends beyond firm-level operational concerns to the broader economic impact of Industry 4.0 adoption on Indonesia's GDP and industrial competitiveness. While automation and lean processes are key enablers, the transition to Industry 5.0 requires organisations to move beyond efficiency and consider sustainability, resilience, and workforce empowerment (Nahavandi, 2019).

Figure 7 Rich picture of Industry 4.0 transformation



> "We adopt mass customization that emphasizes the value creation from our manufacturing process and how to make our cost of goods sold lower than previously. That approach is supported by autonomous, speeding up cycle time, and reducing waste and defects." (GM Supply Chain, Company 3)

> "The cardinal principle in digitalization implementation is centered on waste reduction, emphasizing a strategic focus on SMED, inline processes, and time release reduction, encapsulated by the innovative concept of the plan circle time to expedite product releases. The intricate stages of transformation encompassing management, lean production, and digitalization delineate the roadmap, emphasizing the crucial role of building employee competencies and fostering a progressive mindset. Navigating the challenges and reaping the benefits of digital adaptation within manufacturing unveils a transformative journey toward enhanced efficiency and competitiveness." (Digital Manager, Company 1)

These findings highlight the complex interplay between strategic vision, operational execution, and cultural transformation, underscoring that Industry 4.0 adoption is not merely a technological shift but an organisational and managerial evolution. The rich picture analysis, illustrated in Figure 7, captures these interconnected concerns, showing how companies must integrate operational excellence with digitalisation strategies while preparing for Industry 5.0's human-centred and sustainable approach. Different stakeholders, such as directors, production managers, quality heads, human resource leaders, and external actors such as regulators, operate in interconnected domains characterised by similar issues and different agendas, as illustrated in the visual framework.

Table 2 List of problematic issues extracted from the rich picture

Issue number	*Issue captured in rich picture*
Issues regarding TPM and operational excellence	
1	Embarking on TPM implementation and striving for world-class manufacturing status before the 4.0 era
2	Comparing TPM with digitalisation in terms of methodology, impact, and ease of implementation
3	TPM in 2012 enhanced efficiency through overall equipment effectiveness (OEE)
4	Industry 4.0 is eliminating manual calculations, enabling real-time monitoring, and boosting productivity
5	Operational Excellence improving quality via TPM, IWS, and Y-Couch models
Issues regarding Industry 4.0 and digitalisation	
6	Evolution from digitisation to Industry 4.0 with lean production, robotic integration, and Kanban systems
7	Smart Maintenance, Quality, and Production reshaping world-class manufacturing post-Industry 4.0
8	Waste reduction as a core principle in digitalisation through SMED and inline processes
9	Digital transformation enhancing productivity and reducing customer complexity

Table 2 List of problematic issues extracted from the rich picture (continued)

Issue number	*Issue captured in rich picture*
Issues regarding business strategy and organisational change	
10	SAP's relocation as a transformative journey towards automation and productivity
11	Lean production and digitalisation are driving transformation and progressive mindsets
12	Shifting workforce culture to align with digitisation and competency development
13	Business renovation and simplification as a precursor to digitalisation
14	End-to-end data acquisition to prevent data fragmentation and ensure transparency
15	Technology implementation requires lean workflows before digitalisation
16	Business process revamping, reducing personnel, and transitioning roles
17	Transformation from operational to systemic thinking
Issues regarding Industry 4.0 and digitalisation	
18	Lean manufacturing strategies for reducing changeover time and improving productivity
19	Agile operations accelerating adaptation and enhancing assessment value
20	Challenges in selecting suitable technologies and real-time OEE calculations
21	Initial digitalisation implementation hurdles like machine data integration
22	Global assessments of technology adoption require data accuracy
23	Recognising failures in technology implementation as learning opportunities
24	QA transformation through digitalisation and integration with Oracle
25	Industry 4.0 enabling real-time inspection and diagnostic analysis
Issues regarding market and external factors	
26	Government assessment of Industry 4.0 for digital transformation monitoring
27	Ministry's role in evaluating and guiding digital transformation in industries
28	Small businesses struggling with patent technology adoption and budget constraints
29	Ministry role in accelerating digital transformation in smart factories
30	Indonesia 4.0 policy prioritising five key sectors in alignment with ASEAN

The rich picture illustrates the interconnected challenges and strategic considerations in Industry 4.0 transformation, emphasising the role of top management, operational execution, and workforce adaptation. While leaders focus on high-level objectives such as efficiency, investment, and competitive positioning, operational managers grapple with digital competency gaps, implementation hurdles, and mindset shifts. The transition towards Smart Factory and Industry 4.0 requires alignment between technological advancements and human capital development, particularly in bridging the digital knowledge gap across generations. Organisations can more easily diagnose bottlenecks, pinpoint cross-functional leverage points, and create a roadmap that addresses both technology modernisation and the development of human capabilities by incorporating insights from this rich picture into a larger transformation framework. By doing this, this systemic mapping aids in the creation of an integrated readiness model that is essential to robust and sustainable industrial advancement. Table 2 categorises key issues extracted from the rich picture, highlighting the complexity of digital transformation across TPM, operational excellence, business strategy, and external market factors.

4.3 Step 3: building root definitions of relevant systems

Building upon the rich picture analysis, CATWOE serves as a diagnostic lens through which key actors (customers, actors, transformation process, worldview, owners, and environmental constraints) are evaluated to derive contextualised pathways for transformation. The CATWOE analysis identifies key challenges and enablers in Industry 4.0 transformation across five dimensions: management and organisation, people and culture, factory operation, technology, and product and service. By comparing the INDI 4.0 model with practitioner insights, gaps between strategic vision and implementation emerge, particularly regarding operational excellence thinking as a foundation for digitalisation. Stakeholders emphasise that transformation begins with management and strategy, followed by operational improvements, factory operations, and technology adoption, with people and culture serving as a critical enabler. Unlike the INDI 4.0 model, which treats cultural aspects as supportive, industry experts highlight the need for competency classification and cultural readiness before transformation can succeed. This aligns with findings from Sony and Naik (2020), who emphasise that digital transformation requires an adaptive workforce, strong leadership, and cultural alignment to drive change effectively.

The CATWOE analysis, illustrated in Figure 6, highlights systemic misalignments, such as fragmented implementation, disconnected processes, and cultural resistance, reinforcing the importance of aligning digitalisation with operational excellence. Without a structured approach, companies risk interoperability issues, inefficiencies, and resistance from employees lacking digital competencies. Meanwhile, Table 3 presents a structured comparison between INDI 4.0 expectations and industry insights, revealing that practitioners prioritise defining transformation pain points and operational challenges before committing to investment and technology adoption.

More precisely, the worldview component of the management and organisation dimension shows that external directives like the ‘Making Indonesia 4.0’ plan cannot be the only factor driving change. Rather, internal ownership of the transformation goals, strategic alignment, and a common understanding of value creation among all leadership levels are necessary for successful adoption. For instance, strategic priorities and operational problems should guide investment decisions rather than a broad excitement for digital. These findings align with Schumacher et al. (2016), who argue that a lack of strategic alignment in Industry 4.0 initiatives often leads to isolated digitalisation efforts that fail to achieve intended productivity gains. Moreover, Breque et al. (2021) emphasise that Industry 5.0 requires an integrated approach that balances automation with human-centric considerations, supporting the findings that cultural resistance and digital competency gaps hinder transformation.

CATWOE highlights a crucial difference between competency development initiatives and the requirements for real transformation in the people and culture dimensions. Cultural readiness is not only beneficial but also fundamental, as demonstrated by waste reduction, defect prevention, and independent teamwork. Practitioners view culture as a facilitator of transformation that needs to be transformed through operational excellence practices such as TPM, Lean, and Six Sigma, in contrast to the static treatment in INDI 4.0. This supports Sony and Naik's (2020) claim that cultural inertia is a major barrier to change, especially when digital efforts take precedence over process readiness and staff capability development.

