Demystifying the Lean 6.0 concept: integrating Industry 6.0 technologies with lean culture for innovation

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Abstract

Purpose – This research paper aims to examine how companies are preparing to adopt Industry 6.0 (I6.0) and Lean Culture by identifying challenges, best practices, and the maturity of their integration with Knowledge Management (KM). It proposes the concept of Lean 6.0, which integrates Lean principles with advanced and sustainable I6.0 technologies to promote the creation, preservation, and dissemination of organisational knowledge.

Design/methodology/approach – Data were collected through a questionnaire survey. Based on 103 valid responses, Covariance-Based Structural Equation Modelling (CB-SEM) was used to test four hypothesised relationships among Lean, I6.0, and KM.

Findings – The findings suggest that companies with higher Lean maturity are more likely to successfully adopt I6.0 practices, which support knowledge preservation and dissemination through technologies such as Artificial Intelligence, the Internet of Things, and Digital Twins.

Practical implications – The findings integrate human and technological dimensions within I6.0, demonstrating that the synergy between Lean and I6.0 strengthens knowledge management and fosters sustainable innovation in organisations.

Originality/value – This study provides an integrated investigation of Lean Culture and I6.0, highlighting their combined effects on Knowledge Management.

Keywords Knowledge management, Lean culture, Hyper-automation, Human-robotic collaboration

Paper type Research article

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1. Introduction

Throughout history, gradual updates have been pursued to achieve efficient production and quick responses to customer demand (Duggal *et al.*, 2022). Industry 4.0 introduced smart and interconnected technologies (Pandey *et al.*, 2023; Hansen *et al.*, 2024; Emon and Khan, 2025) to reduce manufacturing lead times (Kaswan *et al.*, 2024), including cyber-physical systems (CPS), AI, machine learning (ML), IoT, Big Data, among other technologies (Khan *et al.*, 2023; Zheng *et al.*, 2023). Expanding on this concept, Industry 5.0 (I5.0) emerged, bringing human centrality (Passalacqua *et al.*, 2025; Tengblad *et al.*, 2026) and social and environmental considerations, along with greater flexibility and adaptability to improve the efficiency and effectiveness of organisational processes (Xu *et al.*, 2021a, b; Ivanov *et al.*, 2019; Hansen *et al.*, 2024; Kaswan *et al.*, 2026).

More recently, the need for deeper integration between human factors and technologies, such as robots, has given rise to Industry 6.0 (I6.0), an advancement of I5.0 characterised by hyper-automation and near-complete machine autonomy (Singh *et al.*, 2023). While I5.0 already considered automated processes with significant technological support, the Era of I6.0 will be characterised by machines' complete independence (Duggal *et al.*, 2022). In this context, I6.0 can be defined as the combination of human-centred concepts, established by I5.0, with the introduction of hyper-automation of activities and human-robot collaboration (Anandraj, 2024), employing technologies such as generative AI and quantum computing (Shahin *et al.*, 2026), with a renewed focus on sustainability (Xuan, 2025; Shahin *et al.*, 2026).

In line with I6.0 definitions, Lean Culture (LC) is a key enabler of the practical application of I6.0, as it creates value and eliminates waste through initiatives led by trained and motivated employees (Womack *et al.*, 1990; Gatell and Avella, 2024), embedding organisational values in daily practices and aligning with I6.0's human-centred orientation (House *et al.*, 2004).

Previous studies have examined I6.0 through hyper-automation, sustainability, and human-centred manufacturing (Singh *et al.*, 2023; Anandraj, 2024; Shahin *et al.*, 2026). Likewise, LC is recognised as a philosophy for continuous improvement (CI) and employee engagement (Womack *et al.*, 1990; Gatell and Avella, 2024), while KM is a strategic capability for organisational competitiveness (Demir *et al.*, 2021; Meher *et al.*, 2023). However, these research streams have largely evolved independently, with limited empirical evidence on how LC supports KM in I6.0 environments. Thus, the relationships among these concepts remain poorly understood, representing a theoretical and practical gap.

Based on this gap, the following research question is proposed: How does Lean Culture, in combination with Industry 6.0 practices, shape organisational knowledge management in contexts of volatile and fast-moving information? In pursuing this question, the study analyses how organisations are preparing to implement I6.0 alongside LC by identifying the challenges, best practices, and organisational maturity associated with KM. It proposes the concept of Lean 6.0 (L6.0), the integration of Lean principles with advanced I6.0 technologies to support the creation, preservation, and dissemination of organisational knowledge (Araújo *et al.*, 2024; Gatell and Avella, 2024).

Theoretically, this study contributes by proposing and empirically testing an integrated framework linking I6.0, LC, and KM, which prior research has largely examined separately (Singh *et al.*, 2023; Gatell and Avella, 2024; Demir *et al.*, 2021). By modelling these constructs as interrelated, the study clarifies how Lean culture and I6.0 technologies jointly shape knowledge outcomes and whether they operate as complementary or substitutive mechanisms. This extends the I6.0 literature beyond its technological and sustainability focus toward its human and organisational dimensions.

Practically, the findings help organisations preparing for I6.0 adoption to understand which capabilities, cultural or technological, most reliably sustain knowledge management under increasing automation, informing workforce development and knowledge-preservation strategies before significant investments are made in digital transformation. This contributes to United Nations SDG 9 (Industry, Innovation, and Infrastructure) by demonstrating how Lean and I6.0 support sustainable industrial development and aligns with SDG 12 (Responsible Consumption and Production) by promoting waste reduction and resource efficiency.

This article is organised into six sections. Section 1 introduces the research question and context; Section 2 reviews the theoretical framework and relevant literature; Section 3 describes the research methodology; Section 4 presents the Structural Equation Modelling results; Section 5 discusses the theoretical and empirical findings; and Section 6 outlines the conclusions, limitations, implications, and directions for future research.

2. Theoretical background and hypothesis development

In this section, we develop the theoretical framework, divided into four units: "Lean Culture", "Industry 6.0", "Lean 6.0", and "Knowledge Management".

2.1 Lean culture

Lean culture is grounded in the principles of Respect for People (RP) and CI. The RP principle enables individuals to develop and contribute their knowledge by actively participating in the development, standardisation, and improvement of the tasks they perform, as well as in decision-making. The CI principle forms the foundation of Lean processes, requiring individuals to apply their skills in problem identification and to use routines based on scientific evidence to solve problems (Goodridge *et al.*, 2015; Snyder *et al.*, 2016; Zarbo, 2012; Araújo *et al.*, 2024; Gatell and Avella, 2024).

Implementing Lean requires the engagement and commitment of all employees across the production chain. It involves the interplay between soft practices, which consider people and their relationships, and *hard practices*, which rely on technical and analytical tools. Organisations often prioritise hard tools over soft practices, focusing their efforts exclusively on technical tools (Hines *et al.*, 2011; Bortolotti *et al.*, 2015). According to Mann (2015), LC emerges as leaders become attuned to the mindset needed to solve current problems and address organisational challenges.

From this perspective, the establishment of an organisational culture becomes essential for the sharing of characteristics such as beliefs, values, norms, customs, rituals, and ways of making sense of the activities performed (Abdalla *et al.*, 2020), so that everyone perceives the organisation through the same lens of CI (Bagga *et al.*, 2022; Alves and Alves, 2015). Among studies addressing LC, many discuss the pillars of RP and CI (Fadnavis *et al.*, 2020; Araújo *et al.*, 2024). Another way in which LC has been characterised is through the principles of *Lean Thinking*, as seen in the works of Amaro *et al.* (2020) and Araújo *et al.* (2024).

Given that Lean focuses on developing products, processes, technologies, and associated means in a lean manner, there is also a need to develop people, thereby highlighting the formation of a system focused on the human element (Medeiros *et al.*, 2025). LC can therefore be regarded as the application of Lean principles and tools to operationalise and sustain improvement within the work environment by providing a structure that supports process standardisation, training, leadership, and a unified culture (Gatell and Avella, 2024; Al-Balushi *et al.*, 2014; Bhasin, 2013; Jadhav *et al.*, 2014). This makes the application of Lean practices more consistent and replicable across organisations. Consequently, LC enhances understanding of organisational processes and outcomes, enabling the assessment of Lean practices and organisational orientation towards results (Bortolotti *et al.*, 2015).