Findings from factory operation and technology dimensions indicate that poor system integration and operational silos hinder real-time decision-making, limiting the effectiveness of autonomous processes, smart supply chains, and predictive maintenance. Additionally, the product and service dimension highlights the tension between mass customisation and production efficiency, as firms struggle to balance consumer demands with resource constraints. These insights align with Frank et al. (2019), who highlight that while Industry 4.0 enables data-driven customisation, operational rigidity and high costs remain key barriers to its widespread adoption. Similarly, Kiel et al. (2017) identify organisational inertia and limited cross-functional collaboration as major challenges in digital transformation, reinforcing the need for an integrated, step-by-step approach to implementation.

Figure 8 CATWOE analysis (see online version for colours)

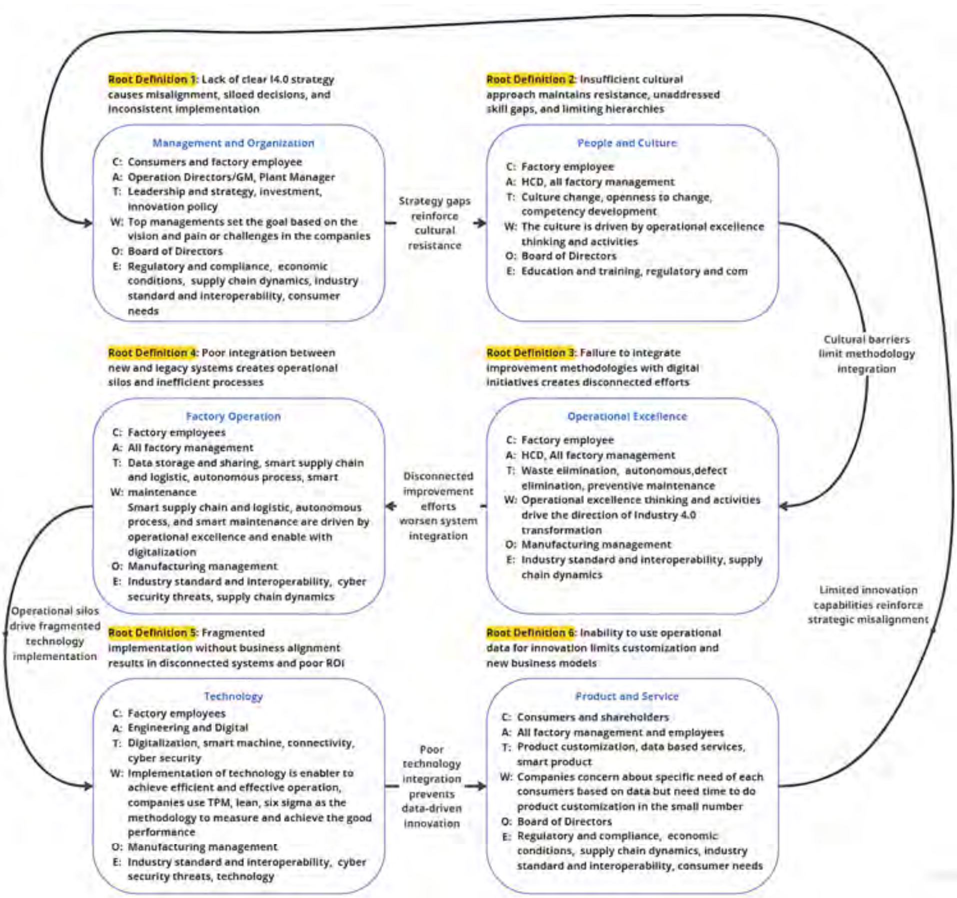


Table 3 Worldview of Industry 4.0 transformation from stakeholders

No.	*INDI 4.0 model*	*Input*	Output	*Worldview*
1. Management and organisation				
1.1	Strategy and leadership	Making Indonesia 4.0 program from the Ministry of Industry	1 Support from management to transform to Industry 4.0 2 Management understands the benefit of the transformation 3 Management defines strategy for the implementation	Top management set the goal and commit to reaching it with team members
1.2	Investment	Company strategy related to Industry 4.0 transformation	Companies have an appropriate investment for Industry 4.0 transformation	Investment can be defined after setting a goal, defining the pain, and prioritising the part of the operation that needs to be improved
1.3	innovation policy	Innovation policy and strategy from top management	1 Support from management for innovations 2 Good environment for innovation 3 Acknowledgement for innovation to increase companies competitiveness	Innovation can be defined from the pain of the process and the voice of consumers/customer
2. People and culture				
2.1	Competency development	Management's policy and implementation of competency development for employees	Companies develop competency for Industry 4.0 transformation, including training, certification, workshops, advanced study, problem solving, etc.	Competency development consists of: • Competency for the transformation • Competency to improve the process, including efficiency and effectiveness
2.2	Culture	Corporate culture that supports the transformation	Measurement of corporate culture, including on-time culture, consistency, continuous learning, etc. Those cultures impacts on the transformation	The culture is driven by operational excellence thinking and activities, including • Waste elimination that is built with loss tree analysis • Defect elimination as the quality factor • Autonomous • Preventif and predictive process (maintenance, production, quality)
2.3	Openness to change	Reference, advanced study and/or benchmarking from a previous lighthouse company	Open-minded for any changes, including technology to enable efficiency and effectiveness.	It is important to do benchmarking with other companies to know the steps to transform

Table 3 Worldview of Industry 4.0 transformation from stakeholders (continued)

No.	*INDI 4.0 model*	*Input*		Output	*Worldview*
3. Factory operation					
3.1	Data storage and sharing	Operation data, in the context of a smart factory, manufacturing and supply chain data	1	Company data for process optimisation as well as data-based services are already well managed.	Data storage, security, and sharing are the basic requirements of the Industry 4.0 transformation
			2	Apart from that process data storage, data transfer and the use of data already have a standard process.	
			3	There is data storage in the cloud or on one of the internal servers as measured in the storage area and sharing data	
3.2	Smart supply chain and logistics	Data and strategy of supply chain and logistics	1	Application monitoring technology and location, including incoming and outgoing goods, are examples from the application of supply chain and logistics intelligence	A smart supply chain is triggered by operational excellence and enabled by digitalisation
3.3	Autonomous processes	Current operation and future improvement	1	Refers to factory operations that are already autonomous both in the production process and in the process of taking decisions. For example, automatic process control and automatic machine operation based on big data analysis	Autonomous process is preceded by process pain mapping that is triggered by operational excellence culture
3.4	Smart maintenance system	Integration between internet and machine operation	1	For example, the process of operating the machine and machine maintenance that is already internet-based. There is a monitoring system for centralised engine performance (OEE) via the internet, diagnosis, and prognosis of machine condition to determine repair or replacement schedule (smart care).	Integration between machine, process, and internet has to be prepared with the implementation of 'conservative' performance measurement and improvement
4. Technology					
4.1	Cybersecurity	Cybersecurity policy, strategy, and implementation in the company	1	Internal security storage, transfering, and processing data also become important so that industry implementing Industry 4.0 must have systems and methods that guarantee that data-based connectivity is secured.	Basic requirement of digitalisation in a factory
4.2	Connectivity	Infrastructure and connectivity program	1	Refers to connectivity between machines or systems in a factory or between factories.	Prior to developing connectivity, pain and the need for the process must be measured and analysed
			2	Connectivity can also be the existence of real-time interconnection with vendors or with factories that become corporate partners	

Table 3 Worldview of Industry 4.0 transformation from stakeholders (continued)

No.	*INDI 4.0 model*	*Input*		Output	*Worldview*
4. Technology					
4.3	Smart machine	Data teaching and improvement plan	1	The existence of a machine or smart system that is already equipped with artificial intelligence and connection, interfaced by internet or intranet.	The objective of the manufacturing process should be defined first and developed with continuous improvement or operational excellence
			2	The machine or system can optimise parameters and sequence of operations independently.	
			3	Smart machines can also accommodate good collaboration between humans and machines or collaboration between machines/systems	
4.4	Digitalisation	Strategy and implementation of digitalisation in the company	1	Implementation of digital technology within the company, including process, product, and decision making. Example: digital factory, digital product, digital twin.	Digital factory is an enabler to achieve efficient and effective operation; companies use TPM, Lean, and Six Sigma as the methodology to measure and achieve good performance
5. Product and service					
5.1	Product customisation	Voice of consumers	1	Refers to products that are custom according to what is desired by consumers.	Mass customisation is something difficult in the food and beverage industry, but it's still possible to develop in the future.
			2	Products offered are not only one of a kind but also have options that custom suit request.	
5.2	Data-driven service	Services and business models of the company are developed based on the obtained data, both from the company's own data, similar companies, and data from consumers.	1	Service and business to consumer, which is driven by obtained data from the company, similar companies, and consumers	Companies are concerned about the specific needs of each consumer based on data but need time to do product customisation in the small number
5.3	Smart product	Product customisation concept from obtained data, consumers voice	1	Products that already have technology in them, as they already have an interface that can be connected with the internet, have features like data storage (RFID, barcodes, etc.)	All of the companies have not resulted in products with these features
			2	Smart products also mean products that are already integrated with sensors and programs that make it easier to use the product	

The widening gap between mass customisation and production efficiency is exemplified by the product and service dimension. Customers, according to CATWOE want new products, but environmental limitations, like industry inertia and market rules, make it difficult for businesses to provide connected and human-centred products. This bolsters the criticism made by Kiel et al. (2017) that the majority of Industry 4.0 deployments lack sufficient market-driven innovation cycles and are reactive.

Ultimately, while Industry 4.0 focuses on automation and efficiency, the transition towards Industry 5.0 will require a more holistic approach, integrating sustainability, adaptability, and human-centric design. The findings reinforce that successful digital transformation is not just about adopting technology but about creating an ecosystem where operational excellence, strategic investment, and workforce capability evolve together. By addressing cultural barriers, refining digitalisation strategies, and fostering cross-functional integration, companies can bridge the gap between vision and execution, ensuring long-term competitiveness in the evolving industrial landscape, as presented in Figure 8.

4.4 Step 4: conceptual model

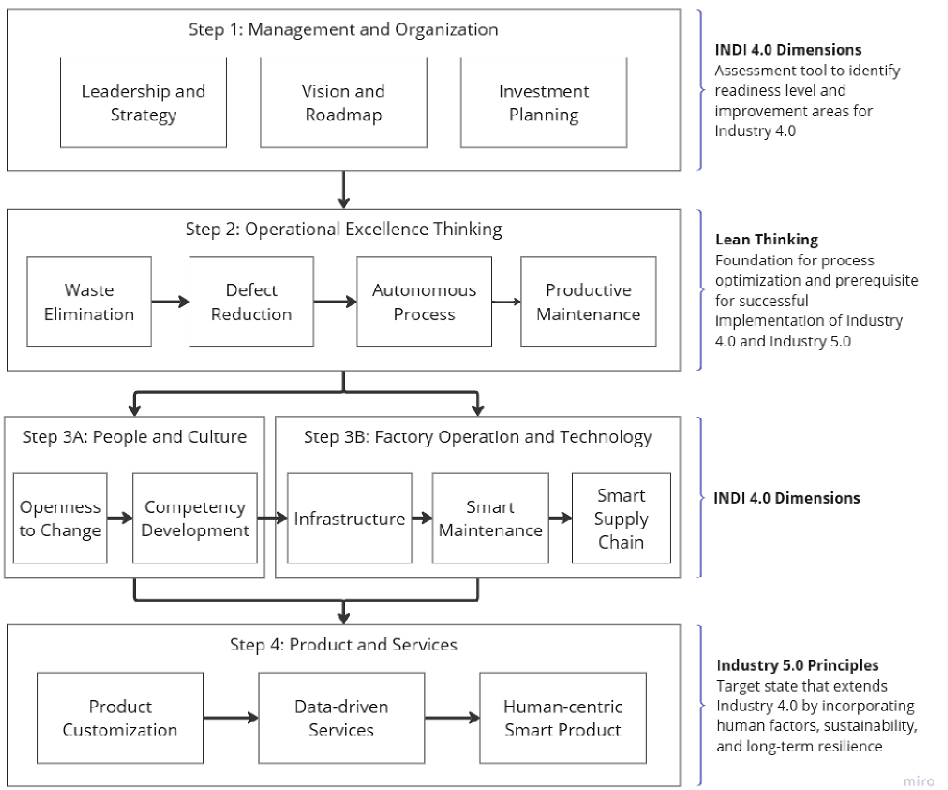
The proposed conceptual model, as shown in Figure 9, presents a structured transformation framework that integrates operational excellence principles with Industry 4.0 readiness while positioning companies for Industry 5.0 adoption. Unlike traditional digital transformation models that focus solely on automation and technology, this model highlights the critical role of LSS principles – waste elimination, defect reduction, autonomous processes, and productive maintenance – as foundational enablers for smart manufacturing. At the core of this model is the belief that the principles of lean thinking – such as waste elimination, defect reduction, and process autonomy – are not add-ons, but rather fundamental to achieving operational stability before digital intervention (Kumar et al., 2021).

A key feature of this model is its emphasis on the interplay between management and organisation, people and culture, factory operations, technology, and products and services. Step 1 initiates the transformation with management and organisational alignment, focusing on leadership vision, strategic objectives, roadmaps, and investment priorities, setting a clear direction for change. These elements echo Schumacher et al. (2016), finding that leadership commitment and clear priorities are critical factors for the success of digital transformation. Following this, step 2 embeds operational excellence principles to serve as a transitional bridge. Through structured initiatives such as autonomous process development and productive maintenance, organisations prepare the ground for seamless digital integration that guides digital adoption through process optimisation before full-scale automation.

Steps 3A and 3B acknowledge that transformation requires a supportive ecosystem that includes both individuals and technological infrastructure. In step 3A, the focus is on developing workforce adaptability, which remains a critical determinant of transformation success, addressing challenges related to competency development, openness to change, and digital upskilling (Nahavandi, 2019; Alviani et al., 2024).

Meanwhile, step 3B addressed the infrastructure aspect: adopting smart maintenance solutions, integrated supply chains, and digital manufacturing processes. These two actions represent the INDI 4.0 aspects of people, technology, and operations, and collectively they create the operational foundation for intelligent manufacturing. This structured approach ensures that technology adoption – such as smart maintenance, smart supply chains, and autonomous processes – is human-centred and resilient to external disruptions (Sony and Naik, 2020). The last phase, step 4, focuses on the results of products and services that adhere to the principles of Industry 5.0. In this context, attention moves from internal facilitators to external value generation via tailored, data-informed, and human-centred solutions. As highlighted by Breque et al. (2021), the future of manufacturing depends not solely on automation but also on solutions that address economic and societal objectives.