Studies by Chen *et al.* (2020), for example, have shown that organisational engagement with "green" practices that promote sustainability is achievable only through approaches such as LC, as these involve organisational culture in meeting sustainability plan targets. Although LC is emphasised as a key factor in organisational transformation and the maintenance of improvements, studies describing it often offer differing or superficial characterisations (Dorval *et al.*, 2019; Werner, 2021).

2.2 Industry 6.0

While I5.0 emphasises social and environmental concerns within a technological context, prioritising employee well-being and sustainable practices to preserve human-centricity (Passalacqua *et al.*, 2025; Hammad *et al.*, 2025; Tengblad *et al.*, 2026), I6.0 emerges as a revolution that encompasses all previous industrial versions, using advanced technologies that work together to enhance processes, improve customer satisfaction, and create increasingly autonomous, intelligent manufacturing systems (Chourasia *et al.*, 2022; Jain, 2024). The human-centric collaboration introduced in I5.0 (Huang *et al.*, 2022) continues to be explored in I6.0 (Shahin *et al.*, 2026), as human creativity remains essential for designing tools that enable the effective application of I6.0's innovations (Chourasia *et al.*, 2022), even as these systems increasingly operate with little or no human involvement (Yadav *et al.*, 2022; Business Finland, 2022). By integrating human knowledge and AI, I6.0 enables collaboration between humans and robots in applying and interpreting concepts emerging from new technologies, such as big data (Almusaed *et al.*, 2023; Biesdorf *et al.*, 2026).

As autonomous tools become more advanced, the premise of I6.0 is to achieve high efficiency and continuous improvement (Allawadi *et al.*, 2024), impacting various organisational sectors, from optimising logistics processes to supporting more accurate management decisions and improving workplace health and safety conditions (Arputharaj *et al.*, 2024). I6.0 also extends beyond production improvements by placing strong emphasis on environmental sustainability, including renewable and carbon-neutral energy sources (Jain, 2024) and organic materials in manufacturing (Almusaed *et al.*, 2023). Overall, I6.0 represents the convergence of hyper-advanced technologies with environmental and social considerations, while maintaining human centrality at the core of the industrial landscape (Deliu and Olariu, 2024; Verma *et al.*, 2025).

For I6.0 to be adopted successfully, however, it requires a well-structured organisational culture (Wiengarten *et al.*, 2015; Solaimani *et al.*, 2019). In such a culture, CI and waste elimination become embedded in organisational routines and employee behaviour, supporting the systematic and collaborative implementation of I6.0 (Chourasia *et al.*, 2022). Because I6.0 relies on autonomous tools driven by the pursuit of efficiency and CI (Allawadi *et al.*, 2024), its value depends not on the technology alone but on how it is integrated into organisational routines. Organisations with greater Lean maturity are better positioned to leverage advanced technologies by combining them with employees' knowledge, experience, and problem-solving capabilities (Anandraj, 2024). This reasoning leads to the study's first hypothesis:

H1. Organisations with higher Lean with Technologies maturity tend to adopt Industry 6.0 practices more successfully.

2.3 Lean 6.0 (L6.0)

If the initial concepts defining I6.0 already embody the pursuit of operational efficiency through hyper-automation combined with cutting-edge technologies (Almusaed *et al.*, 2023), integrating LC may provide a more assertive and results-oriented organisational perspective (Bortolotti *et al.*, 2015). According to Machado and Nogueira (2025), implementing I6.0 requires commitment from organisational leaders to adopt a mindset, mission, and vision aligned with its objectives; without this alignment, adoption may be compromised, as it involves financial risks that require careful management and strong leadership to sustain Lean practices.

Building on this reasoning, this study introduces the concept of Lean 6.0 (L6.0) as a means of aligning people towards these results. Beyond the need for a strong organisational culture (Wiengarten *et al.*, 2015; Solaimani *et al.*, 2019), achieving the sixth industrial revolution will be possible only through systematic work and collaborative effort by the people who constitute the industrial environment (Chourasia *et al.*, 2022).

2.4 Knowledge management (KM)

Implementing and maintaining I6.0 practices, when combined with LC, may create an ecosystem that enables effective management of organisational change (Gatell and Avella, 2024). However, such an ecosystem can only remain alive within organisations if it coexists with effective KM (Song and Sun, 2018), since knowledge is directly linked to innovation management, quality, and competitive advantage (Klein *et al.*, 2023).

Thus, knowledge waste is an important factor to consider, particularly as KM is regarded as a strategic resource for organisational performance (Nakash, 2026). In times of volatile and fast-moving information, a constant challenge for industries is to preserve the skills acquired over the years regarding daily operations (Storey, 2025). The combination, transfer, and sharing of knowledge within and between organisations constitute essential steps towards the construction of Lean Thinking (LeMahieu *et al.*, 2017), making KM a critical factor for companies to innovate and compete (Alavi *et al.*, 2024).

I6.0 technologies contribute to preserving and disseminating this organisational knowledge, as observed through digital twins and augmented reality, which facilitate knowledge sharing and help reduce knowledge loss resulting from employee turnover and retirement, since knowledge can be systematically captured and stored in organisational databases (Zahariev *et al.*, 2024; Duggal *et al.*, 2022). In this sense, I6.0 can also support converting tacit knowledge into explicit knowledge through documentation technologies such as augmented reality, while AI, ML, and IoT support data processing and management, helping transform data into strategic information for decision-making (Pattanaik *et al.*, 2024).

Collaborative robots illustrate this further: preliminary laboratory experiments on training operators in assembly processes found positive effects on process quality (Gervasi *et al.*, 2024), showing how I6.0 technologies enable interactive learning, reduce training time, and preserve operational expertise. Because the objective of I6.0 is the interaction between machines and human beings (Chourasia *et al.*, 2022), and because the creators of organisational knowledge remain the humans who possess process-execution expertise (Tariq *et al.*, 2024), I6.0 technologies function as tools that complement, rather than replace, human capabilities in supporting KM. This leads to the study's second hypothesis:

H2. Industry 6.0 contributes to the preservation and dissemination of organisational knowledge.

Independent of technology, higher levels of Lean maturity favour knowledge sharing among employees by promoting more robust processes, institutionalised CI practices, and a stronger LC. These characteristics encourage employees to share experiences, learn from mistakes, and continuously improve processes, thereby reinforcing organisational learning and the flow of tacit and explicit knowledge (Balle *et al.*, 2019; Kaswan and Rathi, 2020). This aligns with studies identifying Lean as a facilitator of KM, since its principles encourage collaborative problem-solving, communication, and continuous learning (Pearce *et al.*, 2021; Netland and Fredriksson, 2019), and with the broader perspective that lean organisations exhibit greater capacity for learning and innovation (Bortolotti *et al.*, 2015). Accordingly:

H3. Lean with Technologies maturity facilitates knowledge creation and sharing.

Finally, prior studies suggest that I6.0 technologies play a central role in facilitating organisational KM by improving collaboration, information accessibility, and intelligent decision-making (Chourasia, 2025; Osmani *et al.*, 2023), raising the possibility that I6.0 does not merely co-occur with the Lean–KM relationship but actively channels part of it. If organisations with mature Lean cultures rely on I6.0 technologies to translate their cultural strengths into documented, shareable knowledge, then I6.0 should account for part of the effect of Lean with Technologies on KM, rather than the two constructs affecting KM through fully independent paths. This motivates a partial mediation hypothesis:

H4. I6.0 mediates part of the relationship between Lean with Technologies and Knowledge Management.

3. Methodological procedures

The data collection instrument was developed in Google Forms based on the literature, with questions aligned to the research objectives. The questionnaire initially comprised three dimensions: Lean with Technologies, I6.0, and KM. These constructs were derived from an exploratory literature search identifying studies that addressed these dimensions from an initial and limited perspective, highlighting opportunities for further research (Duggal *et al.*, 2022; Heilala and Parchegani, 2023; Carayannis *et al.*, 2024).

Nine specialists validated the questionnaire by assessing the clarity and objectivity of the questions; the instrument was refined based on their feedback before distribution. After content validation, the final questionnaire comprised 15 closed-ended questions using a five-point Likert scale (strongly agree to strongly disagree), along with a section collecting respondents' demographic information. Identical versions were prepared in English and Portuguese.