Figure 9 LSS-I4.0-I5.0 a new conceptual model for Industry 4.0 readiness and Industry 5.0 transition (see online version for colours)



This conceptual model not only enhances Industry 4.0 readiness but also serves as a roadmap for transitioning toward Industry 5.0, where sustainability, human-machine collaboration, and long-term resilience become strategic priorities. The integration of Industry 5.0 principles – human-centric smart products and data-driven services – ensures that technological advancements are leveraged not just for efficiency but also for social and environmental sustainability (Frank et al., 2019). By adopting this approach, companies in emerging economies like Indonesia can accelerate their transformation while mitigating the risks of misaligned digitalisation efforts. This model offers practical insights for policymakers and industry leaders, demonstrating how a balanced approach between operational excellence and digital innovation can drive sustainable industrial competitiveness.

4.5 Step 5: comparing models with reality

The fifth step of SSM involves comparing the developed conceptual model with the real-world situation in lighthouse companies to identify potential gaps and improvement opportunities. This comparison revealed several key insights regarding the implementation of Industry 4.0 and the transition toward Industry 5.0 in Indonesia's food and beverage sector.

Firstly, while the conceptual model emphasises the integration of LSS principles as a foundation for digital transformation, the real-world implementation often shows technological adoption preceding operational excellence initiatives. This sequencing creates efficiency gaps, as companies invest in automation before optimising underlying processes. As one Operations Director noted, "We realized that implementing smart technologies without first addressing process inefficiencies resulted in digitizing waste rather than eliminating it." This observation aligns with literature suggesting that operational excellence should precede technological implementation (Wang et al., 2022).

Secondly, the comparison highlighted a significant gap in workforce readiness and cultural adaptation. Although the conceptual model positions People and Culture as critical enablers, many lighthouse companies reported challenges in building digital competencies, particularly among senior employees. As shared by a Performance Manager, "The digital knowledge challenges among senior generations pose hurdles in technology adoption... integrating digital tools into a predominantly senior workforce environment becomes intricate." This reality emphasises the need for comprehensive human capital development strategies that address generational differences and foster a culture of continuous learning. This reinforces the call in the literature for tailored upskilling strategies and intergenerational learning ecosystems to support sustainable digital transformation (Sony and Naik, 2020).

Thirdly, the comparison revealed varying levels of alignment between transformation strategies and business objectives. While the conceptual model emphasises strategic alignment, real-world implementations often reflected siloed approaches where digitalisation efforts were not fully integrated with broader business goals. The Digital Manager from company 1 emphasised that "the cardinal principle in digitalization implementation is centred on waste reduction", highlighting that successful transformation initiatives are those directly addressing business pain points. This gap highlights the need for a transformation framework that links strategy, execution, and learning in an integrated cycle (Schumacher et al., 2016).

Finally, the comparison showed that companies further in their Industry 4.0 journey were beginning to incorporate elements of Industry 5.0, such as sustainability considerations and human-machine collaboration, though often without explicit recognition of these as Industry 5.0 principles. This suggests an organic evolution toward more human-centric and sustainable manufacturing practices, even as formal Industry 5.0 frameworks remain emergent. This is in line with Breque et al. (2021), who stated that Industry 5.0 can evolve organically from a mature Industry 4.0 environment when humanitarian values and long-term sustainability goals are prioritised.

4.6 Step 6: defining feasible and desirable changes

Based on the comparison between the conceptual model and real-world implementation, several feasible and desirable changes were identified to accelerate the transition toward Industry 5.0 in Indonesia's food and beverage sector, as presented in Table 4.

Table 4 Feasible and desirable changes for Industry 5.0 transition in the food and beverage sector

No.	*Change initiative*	*Description*	*Expected impact*
1	Sequential implementation approach	Companies should adopt a structured sequence for transformation, beginning with operational excellence initiatives (waste elimination, defect reduction, autonomous processes, and productive maintenance) before implementing advanced technologies.	Ensures digitalisation enhances optimised processes rather than automating inefficiencies. Creates a solid foundation for sustainable digital transformation.
2	Competency development framework	Organisations require a comprehensive competency framework that classifies required skills for Industry 4.0 and 5.0, distinguishes between technical and adaptive capabilities, and provides clear development pathways for employees at different organisational levels.	Addresses workforce readiness challenges, particularly the digital knowledge gap between generations. Supports systematic human capability development.
3	Cross-functional transformation teams	Cross-functional teams comprising representatives from operations, technology, quality, and human resources should be established to ensure holistic transformation approaches.	Reduces siloed implementation. Facilitates knowledge sharing and aligns digitalisation efforts with operational realities across the organisation.
4	Human-centric technology assessment	A framework for evaluating technologies based on their contribution to human capability enhancement rather than solely on efficiency gains.	Prioritises technologies that augment human skills, improve working conditions, and foster collaboration between employees and machines. Supports the shift from automation-centred to human-centred manufacturing.
5	Sustainability integration	Companies should explicitly incorporate sustainability metrics within their transformation frameworks, measuring not only economic gains but also environmental and social impacts.	Aligns transformation efforts with broader sustainability goals and societal impact. Ensures Industry 5.0 implementation addresses triple bottom line considerations.
6	Knowledge exchange platforms	Establishing formal mechanisms for knowledge sharing among lighthouse companies, academia, and industry associations.	Accelerates transformation by disseminating best practices, lessons learned, and implementation strategies across the sector. Reduces duplication of effort and common implementation errors.

Table 5 Strategic implementation planning

No.	*Action initiative*	*Description*	*Potential Risks*	*Priority (H/M/L)*	*Timeframe*
1	Operational excellence foundation program	Develop an industry-specific operational excellence framework that integrates Lean Six Sigma principles with the INDI 4.0 model.	Resistance to process changes before technology adoption Lack of skilled LSS practitioners in the region Difficulty in contextualising global frameworks to local conditions	High	Short-term (0–12 months)
2	Digital competency academy	Establish a collaborative industry-academia initiative focused on building digital skills among the workforce, with specialised tracks for different career stages and technical backgrounds.	Gap between academic curriculum and industry needs Limited engagement from senior employees Rapid technology changes are making training obsolete	High	Medium-term (6–18 months)
3	Transformation roadmap tool	Create a diagnostic and planning tool that helps companies assess their current state across operational excellence and digital readiness dimensions and generate customised transformation roadmaps.	Oversimplification of complex transformation processes One-size-fits-all approach despite unique company contexts Tool adoption without proper implementation support	Medium	Medium-term (12–24 months)
4	Industry 5.0 pilot projects	Implement a series of pilot projects within lighthouse companies that explicitly incorporate Industry 5.0 principles, particularly human-machine collaboration, sustainability, and resilience.	Resource constraints limiting scale and scope Difficulty measuring human-centric outcomes Challenges in scaling successful pilots	Medium	Medium-term (12–24 months)
5	Policy recommendations	Develop evidence-based policy recommendations for the Ministry of Industry to enhance the INDI 4.0 framework by incorporating operational excellence prerequisites and Industry 5.0 principles.	Policy implementation delays Changing political priorities Limited enforcement mechanisms	Low	Long-term (18–36 months)
6	Knowledge sharing platform	Establish a digital platform and regular industry forums where stakeholders can share transformation experiences, best practices, and implementation strategies.	Reluctance to share proprietary information Platform sustainability and maintenance challenges Varying levels of digital accessibility among stakeholders	High	Short-term (0–12 months)

These changes are both feasible, given the existing capabilities and commitments of lighthouse companies, and desirable, as they address identified gaps while advancing the transition toward human-centric, sustainable, and resilient manufacturing. Together, they offer a contextual and measurable roadmap to accelerate the transition from digitisation driven by efficiency to an inclusive and adaptive Industry 5.0 ecosystem.