The instrument included question 01, which was not linked to any specific construct and was intended to assess the respondent's prior understanding of L6.0. Questions 02, 03, 04, and 12 were designed to address the construct Lean with Technologies and originate from questions asking whether current industrial management aligns with the L6.0 approach (I2), whether L6.0 improves organisational processes and employee engagement (I3), whether L6.0 facilitates value co-creation among stakeholders (I4), and whether LC can promote human–machine collaboration (I12).

Questions 05, 06, 07, 08, and 09 were developed with the KM construct in mind; the retained questions ask whether LC is preserved during employee turnover once I6.0 is implemented (I06), whether I6.0 technologies help preserve organisational knowledge during high turnover (I07), and whether LC can be dispersed or lost with I6.0 adoption (I09), reflecting concerns, grounded in Storey (2025), about preserving organisational and process-related knowledge under volatile information conditions.

Questions 10, 11, 13, 14, and 15 were constructed to evaluate the I6.0 construct; the retained questions ask whether I6.0 implementation may face barriers related to collaboration within the organisation (I11), whether I6.0 enables greater collaborative effort in developing LC (I13), and whether increasing systems autonomy will sustain Lean culture's involvement in I6.0 in the long term (I14), drawing on Almusaed *et al.* (2023), who argue that I6.0 combines human knowledge with AI so both can jointly apply and give meaning to emerging technological concepts, and on Machado and Nogueira (2025), who stresses that effective I6.0 implementation requires engaged leadership and strong team management to sustain Lean practices. Table 1 presents the full instrument.

Regarding respondents, population, and sample, we searched for published studies on I6.0 in February 2025, yielding 190 publications. After reviewing the abstracts and introductions, 107 studies were excluded, along with 27 duplicates, resulting in a final sample of 56 studies. We identified all authors of these 56 studies and collected their contact information (email or LinkedIn) to distribute the questionnaire. Additionally, individuals with expertise in Lean, I4.0, I5.0, and I6.0 were identified on LinkedIn and invited to participate.

3.1 Respondents' profile

The questionnaire received 103 valid responses. Most respondents (53.8%) are employed in the private sector (see Figure 1).

3.2 Analysis

For the initial analysis of the constructs, Exploratory Factor Analysis (EFA) was employed, conducted in *R* using the psych package. Three factor analyses were performed considering the

Table 1. Description of the data collection instrument

Item	Description
1	In your perception, how well do you understand Lean 6.0?
2	Based on your experience, do you believe that the current management practices in industrial sector organisations are aligned with the Lean 6.0 approach?
3	Do you consider that the application of Lean 6.0 can provide process-related benefits, such as improvements in organisational processes, workflows, waste reduction, and increased efficiency, while also encompassing employee engagement?
4	Do you believe that the implementation of Lean 6.0 concepts can facilitate value co-creation and interaction among all stakeholders involved?
5	In your perception, can applications of Industry 6.0 facilitate knowledge management?
6	Once Industry 6.0 technology is applied, is Lean Culture preserved in scenarios of high employee turnover?
7	Can Industry 6.0 technologies contribute to preserving organisational knowledge during periods of high employee turnover?
8	Can organisations with a well-established Lean Culture throughout their structure facilitate the implementation of Industry 6.0?
9	Can Lean Culture be diluted or lost with the adoption of Industry 6.0?
10	Can an organisational culture focused on operational excellence positively impact the implementation of Industry 6.0 technologies?
11	Could the implementation of Industry 6.0 face barriers regarding collaboration among the organisation's employees?
12	Can Lean Culture promote and/or facilitate human–machine collaboration?
13	Does Industry 6.0 allow for increased collaborative efforts among people for the development of Lean Culture?
14	With increasingly autonomous systems, will the involvement of Lean Culture in Industry 6.0 be sustainable in the long term?
15	Are leaders or management teams prepared to conduct the process of implementing Industry 6.0 technologies?

Source(s): The Authors Analysis (2025)

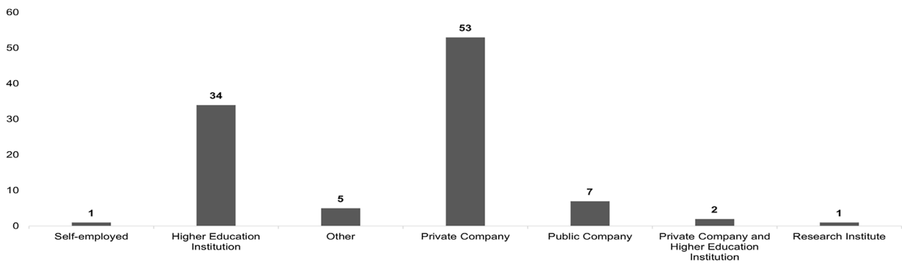

Figure 1. Respondents' field of work. Source: The authors

14 questions corresponding to the three proposed dimensions (item 01 was excluded, as it was only an initial probe on respondent familiarity with the topic). Four questions were excluded due to factor loadings below 0.400: I05 (whether I6.0 applications facilitate KM), I08 (whether a fully developed LC facilitates I6.0 implementation), I10 (whether an operational-excellence-oriented culture positively impacts I6.0 technology implementation), and I15 (whether leaders are prepared to conduct I6.0 implementation).

Following this exploratory step, the structural model was developed, and the hypotheses formulated in Section 2 were tested using Structural Equation Modelling (SEM), as shown in Figure 2. This step was performed in *R* using the lavaan package. Based on the responses obtained, the Covariance-Based SEM (SEM-CB) method was employed to test the four

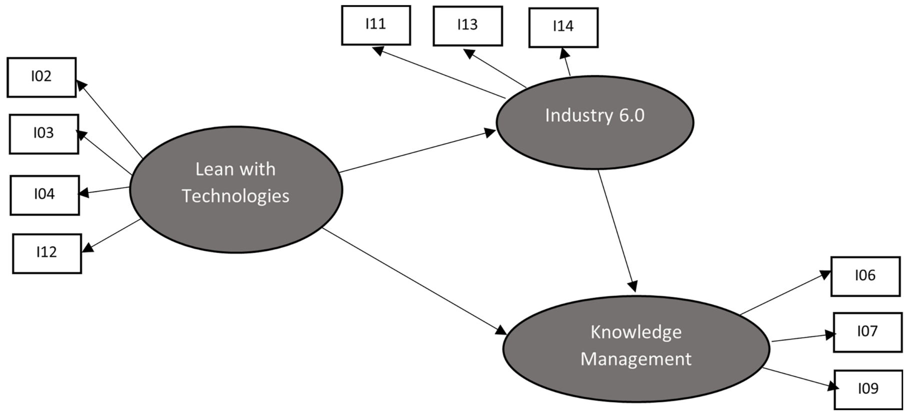

Figure 2. Proposed model. Source: The authors

hypothesised relationships among Lean with Technologies, I6.0, and KM; this method is part of a family of statistical models aimed at explaining the relationships among multiple variables (Hair *et al.*, 2019) by examining the structure of interrelationships expressed in a series of equations describing all relationships between the dependent and independent variables involved.

Model adequacy was evaluated using the Goodness-of-Fit Index (GFI), Comparative Fit Index (CFI), Tucker–Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardised Root Mean Square Residual (SRMR).