4.7 Step 7: taking action to improve the situation

The final step of SSM involves implementing defined changes to improve the real-world situation. Based on the research findings and stakeholder engagements, six key action initiatives were identified to support food and beverage companies in Indonesia in accelerating their Industry 5.0 transformation. To enhance the actionability of these initiatives, a risk assessment and prioritisation framework has been developed, categorising each action based on its relative importance, implementation timeline, and potential challenges. Table 5 presents these action initiatives along with their supplementary analysis of risks and priorities, which can guide stakeholders in strategic implementation planning.

Implementation of these action plans would require collaborative efforts from multiple stakeholders, including company leadership, industry associations, government agencies, and academic institutions. The research findings suggest that such collaboration is essential for addressing the complex challenges of industrial transformation in emerging economies.

By following this structured approach based on SSM, food and beverage companies in Indonesia can accelerate their transformation journey toward Industry 5.0, building on operational excellence foundations to achieve sustainable, human-centric, and resilient manufacturing practices that enhance both competitiveness and societal impact.

5 Discussion

The analysis of lighthouse food and beverage companies in Indonesia reveals significant gaps between operational excellence capabilities and digital transformation readiness. A crucial point is made in the Rich Picture section about how strategic vision and execution competency are misaligned. Top executives proclaim goals of competitiveness, customer focus, and digital investment, but middle management often faces execution challenges due to suboptimal operational excellence practices, a legacy mindset, and a lack of digital competency, particularly among the older workforce. The lack of organised top-down tactics and the misalignment between Lean, TPM, and digital initiatives exacerbate this conflict. Additionally, the rich picture discussion reveals a range of pain points across managerial roles, ranging from system-level issues such as digital security, data validity, and autonomous operations to concerns about workforce adaptability (emphasised by human resource managers) and uncertainty about the value of technology (in quality and engineering functions). While these companies have achieved certification through the INDI 4.0 assessment, our findings indicate an incomplete integration between foundational operational practices and advanced technologies.

Most notably, companies often prioritise technological adoption without first establishing robust operational excellence frameworks, leading to what one Operations Director described as ‘digitising waste rather than eliminating it’. This gap aligns with observations by How and Cheah (2024), who emphasise that "to fully leverage the potential of technological advancements, companies must simultaneously invest in their human capital and cultivate a culture of operational excellence, recognizing that technology alone is insufficient to drive sustainable success." This represents a critical barrier to effective Industry 5.0 transformation, where technology should seamlessly augment human capabilities rather than create new inefficiencies. In summary, transformation readiness must be evaluated not only in terms of technological infrastructure but also in terms of cultural readiness, learning agility, and interdepartmental alignment. This aligns with the assertion that interdependence reflects a broader systems-thinking perspective (Senge, 1990).

Additionally, the CATWOE that applies to the INDI 4.0 dimensions supports practical insights for practitioners and policymakers. In particular, transformation must be anchored in clearly defined pain points, competency-driven cultural alignment, and performance measurement frameworks grounded in LSS and TPM. Prior to investing in automation and digital technology, this must also follow a methodical and recursive process that starts with operational excellence, strategy formulation, and people preparedness. The interdependence of organisational subsystems is highlighted by this systems perspective (Senge, 1990), which cautions against the solitary adoption of technology without balancing structural, cultural, and human elements. In order to move toward Industry 5.0, where flexibility, sustainability, and human-centricity become key pillars, these enablers provide a capability-driven roadmap (Ghobakhloo et al., 2024). In summary, the CATWOE comparison shows that transformation preparedness is a multifaceted process encompassing cultural change, strategy coherence, and basic operational maturity rather than just technology deployment. Bridging the gap between conceptual ideals and real-world complexities requires an adaptive, human-centred transformation pathway – particularly relevant in developing countries like Indonesia, where capacity building and contextual adjustments are crucial.

A second notable gap exists in the current industry readiness models, which inadequately address the sequencing relationship between operational excellence and digital transformation. The INDI 4.0 framework, while comprehensive in assessing technological and organisational dimensions, does not explicitly position process optimisation as a prerequisite for successful digitalisation. This omission creates a strategic blind spot, as companies may invest in advanced technologies without first optimising underlying processes through waste elimination, defect reduction, autonomous processes, and productive maintenance. As Sgarbossa et al. (2020) argue, "integrating human factors into planning models is crucial, as neglecting their impact on system or employee performance leads to inaccurate planning and underperforming systems." This aligns with Daniel et al. (2024), who found that the combination of Industry 4.0 technologies with lean manufacturing techniques enhances operational performance and promotes sustainability goals. Their results support the idea that LSS offers a crucial basis for long-term digital transformation by reaffirming the necessity of organised capability development and waste reduction frameworks before the adoption of digital technologies. Our study addresses this gap by introducing a novel integrated framework that embeds LSS principles within the digital readiness assessment, establishing a clear implementation sequence that begins with operational excellence before progressing to technological adoption.

Table 6 Comparison of Industry 4.0 readiness/maturity

Model	*Origin*	*Core dimension*	*Readiness level*	*Strength*	*Focus*
INDI 4.0 + LSS + Industry 5.0 (LSS-I4.0-I5.0)	Indonesia/authors	Management, operational excellence, people and technology, product and services	Sequential stages with enabling logic	Integrates LSS, INDI 4.0 and Industry 5.0 into one practical roadmaps	Sequential transformation aligned with operational maturity and human-centric outcomes
IMPULS Industry 4.0	Germany/Acatech	Strategy, smart factory, smart operations, smart products, data services, people	0–5 (outsider to top performer)	Detailed evaluation and benchmarking for manufacturing firms	Benchmarking current digital capability and planning for Industry 4.0
Singapore SIRI	Singapore/EDB	Process, technology, organisation	0–5 across sub-dimensions	Government-backed, broad adoption across Asia-Pacific	Self-assessment and strategy planning for SMEs
I4AMM	Malaysia/SIRIM Berhad	Strategy and organisation, process and operations, people and culture, technology	1–5 (pre-digital to smart organisation)	Tailored to local SME context and focus in enablers and barriers	Capability maturity for SMEs and digital ecosystems readiness
Schumacher et al. (2016)	Germany/academic	Strategy, resources, organisation, culture, information system	6 maturity stages (computerisation to adaptability)	Conceptual clarity, strategic and cultural integration focus	Theoretical structure for maturity modeling

The novelty of our research lies in its holistic integration of operational and digital domains within a structured transformation roadmap specifically tailored for emerging economies. Unlike existing models that typically originate from developed economies with mature industrial infrastructure, our framework acknowledges the unique challenges faced by manufacturers in nascent digital ecosystems. By embedding LSS methodologies within the INDI 4.0 assessment, our model provides a practical pathway for companies to enhance process efficiency before implementing advanced technologies. This approach responds to what Alviani et al. (2024) describe as a "paradigm shift, compelling organisations to fundamentally re-evaluate their strategies, processes, and management practices to not only survive but also thrive in an increasingly dynamic and competitive landscape." The framework is particularly relevant for economies like Indonesia, where resource constraints necessitate strategic prioritisation of improvement initiatives.

Furthermore, our research contributes to the emerging discourse on Industry 5.0 by positioning human-centric considerations at the core of digital transformation. While Industry 4.0 frameworks predominantly focus on automation and cyber-physical systems, our integrated model emphasises the critical role of human capability development and adaptation. This is aligned with Mangler et al. (2021), who advocate for "a re-evaluation of human-machine interaction, moving away from the notion of humans as mere operators towards a collaborative partnership where human cognition and skills are leveraged alongside advanced technologies." The proposed competency development framework addresses this human dimension of transformation, ensuring that technological implementation is supported by appropriate workforce capabilities and cultural readiness.