4. Results

This section presents the results of the Structural Equation Modelling (SEM) analysis. Figure 3 illustrates the final structural model, while Table 2 summarises the estimated path coefficients and the statistical significance of the proposed hypotheses. The goodness-of-fit indices indicated that the proposed model achieved an acceptable fit to the observed data (GFI = 0.91; CFI = 0.95; TLI = 0.92; RMSEA = 0.08; SRMR = 0.06). According to Hair *et al.* (2019),

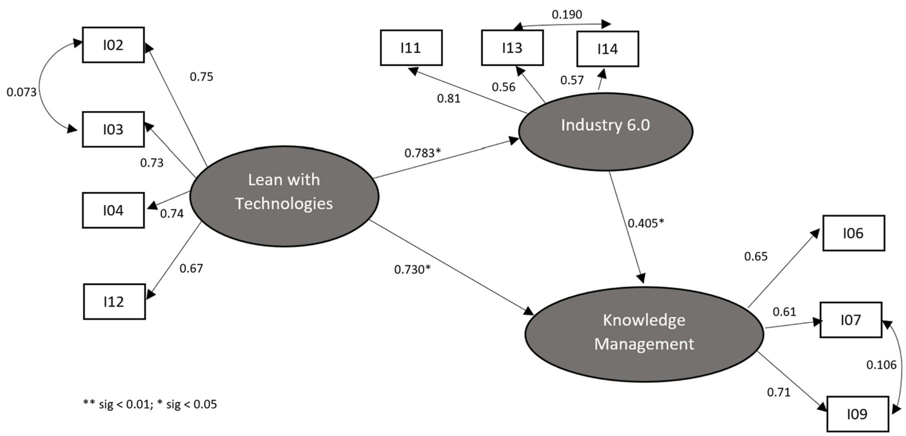

Figure 3. Tested causal relationship. Source: The authors

Table 2. Structural model results

Tested causal relationship (hypotheses)	Estimate	S.E. (Standard error)	Sig. (Significance)	Results
H1: Lean with Technologies → Industry 6.0	0.783	0.164	<0.001	Supported
H2: Industry 6.0 → Knowledge Management	0.405	0.185	0.029	Supported
H3: Lean with Technologies → Knowledge Management	0.730	0.222	0.001	Supported
H4: Mediation by Industry 6.0	0.317 < 0.730			Not Supported

Source(s): The Authors (2025)

CFI and TLI values above 0.90 and RMSEA and SRMR values equal to or below 0.08 indicate an adequate model fit; the obtained indices therefore support the validity of the proposed structural model. The average variance extracted (AVE) was close to 0.50, as shown in Table 3, and a larger sample size in a subsequent application of the model is likely to improve this index. Composite reliability showed very satisfactory results, with values of 0.70 or higher.

Hypothesis 1, which examined the relationship between Lean with Technologies and I6.0, was supported (β = 0.783; $p < 0.001$), indicating that companies applying Lean with Technologies are more likely to adopt I6.0 practices successfully. Hypothesis 2, examining the relationship between I6.0 and KM, was also supported (β = 0.405; $p = 0.029$), showing that I6.0 contributes to the preservation and dissemination of organisational knowledge. Hypothesis 3, concerning Lean with Technologies and KM, was also supported (β = 0.730; $p < 0.001$), indicating that Lean maturity facilitates knowledge creation and sharing.

However, Hypothesis 4 was not supported: the indirect effect of Lean with Technologies on KM through I6.0 ($\beta\_indirect \approx 0.783 \times 0.405 = 0.317$) was smaller than, and statistically distinct from, the direct effect of Lean with Technologies on KM (β = 0.730). This indicates that I6.0 does not mediate the relationship between Lean with Technologies and KM in this sample.

L6.0 was treated as a latent construct, measured by indicators I02, I03, I04, and I12. Factor loadings were 0.756 for I02, 0.736 for I03, 0.749 for I04, and 0.572 for I12, indicating adequate convergent validity per Hair *et al.* (2019). The construct exhibited a direct and significant influence on both I6.0 (coefficient = 0.783; $p < 0.01$) and KM (coefficient = 0.730; $p < 0.01$), confirming its central role in the model.

Correlations between measurement errors (I07 and I09, I13 and I14, and I02 and I03) were observed, which are expected in empirical models and contribute to improved overall model fit (Hair *et al.*, 2019). Taken together, the fit indices reported in Section 3 (CFI = 0.95; TLI = 0.92; RMSEA = 0.08; SRMR = 0.06) and the path coefficients above confirm the robustness of the proposed relationships: KM is strongly influenced by Lean with

Table 3. Tests on the validity of the constructs

Latent variable	Average variance extracted	Composite reliability
Lean with technologies	0.44	0.82
Industry 6.0	0.44	0.70
Knowledge Management	0.53	0.70

Source(s): The Authors

Technologies maturity, while I6.0 exerts a positive but comparatively smaller direct effect on KM and does not act as a mediating mechanism between the two.

5. Discussion

The SEM results provide empirical evidence of the relationships among Lean with Technologies, Industry 6.0 (I6.0), and Knowledge Management (KM). Three of the four proposed hypotheses were supported, indicating that Lean maturity constitutes the primary organisational capability driving both the adoption of I6.0 practices and the effectiveness of KM. At the same time, I6.0 operates as a complementary technological enabler rather than the mechanism through which Lean influences KM.

This section discusses the findings, explaining not only what was found but also why each relationship behaved as it did and how it advances existing theory.

5.1 Lean as an organisational capability

The results demonstrated a strong positive relationship between Lean with Technologies and I6.0 ($\beta = 0.783$; $p < 0.001$), supporting H1. This suggests that Lean functions not only as a set of practices but as an organisational capability that enables the effective integration of advanced technologies into organisational processes and converts them into operational value. Lean-developed routines, particularly CI, waste elimination, collaboration, and problem-solving, may provide the foundation for implementing and operationalising hyper-automation (Chourasia *et al.*, 2022; Wiengarten *et al.*, 2015; Solaimani *et al.*, 2019). Thus, Lean's contribution to I6.0 lies not simply in using Lean practices alongside technology, but in the organisational routines and behaviours that enable technologies to generate operational value (Allawadi *et al.*, 2024).

This interpretation reinforces the view of Lean as an organisational capability rather than merely a set of operational tools. Lean routines support organisational learning and innovation by enabling problems to be identified, addressed, and transformed into improvement opportunities (Bortolotti *et al.*, 2015; Balle *et al.*, 2019; Kaswan and Rathi, 2020). This is particularly relevant to I6.0, where technologies generate large amounts of data and enable autonomous processes but require organisational capabilities to interpret information and translate it into improvements. Thus, Lean maturity may provide an organisational foundation for I6.0 by supporting problem identification, information interpretation, and continuous adaptation, positioning Lean as an antecedent of technological integration.

Lean's role as an organisational capability also extends to KM. The positive and statistically significant relationship between Lean with Technologies and KM ($\beta = 0.730$; $p < 0.001$) supports H3 and represents the strongest relationship with KM in the model, exceeding the direct effect of I6.0 on KM ($\beta = 0.405$). This difference suggests that knowledge creation and sharing may be more strongly associated with organisational routines than with technological infrastructure alone. Institutionalised CI and a robust LC enable employees to exchange experiences, learn from mistakes, engage in collaborative problem-solving, and standardise improvements (Balle *et al.*, 2019; Kaswan and Rathi, 2020). These mechanisms can operate independently of specific digital technologies, providing conditions for knowledge creation and circulation (Pearce *et al.*, 2021; Netland and Fredriksson, 2019).

The stronger relationship between Lean with Technologies and KM therefore suggests that Lean contributes to KM through behavioural and operational mechanisms. While technologies can facilitate the capture, processing, and dissemination of information (Zahariev *et al.*, 2024; Duggal *et al.*, 2022), Lean routines create an organisational context in which knowledge can be generated, shared, and embedded in everyday practices. Thus, Lean not only supports the technological infrastructure required for KM, but also establishes routines through which individual experiences and problem-solving activities can become part of organisational practices (Balle *et al.*, 2019; Kaswan and Rathi, 2020). This finding extends the understanding of Lean as an organisational capability, showing that its contribution goes beyond process efficiency and technological readiness to include organisational conditions that support learning and knowledge circulation.

Taken together, the findings indicate that Lean has a dual role in the relationship between organisational capabilities, I6.0, and KM. Lean maturity is strongly associated with I6.0, suggesting that Lean routines provide conditions for integrating advanced technologies (Chourasia *et al.*, 2022; Wiengarten *et al.*, 2015; Solaimani *et al.*, 2019). At the same time, Lean has a stronger direct relationship with KM than I6.0, indicating that knowledge processes are more rooted in organisational practices than technology alone. Thus, digitalisation should not replace Lean maturity, but rather complement the organisational capabilities developed through Lean (Antony *et al.*, 2021; Buer *et al.*, 2018). These findings position Lean as an organisational capability supporting both technological integration and knowledge-related processes.

5.2 Industry 6.0 as a technological enabler

I6.0 showed a significant, positive effect on KM ($\beta = 0.405$; $p = 0.029$) supporting H2, consistent with the premise that technologies such as digital twins, augmented reality, AI, ML, and IoT support the documentation, storage, and retrieval of organisational knowledge (Zahariev *et al.*, 2024; Pattanaik *et al.*, 2024) and help convert tacit knowledge into explicit, transferable formats (Duggal *et al.*, 2022; Nonaka and Takeuchi, 1995; Dombrowski and Mielke, 2014). By recording and making information available through digital systems, these technologies reduce the dependence of organisational knowledge on individual employees and facilitate its retrieval and transfer across the organisation, which is particularly relevant for tacit knowledge that would otherwise remain with individuals and be lost through employee turnover (Duggal *et al.*, 2022; Pattanaik *et al.*, 2024).

Theoretically, this effect was significant but smaller than the direct effect of Lean with Technologies on KM ($\beta = 0.730$, H3). This suggests that I6.0 is more strongly associated with capturing, preserving, and disseminating existing knowledge than with its initial creation. In other words, technology does not generate knowledge alone but helps capture and preserve knowledge already developed through Lean routines. This distinction is relevant in practice, as I6.0 technologies may underperform without collaborative routines for knowledge creation and may also involve risks such as tacit-knowledge loss, technological dependence, and organisational resistance (Sony and Naik, 2020; Sony, 2022).

The mediation analysis confirms this division of labour. Contrary to the study's hypothesis, and to prior studies suggesting that I6.0 technologies play a central role in facilitating KM through improved collaboration, information accessibility, and intelligent decision-making (Chourasia, 2025; Osmani *et al.*, 2023), the mediation test did not support H4, the indirect effect of Lean with Technologies on KM through I6.0 ($0.783 \times 0.405 = 0.317$) was smaller than, and statistically distinct from, the direct effect of Lean with Technologies on KM (0.730). This is a theoretically informative null result rather than a weak one: if I6.0 were the principal mechanism through which Lean practices generate knowledge outcomes, the indirect path would be expected to approach or exceed the direct path; instead, the direct path remains dominant, indicating that Lean maturity affects KM largely independently of whether organisations have adopted I6.0 technologies.

A plausible explanation is that mature Lean cultures already have established routines for knowledge creation and sharing, reducing the additional contribution of individual technologies. This aligns with the view that Lean provides the cultural and operational foundations for intelligent digitalisation through process stability and continuous human engagement (Antony *et al.*, 2021; Buer *et al.*, 2018). Rather than substituting or mediating Lean's effect on KM, I6.0 should be seen as a complementary capability: Lean enables collaboration and continuous learning, while I6.0 supports the capture and dissemination of knowledge that might otherwise remain tacit or be lost through employee turnover (Storey, 2025).

5.3 Human-centred knowledge management

Taken together, H1 to H4 show a consistent pattern: Lean maturity is the dominant organisational capability shaping both I6.0 adoption and KM; I6.0 makes a real but secondary contribution to KM; and this contribution operates in parallel with, rather than through, Lean's own effect on KM. This pattern reinforces a human-centred reading of I6.0 that is often underdeveloped in accounts emphasising hyper-automation and machine autonomy (Almusaed *et al.*, 2023; Chourasia *et al.*, 2022).

Although I6.0 technologies can support the preservation and dissemination of organisational knowledge, knowledge creation and application still depend on employees who possess process-execution expertise (Tariq *et al.*, 2024), a distinction consistent with the human-centred premise of I6.0, in which the interaction between humans and machines, not the replacement of one by the other, remains central to the use of advanced technologies (Chourasia *et al.*, 2022). Collaborative robots, for instance, support interactive learning and reduce training time (Gervasi *et al.*, 2024). Still, the knowledge being disseminated originates from, and is validated by, people embedded in Lean problem-solving and standardisation routines.

From this perspective, the non-support of H4 is reassuring rather than negative: it indicates that organisational knowledge under I6.0 does not become dependent on technology to the point of displacing the human and cultural mechanisms that generate it in the first place. This reading is consistent with Lean thinking's emphasis on converting tacit into explicit knowledge as a human-driven process that technology can support but not originate (Nonaka and Takeuchi, 1995; Dombrowski and Mielke, 2014) and reinforces that the sustainability of KM under I6.0 depends on preserving, rather than automating away, the cultural mechanisms through which employees generate and share knowledge, technological infrastructure can support KM. Still, it does not replace the human and organisational processes through which knowledge is created and applied.

5.4 Structural relationships

The four hypotheses depict a consistent pattern: Lean maturity is the dominant organisational capability shaping both I6.0 adoption (H1) and KM (H3); I6.0 makes a real but secondary contribution to KM (H2); and this contribution operates in parallel with, rather than through, Lean's own effect on KM (H4, not supported). This pattern reinforces a human-centred reading of I6.0 that is often underdeveloped in accounts emphasising hyper-automation and machine autonomy (Almusaed *et al.*, 2023; Chourasia *et al.*, 2022). Because the creators of organisational knowledge remain the humans who possess process-execution expertise (Tariq *et al.*, 2024), I6.0 technologies function as a complement to human capability rather than a substitute for it. Collaborative robots, for instance, support interactive learning and reduce training time (Gervasi *et al.*, 2024), but the knowledge being disseminated originates from, and is validated by, people embedded in Lean routines of problem-solving and standardisation.

5.5 Theoretical implications

From a theoretical perspective, this study extends the I6.0 literature, which has so far emphasised hyper-automation, sustainability, and human-centred manufacturing largely as technological phenomena (Singh *et al.*, 2023; Anandraj, 2024; Shahin *et al.*, 2026), by demonstrating that its human and organisational dimensions are not peripheral but foundational.

By showing that Lean with Technologies exerts a stronger direct effect on KM ($\beta = 0.730$) than I6.0 itself ($\beta = 0.405$), and that I6.0 does not mediate Lean's effect on KM, the findings challenge the implicit assumption in much of the digital transformation literature that advanced technology is the primary driver of organisational knowledge outcomes (Chourasia, 2025; Osmani *et al.*, 2023). Instead, they support a capability-based reading in which Lean culture conditions the return an organisation can extract from I6.0 technologies, positioning

L6.0 as a theoretical bridge between Lean management theory and the emerging I6.0 paradigm.

5.6 Practical implications

From a practical perspective, the findings translate into recommendations for organisations preparing to adopt I6.0. First, investment should be sequenced, not merely budgeted: before allocating capital to I6.0 technologies (digital twins, AI-driven analytics, collaborative robots), organisations should assess their Lean maturity, for example, through an internal audit of the extent to which CI routines, standardised problem-solving, and employee-led process ownership are already institutionalised, since the results indicate that technology adoption without this foundation yields a smaller return on KM ($\beta = 0.405$ versus 0.730).

Second, every I6.0 deployment should be paired with an explicit knowledge-capture protocol: because I6.0 technologies preserve knowledge that Lean routines generate rather than generating it themselves, any new digital twin, AR, or IoT deployment should be accompanied by a structured process for documenting the tacit knowledge of the employees whose work it digitises, such as process-mapping sessions before automating a task, not after.

Third, responsibility for knowledge preservation during I6.0 rollout should sit with operational and Lean leadership rather than IT, since Lean maturity, not technology, was the dominant driver of KM outcomes in this study. Fourth, organisations should review and expand their current KPIs to ensure that they can measure the benefits and requirements associated with I6.0. These may include the proportion of critical processes with documented and accessible knowledge records, allowing organisations to assess whether digital transformation is effectively contributing to the preservation and dissemination of organisational knowledge or merely automating tasks without capturing the expertise that underpins them.

Furthermore, this study contributes to the advancement of United Nations SDG 9 (Industry, Innovation, and Infrastructure) by showing that sustainable industrial innovation depends on sequencing cultural and technological investment rather than treating them as substitutes, and SDG 12 (Responsible Consumption and Production), as embedding knowledge-preservation protocols reduces the waste of re-learning or re-developing expertise lost during automation. They further imply that engineering education and professional training programmes should teach I6.0 technologies alongside Lean problem-solving methods, rather than as a separate digital curriculum, since the two are complementary rather than substitutable capabilities.