A significant finding from our study is the critical role of cultural transformation as both an enabler and a potential barrier to Industry 5.0 adoption. Lighthouse companies consistently identified that successful digital implementation hinged on workforce adaptability and openness to change. As one Human Capital Manager noted, "The portion of people and culture is bigger because what needs to be changed is the habit." This reflects Hozdić and Makovec's (2023) observation about "the evolution of the human role in manufacturing systems," which necessitates "a workforce equipped with advanced technical skills, problem-solving capabilities, and adaptability to navigate the complexities of interconnected systems and data-driven decision-making." Traditional readiness models often treat culture as a secondary consideration, but our research positions it as a fundamental prerequisite for transformation. The proposed model addresses this by incorporating cultural development as an integral component of the readiness assessment, recognising that technological adoption without corresponding cultural evolution is unlikely to achieve desired outcomes.

Finally, our research makes a practical contribution by providing a structured transformation roadmap that bridges the gap between operational excellence and Industry 5.0 implementation. By identifying specific action initiatives with associated risks and prioritisation, the model offers actionable guidance for both industry practitioners and policymakers. This addresses what Vogler et al. (2024) identify as the need for "a redesign of the distribution of roles between humans and machines, influencing not only industrial processes but also the requirements for human-resource management and personnel development." The potential impact extends across multiple domains: at the firm level, our sequenced approach provides manufacturers with a diagnostic tool to assess transformation readiness before technology adoption; at the policy level, our findings can inform revisions to national Industry 4.0 frameworks to incorporate operational excellence prerequisites; and for educational institutions, our competency framework provides a blueprint for curriculum design bridging traditional operations management and emerging digital skills. The sequenced approach – beginning with operational excellence foundations, progressing through digital competency development, and culminating in human-centric smart manufacturing – offers a practical roadmap for sustainable transformation. This structured methodology responds to Roblek et al.'s (2021) characterisation of Industry 4.0 as a 'disruptive innovation' requiring careful management and is particularly valuable for emerging economies navigating the complex transition from traditional manufacturing to digital and ultimately human-centric industrial paradigms.

Table 6 offers a comparative overview of the most important Industry 4.0 readiness and maturity models in order to summarise the results and place the suggested framework within the global conversation. This includes the academic model by Schumacher et al. (2016) as well as well-known frameworks in advanced and emerging countries, like IMPULS (Germany), SIRI (Singapore), and I4AMM (Malaysia). The genesis, fundamental dimensions, readiness level definitions, strengths, and strategic focus of each model are taken into consideration while evaluating it.

The LSS-I4.0-I5.0 model presents a phased transformation roadmap that incorporates LSS, operational excellence, and human-centric considerations in line with Industry 5.0 concepts, in contrast to previous models that primarily highlight technological or strategic issues. This comparison draws attention to each model's unique contributions as well as its similarities. Although I4AMM is designed for Malaysia's SME ecosystem and IMPULS and SIRI offer strong benchmarking capabilities for advanced economies, the suggested model closes a significant gap by clearly tying process excellence, digital readiness, and cultural transformation into a single framework. It also includes a phased readiness logic that addresses the implementation gaps found in lighthouse companies by giving foundational improvements priority over digitalisation.

6 Conclusions

This study presents a novel, integrated framework that bridges operational excellence and Industry 4.0 readiness to accelerate the transition toward Industry 5.0 in Indonesia's food and beverage sector. By employing Soft System Methodology and enriched by practitioner insights from lighthouse companies, the research reveals critical gaps in current transformation approaches, particularly the disconnect between process optimisation and technological adoption. While current readiness models such as INDI 4.0 provide diagnostic guidance, they often lack prescriptive sequencing – resulting in digitisation efforts that automate inefficiencies rather than eliminate them.

The proposed model addresses these limitations by embedding LSS principles – waste elimination, defect reduction, autonomous processes, and productive maintenance – within the INDI 4.0 framework, establishing a structured sequence for implementation that positions operational excellence as a prerequisite for digital transformation. Our findings emphasise that successful transformation extends beyond technological infrastructure and requires deliberate investment in human capability development, cultural adaptation, and sustainability considerations. The principles of Industry 5.0 – human-machine collaboration, sustainability, and resilience – demand a shift from a paradigm that is entirely technology-centric to one that is rooted in human capabilities and organisational adaptability.

The unique contribution of this research lies in its capability-driven sequencing approach that provides a practical roadmap for companies to navigate the complex transformation journey, focusing on both operational and organisational dimensions. As Indonesia continues its transition toward an advanced industrial ecosystem, this integrated approach offers a pathway for companies to achieve not only increased automation and connectivity but also enhanced human-machine collaboration, workforce empowerment, and sustainable manufacturing practices that align with the human-centric vision. The model essentially reinterprets transformation readiness as an evolution driven by capabilities that responds to the new demands of Industry 5.0.

For the practitioners and policymakers, this framework offers practical guidance for navigating challenging transformation journeys. It emphasises that investing in technology alone will not be enough to successfully navigate Industry 4.0 and Industry 5.0 efforts. Instead, businesses must first empower their employees, develop procedural discipline, and encourage cross-functional collaboration. The roadmap suggested in this study provides a series of actions managers can take to evaluate and improve their current transformation efforts, from competency mapping and cultural readiness to implementing sustainability measures.

7 Limitation and future research

Despite its contributions, this study has several limitations that present opportunities for future research. First, our analysis focused exclusively on lighthouse companies in Indonesia's food and beverage sector, which may limit the generalisability of findings to other industries or regions with different manufacturing characteristics and digital maturity levels. Future studies should extend this research across diverse industrial sectors and geographical contexts to validate the proposed model's applicability.

Second, while the Soft System Methodology provided rich qualitative insights, the study lacks quantitative measurements of transformation outcomes, making it difficult to precisely evaluate the impact of operational excellence on digital transformation success. Future research should develop mixed methods and conduct longitudinal studies to quantitatively assess how the sequencing of operational excellence and digital initiatives affects implementation outcomes. Following these guidelines, the authors intend to use the analytical hierarchy process (AHP) to perform a quantitative validation of the suggested LSS-I4.0-I5.0 model. Twenty important stakeholders from the lighthouse companies will be involved in this follow-up study, which will allow the model's primary dimensions and subcomponents to be prioritised and weighted. The model's suitability as a transformation preparation tool for emerging economies will be strengthened by this AHP-based validation, which will aid in evaluating the model's internal consistency, practical relevance, and strategic alignment across a range of operational responsibilities.

Third, the action plan proposed in this study, though comprehensive, would benefit from practical validation through implementation case studies. Future research should focus on documenting the implementation of this integrated approach in real-world settings, tracking both challenges and success factors. Additionally, as Industry 5.0 continues to evolve, further exploration is needed on specific human-machine collaboration models that optimise both technological efficiency and human well-being, particularly in labour-intensive sectors like food and beverage manufacturing. Finally, future studies should investigate how policy frameworks can better integrate operational excellence principles with digital readiness assessments to create more effective national transformation strategies in emerging economies.

Declarations

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

The authors conduct consent declaration to the participants that they agree to be interviewed for this project and received a detailed explanation regarding what will be done during the interview process and understand that the interview or research process as a whole will not have any negative impact on their selves. They aware that the confidentiality of the research will be maintained by the authors and that the information provided will only be used for research purposes.

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References

Al Harassi, N. (2017) *Soft Systems Model (SSM)*, pp.1–26, IGI Global, PA, USA.

Ali, I., Nguyen, K. and Oh, I. (2025) ‘Systematic literature review on Industry 5.0: current status and future research directions with insights for the Asia Pacific countries’, *Asia Pacific Business Review*, pp.1–28, DOI: 10.1080/13602381.2025.2452877.

Alviani, F., Prabowo, H. and Yuliana, L. (2024) ‘Reframing Industry 5.0 for emerging economies: operational transformation in human-centric systems’, *Asia Pacific Journal of Innovation and Entrepreneurship*, https://doi.org/10.1108/APJIE-10-2023-0147.

Anackovski, F. and Pasic, R. (2020) ‘Impact of Industry 4.0 on achieving operational excellence in lean production: real-time OEE monitoring systems’, *Knowledge International Journal*, Vol. 4, No. 2, pp.1–8.

Breque, M., De Nul, L. and Petridis, A. (2021) ‘Industry 5.0: towards a sustainable, human-centric, and resilient European industry’, *Publications Office of the European Union*, p.48, https://doi.org/10.2777/308407.

Business Indonesia (2024) ‘Indonesia’s F&B sector to continue to grow in 2023, 2024’ [online] https://businessindonesia.org/news/indonesias-fb-sector-to-continue-to-grow-in-2023-2024 (accessed 10 August 2025).

Central Bureau of Statistics Indonesia (2023) *Official Statistic Publication (Badan Pusat Statistik)* [online] https://www.bps.go.id/id/publication/2023/02/28/18018f9896f09f03580a614b/statistik-indonesia-2023.html (accessed 13 April 2025).

Checkland, P. (1990) *Systems Thinking, Systems Practice*, Wiley, Chichester.

Chentoufi, S.A. and Ennadi, A. (2023) 'Analysis of the implementation of the LSS approach in Moroccan services: benefits, tools, difficulties, critical success factors', *International Journal of Services and Operations Management*, Vol. 48, No. 1, pp. 1–22. https://doi.org/10.1504/IJSOM.2023.10062576.

Clancy, R., Bruton, K., O'Sullivan, D. and Cloonan, A.J. (2022) 'The HyDAPI framework: a versatile tool integrating Lean Six Sigma and digitalization for improved quality management in Industry 4.0', *International Journal of Lean Six Sigma*, Vol. 13, No. 5, pp.1109–1128, https://doi.org/10.1108/IJLSS-09-2021-0147.

Dahlgaard, J.J. and Dahlgaard-Park, S.M. (2006) 'Lean production, six sigma quality, TQM, and company culture', *The TQM Magazine*, Vol. 18, No. 3, pp.263–281, https://doi.org/10.1108/09544780610659998.

Daniel, N.A., Pathak, A., Ravichandran, P., Adith, S.V. and Kumar, N. (2024) 'Analyzing the role of Industry 4.0 in sustainable lean manufacturing', *International Journal of Services and Operations Management*, Vol. 48, No. 1, pp.62–79, https://doi.org/10.1504/IJSOM.2024.138592.

Dascalu, N-M. and Pislaru, M. (2025) 'Digital Lean manufacturing in the textile industry', in *Proceedings of the 19th Romanian Textiles and Leather Conference*, Gheorghe Asachi Technical University of Iași, Iași, Romania, 7–9 November 2024, pp.307–315, DOI: 10.2478/9788367405829045.

Dave, D.K., Murugesh, R., and Devadasan, S.R. (2015) 'Origin, principles, and applications of the Lean Six Sigma concept: extractions from the literature arena', *International Journal of Services and Operations Management*, Vol. 22, No. 2, pp.123–142, https://doi.org/10.1504/IJSOM.2015.071526.

Delahoz-Dominguez, E., Fontalvo-Herrera, T. and Zuluaga-Ortiz, R. (2024) 'A Six Sigma approach for package management process in a courier company', *International Journal of Services and Operations Management*, Vol. 47, No. 2, pp.198–210, https://doi.org/10.1504/IJSOM.2024.136794.

Duggan, K. (2011) *Design for Operational Excellence: 'A Breakthrough Strategy for Business Growth'*, pp.1–304, McGraw-Hill Education, NY, USA.

European Commission (2021) 'Industry 5.0: Towards a sustainable, human-centric and resilient European industry', pp.3–44, Directorate-General for Research and Innovation, European Commission, Brussels.

Fernández-Caramés, T.M. and Fraga Lamas, P. (2024) 'Forging the industrial metaverse – where Industry 5.0, augmented and mixed reality, IIoT, opportunistic edge computing, and digital twins meet', *IEEE Access*, Vol. 3, Article no. 3422109, pp.1–25, https://doi.org/10.1109/ACCESS.2024.3422109.

Frank, A.G., Dalenogare, L.S. and Ayala, N.F. (2019) 'Industry 4.0 technologies: implementation patterns in manufacturing companies', *International Journal of Production Economics*, Vol. 210, pp.15–26, https://doi.org/10.1016/j.ijpe.2019.01.004.

Ghobakhloo, M., Fathi, M. and Nazemi, S. (2024) 'Building operational antifragility through a sequenced Industry 4.0 roadmap: enhancing organizational resilience', *International Journal of Production Economics*, Vol. 296, Article 107123, https://doi.org/10.1016/j.ijpe.2024.107123.

Gomaa, A.H. (2025) 'Achieving maintenance excellence in manufacturing through integration of Lean Six Sigma and proactive approaches: a case study', *International Journal of Inventive Engineering and Sciences (IJIES)*, Vol. 1, No. 1, pp.1–14, https://doi.org/10.35940/ijies.B1099.12030325.

Hasbullah, H. and Bareduan, S.A. (2024) 'Identifying weaknesses and strengths of existing Industry 4.0 readiness indices to enhance INDI 4.0', *Sinergi*, Vol. 28, No. 1, pp.129–140, https://doi.org/10.22441/sinergi.2024.1.013.

Hasbullah, H., Bareduan, S.A. and Hasibuan, S. (2022) 'A maturity model of I4.0 in developing country: challenges and enablers in Indonesia for using INDI 4.0 as a measuring instrument', *AIP Conference Proceedings*, Vol. 2566, No. 1, Article ID 050003, https://doi.org/10.1063/5.0110246.

How, Y.H. and Cheah, M. (2024) 'Integrating human capability development with digital transformation: pathways for sustainable smart manufacturing', *Journal of Manufacturing Technology Management*, Vol. 35, No. 2, pp.268–290, https://doi.org/10.1108/JMTM-06-2023-0224.

Hozdić, E. and Makovec, D. (2023) 'The rise of cognitization in Industry 5.0: human-centric and cognitive automation in manufacturing systems', *Procedia CIRP*, Vol. 116, pp.388–393, https://doi.org/10.1016/j.procir.2023.03.066.

Ibrahim, A. and Kumar, G. (2024) 'Selection of Industry 4.0 technologies for Lean Six Sigma integration using the fuzzy DEMATEL approach', *International Journal of Lean Six Sigma*, Vol. 15, No. 3, pp.1025–1042, https://doi.org/10.1108/IJLSS-05-2023-0090.

Indonesia Ministry of Industry (2018) 'Making Indonesia 4.0: Roadmap for digital transformation in manufacturing industries', pp.1–15, Ministry of Industry, Republic of Indonesia, Jakarta, Indonesia.

Islam, M.T., Sepanloo, K., Woo, S., Woo, S.H. and Son, Y-J. (2025) 'A review of the Industry 4.0 to 5.0 transition: exploring the intersection, challenges, and opportunities of technology and human-machine collaboration', *Machines*, Vol. 13 No. 4, Article 267, https://doi.org/10.3390/machines13040267.

Kagermann, H., Wahlster, W. and Helbig, J. (2013) 'Recommendations for implementing the strategic initiative Industry 4.0', pp.22–79, National Academy of Science and Engineering, Frankfurt, Germany.

Kearney, A.T. (2019) 'Readiness for the Future of Production Report 2018', *World Economic Forum*, pp.6-253, Geneva, Switzerland.