6. Conclusions

This research makes three contributions that advance the emerging literature on Industry 6.0. Theoretically, it is the first study to model Lean maturity, I6.0 adoption, and Knowledge Management as interrelated constructs, clarifying that Lean culture is the primary organisational capability underpinning both I6.0 adoption and KM effectiveness. At the same time, I6.0 operates as a complementary, non-mediating enabler.

Methodologically, it introduces and empirically validates the L6.0 construct through Covariance-Based Structural Equation Modelling, providing a psychometrically tested instrument (Table 1) that future studies can replicate, extend, or apply across sectors and geographies. Practically, it offers organisations preparing for I6.0 adoption an evidence-based sequence of priorities: Lean maturity should be treated as a precondition for, not a parallel track to, digital transformation investment.

This study has some limitations. First, the limited literature on L6.0 restricts broader theoretical comparisons. Additionally, the emerging nature of I6.0 limited the availability of specialists, resulting in a relatively small sample (103). Future research should examine organisations with mature implementations of I4.0, I5.0, Lean 4.0, and Lean 5.0, using larger, more diverse samples to enhance the robustness and generalisability of the findings.

Although the sample was sufficient for the statistical analyses conducted, future studies should also combine perceptual data with objective organisational performance indicators, such as documented knowledge-retention rates or time-to-productivity after employee turnover, to provide a more comprehensive, less self-reported assessment of the relationships between Lean, I6.0, and KM.

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References

Abdalla, W., Suresh, S. and Renukappa, S. (2020), "Managing knowledge in the context of smart cities: an organisational cultural perspective", *Journal of Entrepreneurship, Management and Innovation*, Vol. 16 No. 4, pp. 1-21, doi: 10.7341/20201642.

Alavi, M., Leidner, D.E. and Mousavi, R. (2024), "A knowledge management perspective of generative artificial intelligence", *Journal of the Association for Information Systems*, Vol. 25 No. 1, pp. 1-12, doi: 10.17705/1jais.00859.

Al-Balushi, S., Sohal, A.S., Singh, P.J., Al Hajri, A., Al Farsi, Y.M. and Al Abri, R. (2014), "Readiness factors for lean implementation in healthcare settings – a literature review", *Journal of Health Organization and Management*, Vol. 28 No. 2, pp. 135-153, doi: 10.1108/JHOM-04-2013-0083.

Allawadi, K., Panwar, S. and Chugh, M. (2024), "Advancing autonomous driving through federated learning: a collaborative approach", in Sharma, A., Moses, O., Sharma, R. and Gupta, S. (Eds), *Sustainable Innovation for Industry 6.0*, IGI Global Scientific Publishing, pp. 1-30, doi: 10.4018/979-8-3693-3140-8.ch001.

Almusaed, A., Yitmen, I. and Almssad, A. (2023), "Reviewing and integrating AEC practices into Industry 6.0: strategies for smart and sustainable future-built environments", *Sustainability*, Vol. 15 No. 18, 13464, doi: 10.3390/su151813464.

Alves, J.R.X. and Alves, J.M. (2015), "Production management model integrating the principles of lean manufacturing and sustainability supported by the cultural transformation of a company", *International Journal of Production Research*, Vol. 53 No. 17, pp. 5320-5333, doi: 10.1080/00207543.2015.1033032.

Amaro, P., Alves, A.C. and Sousa, R.M. (2020), "Lean thinking: from the shop floor to an organizational culture", in Lalic, B., Marjanovic, U., Majstorovic, V., von Cieminski, G. and Romero, D. (Eds), *IFIP Advances in Information and Communication Technology*, IFIP, Vol. 592, pp. 406-414. doi: 10.1007/978-3-030-57997-5_47.

Anandraj, J. (2024), "Transforming education with Industry 6.0: a human-centric approach", *International Journal of Computational and Experimental Science and Engineering*, Vol. 10 No. 4, pp. 1851-1862, doi: 10.22399/ijcesen.732.

Antony, J., Sony, M. and McDermott, O. (2021), "Lean Six Sigma for Industry 4.0 and digital transformation: integrating quality and innovation", *The TQM Journal*, Vol. 33 No. 6, pp. 1379-1392, doi: 10.1108/TQM-12-2020-0308.

Araújo, A., Alves, A.C. and Romero, F. (2024), "A conceptual model for pull implementation based on the dimensions leadership, organisation, operation and people", *International Journal of Lean Six Sigma*, Vol. 15 No. 2, pp. 295-325, doi: 10.1108/IJLSS-12-2022-0253.

Arputharaj, J.V., John William, B.N., Haruna, A.A. and Durga Prasad, D. (2024), "Exploring the synergy of IIoT, AI, and data analytics in Industry 6.0", in Reddy, C.K.K., Doss, S., Pamulaparty, L., Lippert, K. and Doshi, R. (Eds), *Industry 6.0: Technology, Practices, Challenges, and Applications*, 1st ed., CRC Press, doi: 10.1201/9781003517993.

Bagga, S.K., Gera, S. and Haque, S.N. (2022), "The mediating role of organisational culture: transformational leadership and change management in virtual teams", *Asia Pacific Management Review*, Vol. 28 No. 2, pp. 120-131, doi: 10.1016/j.apmrv.2022.07.003.

Balle, M., Jones, D., Chaize, J. and Fiume, O. (2019), *The Lean Strategy: Using Lean to Create Competitive Advantage, Unleash Innovation, and Deliver Sustainable Growth*, McGraw-Hill Education.

Bhasin, S. (2013), "Impact of corporate culture on the adoption of the lean principles", *International Journal of Lean Six Sigma*, Vol. 4 No. 2, pp. 118-140, doi: 10.1108/20401461311319329.

Biesdorf, A.J., Nogueira, H., Werner, S.M. and Bonamigo, A. (2026), "Analysis of data quality for traceability in the dairy supply chain from the perspective of Industry 6.0: a Brazilian regulatory perspective", *International Joint Conference on Industrial Engineering and Operations Management, IJCIEOM, 2026*, Aveiro, Portugal.

Bortolotti, T., Boscari, S.E. and Danese, P. (2015), "Successful lean implementation: organisational culture and soft lean practices", *International Journal of Production Economics*, Vol. 160, pp. 182-201, doi: 10.1016/j.ijpe.2014.10.014.

Buer, S.-V., Strandhagen, J.O. and Chan, F.T.S. (2018), "The link between Industry 4.0 and Lean manufacturing: mapping current research and establishing a research agenda", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2924-2940, doi: 10.1080/00207543.2018.1442945.

Business Finland (2022), "From Industry X to Industry 6.0", *Businessfinland.fi*, available at: https://www.businessfinland.fi/julkaisut/from-industry-x-to-industry-6.0

Carayannis, E.G., Posselt, T. and Preissler, S. (2024), "Toward Industry 6.0 and Society 6.0: the quintuple innovation helix with embedded AI modalities as enabler of public interest technologies strategic technology management and road-mapping", *IEEE Transactions on Engineering Management*, Vol. 71, pp. 11238-11252, doi: 10.1109/TEM.2024.3406427.

Chen, P.-K., Lujan-Blanco, I., Fortuny-Santos, J. and Ruiz-de-Arbulo-López, P. (2020), "Lean manufacturing and environmental sustainability: the effects of employee involvement, stakeholder pressure and ISO 14001", *Sustainability*, Vol. 12 No. 18, p. 7258, doi: 10.3390/su12187258.

Chourasia, A. (2025), "From Industry 4.0 to Industry 6.0: the evolution of intelligent automation and emotional AI", *Journal of Intelligent Manufacturing Systems*, Vol. 36 No. 2, pp. 214-230.

Chourasia, S., Tyagi, A., Pandey, S.M., Walia, R.S. and Murtaza, Q. (2022), "Sustainability of Industry 6.0 in global perspective: benefits and challenges", *MAPAN*, Vol. 37 No. 2, pp. 443-452, doi: 10.1007/s12647-022-00541-w.

Deliu, D. and Olariu, A. (2024), "The role of artificial intelligence and big data analytics in shaping the future of professions in Industry 6.0: perspectives from an emerging market", *Electronics*, Vol. 13 No. 24, 4983, doi: 10.3390/electronics13244983.

Demir, A., Budur, T., Omer, H.M. and Heshmati, A. (2021), "Links between knowledge management and organisational sustainability: does the ISO 9001 certification have an effect?", *Knowledge Management Research and Practice*, Vol. 21 No. 1, pp. 183-196, doi: 10.1080/14778238.2020.1860663.

Dombrowski, U. and Mielke, T. (2014), "Lean leadership – fundamental principles and their application", *Procedia CIRP*, Vol. 17, pp. 565-570, doi: 10.1016/j.procir.2014.01.146.

Dorval, M., Jobin, M.-H. and Benomar, N. (2019), "Lean culture: a comprehensive systematic literature review", *International Journal of Productivity and Performance Management*, Vol. 68 No. 5, pp. 920-937, doi: 10.1108/IJPPM-03-2018-0087.

Duggal, A.S., Malik, P.K., Gehlot, A., Singh, R., Gaba, G.S., Masud, M.E. and Al-Amri, J.F. (2022), "A sequential roadmap to Industry 6.0: exploring future manufacturing trends", *IET Communications*, Vol. 16 No. 5, pp. 521-531, doi: 10.1049/cmu2.12284.

Emon, M. and Khan, M. (2025), "The transformative role of Industry 4.0 in supply chains: exploring digital integration and innovation in manufacturing enterprises", *Journal of Innovation and Technology Management and Commerce*, Vol. 11 No. 2, 100516, doi: 10.1016/j.joitmc.2025.100516.

Fadnavis, S., Najarzadeh, A. and Badurdeen, F. (2020), "An assessment of organizational culture traits impacting problem solving for lean transformation", *48th SME North American Manufacturing*

Research Conference, NAMRC 48, 22–26 June 2020, Cincinnati, OH, USA, Vol. 48, pp. 31-42, doi: 10.1016/j.promfg.2020.05.017.

Gatell, I.S. and Avella, L. (2024), "Impact of Industry 4.0 and circular economy on lean culture and leadership: assessing digital green lean as a new concept", *European Research on Management and Business Economics*, Vol. 30 No. 1, p. 12, doi: 10.1016/j.iedeen.2023.100232.

Gervasi, R., Capponi, M., Antonelli, D. and Franceschini, L.M.E.F. (2024), "A human-centered perspective in repetitive assembly processes: preliminary investigation of cognitive support of collaborative robots", *Procedia Computer Science*, Vol. 232, pp. 2249-2258, doi: 10.1016/j.procs.2024.02.044.

Goodridge, D., Westhorp, G., Rotter, T., Dobson, R. and Bath, B. (2015), "Lean and leadership practices: development of an initial realist program theory", *BMC Health Services Research*, Vol. 15 No. 1, doi: 10.1186/s12913-015-1030-x.

Hair, J.F., Black, W.C., Babin, B.J. and Anderson, R.E. (2019), *Multivariate Data Analysis*, 8th ed., Cengage Learning.

Hammad, M.Y., Rahamaddulla, S.R., Tamyez, P.F.M. and Fauzi, M.A. (2025), "From Industry 4.0 to 5.0: leveraging AI and IoT for sustainable and human-centric operations", *International Journal of Industrial Engineering and Operations Management*, pp. 1-19, doi: 10.1108/IJIEOM-04-2025-0070.

Hansen, A.K., Christiansen, L. and Lassen, A.H. (2024), "Technology isn't enough for Industry 4.0: on SMEs and hindrances to digital transformation", *International Journal of Production Research*, Vol. 63 No. 18, pp. 6585-6605, doi: 10.1080/00207543.2024.2305800.

Heilala, J. and Parchegani, S. (2023), "Superhuman-centered design for manufacturing metaverse", *Conference on Technology Ethics – Tethics 2023*, Turku, Finland, University of Turku, Joukahaisenkatu, pp. 3-5.

Hines, P., Found, P.A., Griffiths, G. and Harrison, R. (2011), *Staying Lean: Thriving, Not Just Surviving*, 2nd ed., Lean Enterprise Research Centre, Cardiff University, doi: 10.1201/b10492.

House, R., Hanges, P., Javidan, M. and Dorfman, P. (2004), "Culture, leadership, and organisations", in House, R., Hanges, P., Javidan, M., Dorfman, P. and Gupta, V. (Eds), *The GLOBE Study of 62 Societies*, SAGE Publications, available at: https://www.jstor.org/stable/4131493

Huang, S., Wang, B., Li, X., Zheng, P., Mourtzis, D. and Wang, L. (2022), "Industry 5.0 and Society 5.0: comparison, complementation and co-evolution", *Journal of Manufacturing Systems*, Vol. 64, pp. 424-428, doi: 10.1016/j.jmsy.2022.07.010.

Ivanov, D., Dolgui, A. and Sokolov, B. (2019), "The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics", *International Journal of Production Research*, Vol. 57 No. 3, pp. 829-846, doi: 10.1080/00207543.2018.1488086.

Jadhav, J.R., Mantha, S.S. and Rane, S.B. (2014), "Exploring barriers in lean implementation", *International Journal of Lean Six Sigma*, Vol. 5 No. 2, pp. 122-148, doi: 10.1108/IJLSS-12-2012-0014.

Jain, R. (2024), "Towards a green revolution: sustainable integration of Industry 6.0 technologies and smart banking services in the UAE", in Sharma, A., Moses, O., Sharma, R. and Gupta, S. (Eds), *Sustainable Innovation for Industry 6.0*, IGI Global Scientific Publishing, pp. 31-44, doi: 10.4018/979-8-3693-3140-8.ch002.

Kaswan, M.S. and Rathi, R. (2020), "Integrating lean, six sigma and Industry 4.0 technologies for sustainable manufacturing", *Management of Environmental Quality: An International Journal*, Vol. 31 No. 6, pp. 1457-1472, doi: 10.1108/MEQ-07-2019-0159.

Kaswan, M.S., Chaudhary, R., Garza-Reyes, J.A. and Singh, A. (2024), "A review of Industry 5.0: from key facets to a conceptual implementation framework", *International Journal of Quality and Reliability Management*, Vol. 42 No. 4, pp. 1196-1223, doi: 10.1108/IJQRM-01-2024-0030.

Kaswan, M.S., Chaudhary, R., Rathi, R., Singh, M. and Bonamigo, A. (2026), "Mapping the lens of Industry 5.0 barriers for enriched sustainability: an Indian manufacturing perspective", *International Journal of Industrial Engineering and Operations Management*, pp. 1-22, doi: 10.1108/IJIEOM-09-2025-0205.

Khan, M., Haleem, A. and Javaid, M. (2023), "Changes and improvements in Industry 5.0: a strategic approach to overcome the challenges of Industry 4.0", *Green Technologies and Sustainability*, Vol. 1 No. 2, 100020, doi: 10.1016/j.grets.2023.100020.

Klein, L.L., Vieira, K.M., Alves, A.C. and Pissutti, M. (2023), "Demystifying the eighth lean waste: a knowledge waste scale", *International Journal of Quality and Reliability Management*, Vol. 40 No. 8, pp. 1876-1898, doi: 10.1108/IJQRM-01-2022-0020.

LeMahieu, P.G., Nordstrum, L.E. and Greco, P. (2017), "Lean for education", *Quality Assurance in Education*, Vol. 25 No. 1, pp. 74-90, doi: 10.1108/QAE-12-2016-0081.

Machado, C. and Nogueira, C. da S. (2025), "Industry 6.0: why talk about it now?", in Machado, C. and Davim, J.P. (Eds), *From Industry 4.0 to Industry 6.0*, ISTE/Wiley, London, pp. 291-305. doi: 10.1002/9781394372775.ch8.

Mann, D. (2015), *Creating a Lean Culture: Tools to Sustain Lean Conversions*, 3rd ed., CRC Press, Boca Raton, FL.

Medeiros, N.C.D., Godinho Filho, M., Callefi, M.H., Ganga, G.M.D., Magno Norte da Silva, J., Thürer, M. and Lizarelli, F.L. (2025), "Measuring employee involvement in Lean Manufacturing efforts: proposal of a robust scale", *International Journal of Production Research*, Vol. 63 No. 12, pp. 4590-4615, doi: 10.1080/00207543.2024.2448767.

Meher, J.R., Mishra, R.K., Panigrahi, R.R., Patel, G. and Jena, L.K. (2023), "Does learning culture enhance organisational performance? A serial mediator with knowledge management and organisational intelligence", *Knowledge Management Research and Practice*, Vol. 23 No. 2, pp. 107-118, doi: 10.1080/14778238.2023.2278729.