Khillar, S. (2021) 'Difference between methodology and framework', *DifferenceBetween.net* [online] http://www.differencebetween.net/technology/difference-between-methodology-and-framework (accessed 10 January 2024).

Kiel, D., Arnold, C. and Voigt, K.I. (2017) 'The influence of the industrial internet of things on business models of established manufacturing companies: a business model perspective', *Industrial Management and Data Systems*, Vol. 117, No. 9, pp.1947–1968, https://doi.org/10.1108/IMDS-11-2016-0491.

Kraaijenbrink, J. (2023) 'What is Industry 5.0, and how will it radically change your business strategy?', BINUS University – Industrial Engineering [online] https://ie.binus.ac.id/2023/09/08/what-is-industry-5-0-and-how-it-will-radically-change-your-business-strategy/ (accessed 8 August 2024).

Kumar, P., Bhadu, J., Singh, D. and Bhamu, J. (2021) 'Integration between lean, Six Sigma, and Industry 4.0 technologies', *International Journal of Six Sigma and Competitive Advantage*, Vol. 13, No. 2, pp.124–145, https://doi.org/10.1504/IJSSCA.2021.116738.

Mangler, J. et al. (2021) 'Sustainability through cognition aware safety systems – next level human machine interaction', https://doi.org/10.48550/arXiv.2110.07003.

Montgomery, D.C. (2013) *Introduction to Statistical Quality Control*, 7th ed., p.754, John Wiley and Sons, USA.

Nahavandi, S. (2019) 'Industry 5.0 – a human-centric solution', *Sustainability*, Vol. 11, No. 16, p.4371, https://doi.org/10.3390/su11164371.

Nakajima, S. (1988) *Introduction to TPM: Total Productive Maintenance*, p.129, Productivity Press, USA.

Ohno, T. (1988) *Toyota Production System: Beyond Large-Scale Production*, Diamond Inc., Tokyo, Japan.

Ojha, K. and Deen, S. (2024) 'Applying lean practices in the retail lending sector of a bank in Trinidad and Tobago: a case study', *International Journal of Services and Operations Management*, Vol. 47, No. 2, pp.211–235, https://doi.org/10.1504/IJSOM.2024.136799.

Rahmatulloh, I., Noviaristanti, S. and Awaluddin, M. (2024) 'Industry 4.0 readiness and roadmap in the food industry: insights from Indonesian manufacturing enterprises using explanatory sequential mixed-method design', *Eduvest Journal of Universal Studies*, Vol. 4, No. 2, pp.398–416.

Rajnai, Z. and Kocsis, I. (2018) 'Labor market risks of Industry 4.0, digitization, robots, and AI', *Multidisciplinary Aspects of Production Engineering*, Vol. 1, No. 1, pp.335–346, https://doi.org/10.2478/mape-2018-0043.

Rame, R., Purwanto, P. and Sudarno, S. (2024) 'Industry 5.0 and sustainability: an overview of emerging trends and challenges for a green future', *Innovation and Green Development*, Vol. 3, No. 4, Article No. 100173, https://doi.org/10.1016/j.igd.2024.100173.

Roblek, V., Meško, M., Pušavec, F. and Likar, B. (2021) 'The role and meaning of the digital transformation as a disruptive innovation on small and medium manufacturing enterprises', *Frontiers in Psychology*, Vol. 12, Article 592528, https://doi.org/10.3389/fpsyg.2021.592528.

Russell, R.H. and Koch, J.J. (2009) *Operational Excellence: The New Lever for Profitability and Competitive Advantage*, pp.1–24, Palladium Group, VA, USA.

Saunders, M., Lewis, P. and Thornhill, A. (2019) *Research Methods for Business Students*, 8th ed., Pearson Education Limited, Harlow.

Schumacher, A., Erol, S. and Sihn, W. (2016) 'A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises', *Procedia CIRP*, Vol. 52, pp.161–166, https://doi.org/10.1016/j.procir.2016.07.040.

Sekaran, U. and Bougie, R. (2016) *Research Methods for Business: A Skill-Building Approach*, 7th ed., Wiley, Chichester.

Senge, P.M. (1990) *The Fifth Discipline: 'The Art and Practice of the Learning Organization'*, Doubleday, New York.

Sgarbossa, F., Grosse, E.H. and Neumann, W.P. (2020) 'Human factors in production and logistics systems of the future', *Annual Reviews in Control*, pp.1–11, https://doi.org/10.1016/j.arcontrol.2020.04.007.

Sony, M. and Naik, S. (2020) 'Critical factors for the successful implementation of Industry 4.0: a review and future research direction', *Production Planning And Control*, Vol. 31, No. 10, pp.799–815, https://doi.org/10.1080/09537287.2019.1691278.

Stratechi (2024) *Six Sigma* [online] https://www.stratechi.com/six-sigma/ (accessed 21 July 2025).

Surindra, M.D., Caesarendra, W., Krolczyk, G. and Gupta, M.K. (2024) 'Challenges of implementing Industry 4.0 in developed and developing countries: a comparative review', *Journal of Manufacturing Technology Management*, Vol. 34, No. 9, pp.47–66, https://doi.org/10.1108/JMTM-12-2022-0521.

Tissir, Y., Benabbou, L. and El Barak, K. (2024) 'A hybrid approach for Lean Six Sigma and Industry 4.0 integration: toward operational excellence in smart manufacturing', *International Journal of Advanced Operations Management*, Vol. 16, No. 2, pp.101–122, https://doi.org/10.1504/IJAOM.2024.100557.

Urick, M.J. and Adams, D. E. (2017) 'Taylorism and operational excellence: improving on the 'one best way'', *Journal of Leadership and Management*, Vol. 9, No. 10, pp.17–21.

Verma, D. (2024) 'Industry 5.0: a human centric and sustainable approach to industrial development', *International Journal of Social Relevance & Concern*, Vol. 12, No. 5, pp.17–21, https://doi.org/10.26821/IJSRC.12.5.2024.120507.

Vlachopoulos, D.I. and Dimitriadis, S.G. (2025) 'Promoting operational excellence in organizations: a review of recent trends in the modern manufacturing business context', *International Journal of Services and Operations Management*, https://doi.org/10.1504/IJSOM.2025.10070620.

Vogler, A. et al. (2024) 'Towards a QBLM based qualification management methodology supporting human resource management and development', *Information*, Vol. 15, No. 10, p.600, https://doi.org/10.3390/INFOh501000600.

Vyhmeister, E. and Castané, G.G. (2024) 'When industry meets trustworthy AI: a systematic review of AI for Industry 5.0', *ACM Comput. Surv*., Vol. 1, No. 1, pp.1–33.

Wang, F.K., Rahardjo, B. and Rovira, P.R. (2022) 'Lean Six Sigma with value stream mapping in Industry 4.0 for human-centered workstation design', *Sustainability*, Vol. 14, No. 6, p.3395, https://doi.org/10.3390/su14063395.

Wankhede, V.A., Sangle, S. and Yadav, N. (2023) 'Lean digital transformation for Industry 5.0: a case-based framework for waste elimination and human-machine collaboration', *International Journal of Lean Six Sigma*, https://doi.org/10.1108/IJLSS-03-2023-0073.

Womack, J.P. and Jones, D.T. (2003) 'Lean thinking: Banish waste and create wealth in your corporation', *Journal of the Operational Research Society*, pp.1–8, https://doi.org/10.1038/sj.jors.2600967.

World Economic Forum & A.T. Kearney (2018) *Readiness for the Future of Production Report 2018, Insight Report*, pp.1–31, World Economic Forum, Cologny/Geneva.

Yin, R.K. (2018) *Case Study Research and Applications: Design and Methods*, 6th ed., Sage Publications.