Nakash, M. (2026), "The hidden layers of knowledge management processes: a multidimensional framework for organisational KM excellence", *Journal of Knowledge Management*, Vol. 30 No. 11, pp. 189-213, doi: 10.1108/JKM-08-2025-1169.

Netland, T. and Fredriksson, A. (2019), "Lean production and digitalisation: complementarities and tensions", *International Journal of Production Research*, Vol. 57 No. 14, pp. 4445-4460, doi: 10.1080/00207543.2018.1530477.

Nonaka, I. and Takeuchi, H. (1995), *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation*, Oxford University Press, New York, NY.

Osmani, M., Zhang, T. and Cook, D. (2023), "Industry 6.0 and knowledge ecosystems: the next Frontier for digital transformation", *Technological Forecasting and Social Change*, Vol. 199, pp. 122-152, doi: 10.1016/j.techfore.2024.122152.

Passalacqua, M., Pellerin, R., Magnani, F., Doyon-Poulin, P., Del-Aguila, L., Boasen, J. and Léger, P.M. (2025), "Human-centred AI in Industry 5.0: a systematic review", *International Journal of Production Research*, Vol. 63 No. 7, pp. 2638-2669, doi: 10.1080/00207543.2024.2406021.

Pandey, V., Sircar, A., Bist, N., Solanki, K. and Yadav, K. (2023), "Accelerating the renewable energy sector through Industry 4.0: optimisation opportunities in the digital revolution", *International Journal of Innovation Studies*, Vol. 7 No. 2, pp. 171-188, doi: 10.1016/j.ijis.2023.03.003.

Pattanaik, S., Mohammed, M. and Sood, V. (2024), "Artificial intelligence and machine learning in Industry 6.0", in Em Reddy, C.K.K., Doss, S., Pamulaparty, L., Lippert, K. and Doshi, R. (Eds), *Industry 6.0: Technology, Practices, Challenges, and Applications*, CRC Press, Boca Raton, FL, pp. 37-54, doi: 10.1201/9781003517993.

Pearce, D., Dora, M., Wesana, J. and Gellynck, X. (2021), "Toward sustainable primary production through the application of lean management in South African fruit horticulture", *Journal of Cleaner Production*, Vol. 313, 127815, doi: 10.1016/j.jclepro.2021.127815.

Shahin, M., Maghanaki, M. and Chen, F.F. (2026), "Integration of lean analytics and Industry 6.0: a novel meta-theoretical framework for antifragile, generative AI-orchestrated, circular–regenerative, and hyper-connected manufacturing ecosystems", *Big Data Cognitive Computing*, Vol. 10 No. 2, p. 65, doi: 10.3390/bdcc10020065.

Singh, R., Tyagi, A. and Arumugam, S.K. (2023), "Imagining the sustainable future with Industry 6.0: a smarter pathway for modern society and manufacturing industries", in *Industry 6.0: Future*

Pathways for Sustainable Development, IGI Global, Hershey, PA, doi: 10.4018/978-1-6684-8531-6.ch016.

Snyder, K., Ingelsson, P. and Backstrom, I. (2016), "Enhancing the study of Lean transformation through organizational culture analysis", *International Journal of Quality and Service Sciences*, Vol. 8 No. 3, pp. 395-411, doi: 10.1108/IJQSS-04-2016-0027.

Solaimani, S., Haghighi Talab, A. and Van Der Rhee, B. (2019), "An integrative view on lean innovation management", *Journal of Business Research*, Vol. 105, pp. 109-120, doi: 10.1016/j.jbusres.2019.07.042.

Song, S. and Sun, J. (2018), "Exploring effective work unit knowledge management (KM): roles of network, task, and KM strategies", *Journal of Knowledge Management*, Vol. 22 No. 7, pp. 1614-1636, doi: 10.1108/JKM-10-2017-0449.

Sony, M. (2022), "Industry 6.0: human-centric and sustainable smart manufacturing", *Journal of Industrial Integration and Management*, Vol. 7 No. 3, pp. 345-365, doi: 10.1142/S2424862222500152.

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, doi: 10.1080/09537287.2019.1691278.

Storey, V. (2025), "Knowledge management in a world of generative AI: impact and implications", *ACM Transactions on Management Information Systems*, Vol. 16 No. 3, pp. 1-14, doi: 10.1145/3719209.

Tariq, A., Sumbal, M.S.U.K., Dabic, M., Raziq, M.M. and Torkkeli, M. (2024), "Interlinking networking capabilities, knowledge worker productivity, and digital innovation: a critical nexus for sustainable performance in small and medium enterprises", *Journal of Knowledge Management*, Vol. 28 No. 11, pp. 179-198, doi: 10.1108/JKM-09-2023-0788.

Tengblad, O., Olsson, A.K. and Eriksson, K.M. (2026), "Listening to the pulse – an exploration of manufacturing management and learning in the era of Industry 5.0", *Journal of Organizational Change Management*, Vol. 39 No. 8, pp. 125-142, doi: 10.1108/JOCM-05-2025-0464.

Verma, A., Prasad, V.K., Kumari, A., Bhattacharya, P., Srivastava, G., Fang, K., Wang, W. and Gadekallu, T.R. (2025), "Industry 6.0: vision, technical landscape, and opportunities", *Alexandria Engineering Journal*, Vol. 130, pp. 139-174, doi: 10.1016/j.aej.2025.08.040.

Werner, S.M. (2021), "Modelo de aprendizagem baseada em projetos para implementação de lean baseado em ciclos curtos de experimentação", *Production Engineering*, Universidade Federal de Santa Catarina, Florianópolis, p. 334.

Wiengarten, F., Gimenez, C., Fynes, B. and Ferdows, K. (2015), "Exploring the importance of cultural collectivism on the efficacy of lean practices: taking an organisational and national perspective", *International Journal of Operations and Production Management*, Vol. 35 No. 3, pp. 370-391, doi: 10.1108/IJOPM-09-2012-0357.

Womack, J.P., Jones, D.T. and Roos, E.D. (1990), *The Machine that Changed the World*, Rawson Associates, New York, NY.

Xu, L.D., Xu, E.L. and Li, L. (2021a), "Industry 5.0: towards human-centric solutions for the smart manufacturing era", *Computers and Industrial Engineering*, Vol. 164, 107874, doi: 10.1016/j.cie.2021.107874.

Xu, X., Lu, Y., Vogel-Heuser, B. and Wang, L. (2021b), "Industry 4.0 and Industry 5.0—inception, conception and perception", *Journal of Manufacturing Systems*, Vol. 61, pp. 530-535, doi: 10.1016/j.jmsy.2021.10.006.

Xuan (2025), "Determinants of carbon dioxide emissions in technology Revolution 6.0: new insights from Brunei", *Energy Strategy Reviews*, Vol. 57, 101633, doi: 10.1016/j.esr.2024.101633.

Yadav, R., Arora, S. and Dhull, S. (2022), "A pathway to industrial Revolution 6.0", *International Journal of Mechanical Engineering*, Vol. 7 No. 1, available at: https://kalaharijournals.com/resources/161-180/IJME_Vol7.1_178.pdf

Zahariev, P., Hristov, G., Chaisricharoen, R., Bencheva, N., Beloev, I., Zlatov, N., Le, C.H., Georgiev, G. and Kinaneva, D. (2024), "Industry 4.0 and beyond - present trends, emerging solutions and future technologies in the area of industrial automation", *Proceedings of the IEEE Conference.IEEE*, pp. 525-528, doi: 10.1109/ECTIDAMTNCON60518.2024.10479988.

Zarbo, R.J. (2012), "Creating and sustaining a Lean culture of continuous process improvement", *American Journal of Clinical Pathology,* Vol. 138 No. 3, pp. 321-326, doi: 10.1309/AJCP2QY1XGKTSNQF.

Zheng, T., Ardolino, M., Bacchetti, A. and Perona, M. (2023), "The road towards Industry 4.0: a comparative study of the state-of-the-art in the Italian manufacturing industry", *Benchmarking: An International Journal*, Vol. 30 No. 1, pp. 307-332, doi: 10.1108/BIJ-01-2021-0056.

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